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Physical Measurements Handbook

Tektronix, Inc.
P.O. Box 500
Beaverton, Oregon 97077

Physical Measurements Handbook
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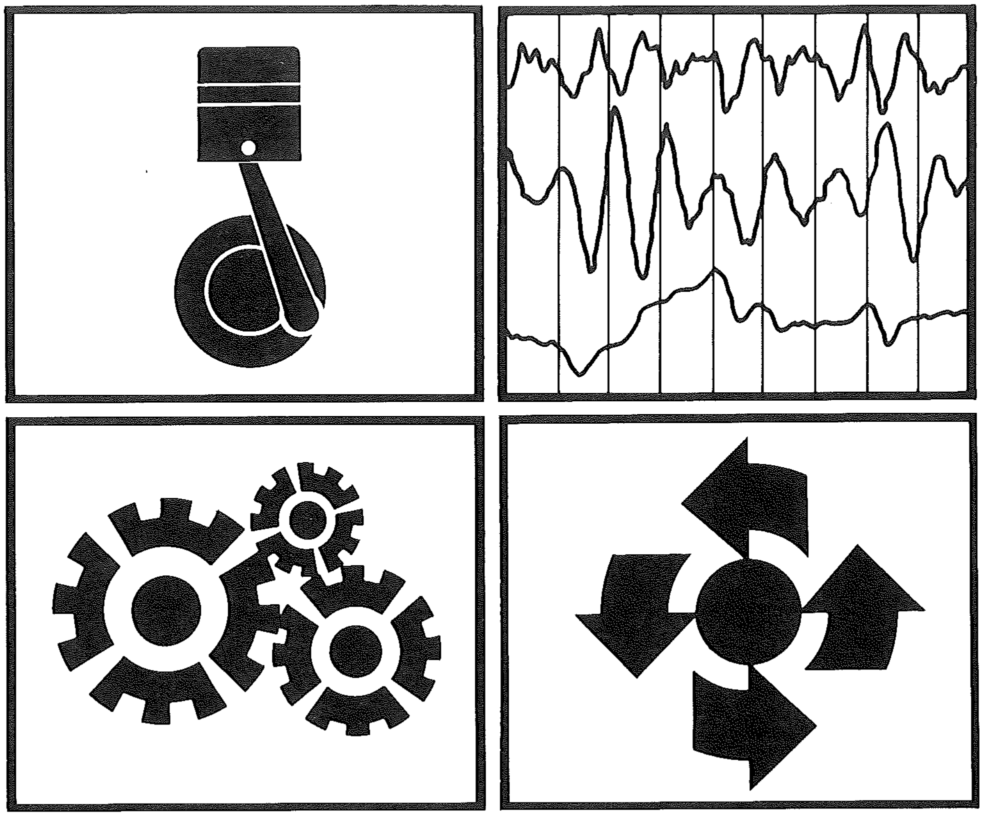

Preface

The primary purpose of this handbook is to supply the answers to the most commonly asked questions relating to the dynamic measurement and display of physical quantities. A great deal of literature is available on the theory of transducers and the application of specific electronic modules. One of the goals of this handbook is to tie these together to make specific measurements. The measurement parameter list is the focal point of this effort. The latter sections explain the background and techniques of measurements for the more common industrial applications of the oscilloscope. Additional articles on specific applications and application notes will be added to this handbook at regular intervals. Complete data are supplied for common transducers and special-purpose modules that are referenced in the parameter list.

Any ambitious effort such as this handbook is the result of the efforts of a large number of people. The assistance of customers, vendors, magazine editors, and applications engineers from various transducer companies is gratefully acknowledged, and specifically, the laboratory work of Bill Verhoef of Tektronix Engineering Department was important. In the process of reducing the vast amount of data these sources supplied, the author often glossed over the surface of many problems. If this has created gross errors or misconceptions, please send the blame and the corrections directly to the author.

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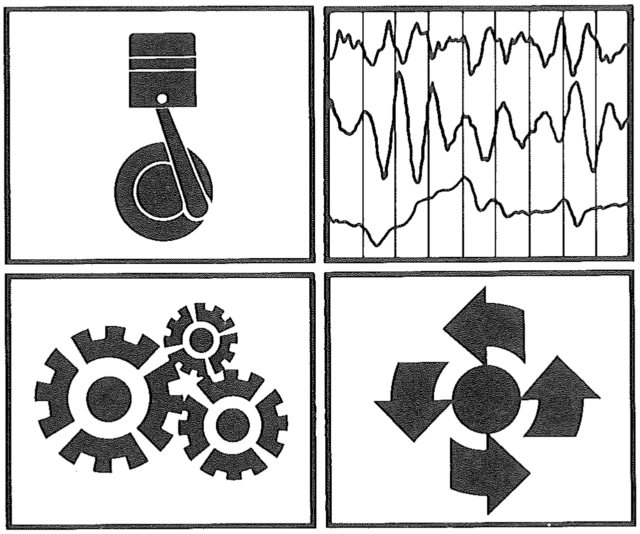

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Section I.

Section I. Introduction

1-1. Modular Concepts and Features

Tektronix offers a wide range of products in the instrumentation and measurements fields. The majority of these product families are built around modular plug-in designs. The remainder are mostly designed for extreme portability or low cost through small size or special designs that are application oriented. The principal Tektronix modular families are the 7000 Series, the 5000 Series and the TM 500 Series. The first two are oscilloscope families and the third is a low cost test and measurement instruments family. The TM 500-Series modules can be configured into mainframes holding from 1 to 6 plug-ins per unit. These come in benchtop, rackmount, SCOPE-MOBILE cartmounted, and portable traveler models. This family design encompasses over 40 different modules from Tektronix and other manufacturers. The TM 500 is becoming a truly universal package design.

TM 500 allows you to assemble a specialized package of instruments to meet your individual measurement needs. Or you may pick one of the standard combinations suggested in this handbook. You may also select an assortment of mainframes and an inventory of plug-in instruments, and then have the freedom to make one kind of measurement today and an entirely different one tomorrow. A condensed module description is given at the end of this handbook and a complete TM 500 module description is available in the Tektronix General Catalog or the TM 500 Family Catalog.

The 7000-Series Oscilloscopes are the finest quality laboratory oscilloscopes available. The series features a wide variety of display types, mainframe performance ranges, and an assortment of plug-in modules.

Mainframes include storage and non-storage displays. The storage types include bistable, variable persistence, and multimode displays. Three of the 10 available mainframes are used and discussed in this handbook. There are 34 different modules available.

These modules cover a wide range of signal levels, frequencies, and measurement techniques. Of these, two amplifiers, one time base, one spectrum analyzer, one digital counter, and one digital voltmeter are used in systems shown in this handbook. Complete information on all 34 modules is available in the Tektronix General Catalog or in the 7000-Series Family Catalog.

The 5000-Series Oscilloscopes are a family of low cost modular laboratory oscilloscopes. The family consists of eight mainframe types and 24 plug-in modules. Mainframe displays are available in both storage and non-storage models. The 5111 Bistable Storage Unit is the most widely used oscilloscope for transducer-oriented measurements. Amplifier plug-ins come with 1, 2 or 4 channels to allow for up to 8 traces at one time. There is a plug-in spectrum analyzer (5L4N), a transistor curve tracer (5CT1N), and a low level differential amplifier (5A22) for transducer signal processing. Short form data on selected modules are included at the end of this handbook and complete information is available in the Tektronix General Catalog.

In addition to the instruments mentioned above, a complete line of cameras, SCOPE-MOBILE® Carts, and accessories are available to support these products in making up complete measurement solutions for difficult instrumentation problems.

1-2. Special Systems and Applications

One of the major benefits inherent in the Tektronix modular-design concept is the flexibility it offers the user in dealing with specific applications problems. For example, with the 40 plus TEKTRONIX TM 500 Modules and 6 power mainframes to choose from, a very large number of combinations are available to meet the most difficult and exacting measurement requirements. Add to this the synergistic effect of intermodule connections, analog outputs, digital outputs, and a number of compatible TEKTRONIX Oscilloscopes, Calculators, and Special Accessories, and the true extent of the TEKTRONIX TM 500 versatility becomes apparent.

Largely as a result of planning, but also because of customer alertness to the full potential of the TM 500-Series, a number of identifiable special-purpose systems have appeared since the line was introduced. Common to all these systems is functional economy; that is, the packaging of all functions necessary to a particular task or group of tasks in a single, portable or mobile unit that results in appreciable savings in space, weight, labor, and capital expenditures.

A number of application areas are well suited to the systems approach. Among these are equipment maintenance, industrial instrument calibration, industrial controls calibration, and professional-vocational training. In each of these areas, large numbers of tests and measurements must be performed, each possibly requiring a different type of instrument. By housing these instruments in a common power supply mainframe with an internal connection arrangement, the usual tangle of power cords and interconnection cables is eliminated. Standardized front-panel markings and controls lead to a reduction in human error. Portability (or mobility in the case of the more sophisticated systems) is enhanced to a degree heretofore unobtainable. Finally, the TM 500 Systems or package approach eliminates the necessity for dealing with a variety of suppliers, each with its own sales, service, and support policies.

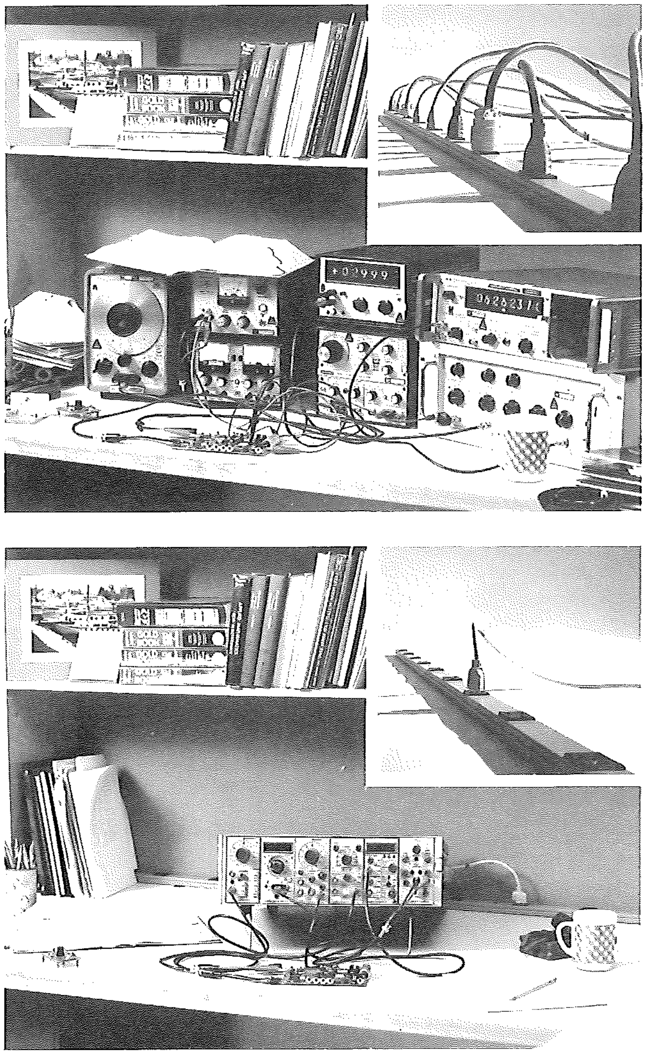


Figure 1-1. Before and after TM 500

1-3. General-Purpose Industrial Test Sets

In recent years, electronic technology has spread rapidly into dozens of new applications areas, all requiring new sophistication in electronic instrumentation. Tektronix recognized early that industry had special requirements for test instruments, and designed systems to meet those requirements.

Industrial process control, computer-aided control, numerical control, and automated production equipment all pose one major problem that was forgotten by many planners. When something breaks, the machine cannot be taken to the local TV service shop. While circuit board cards may be unplugged for checkout or service, generally, service equipment must be brought to the machine, and it must be the right equipment. The TM 500 Mobile Test Lab allows you to roll an extensive laboratory of equipment throughout your plant. What's more, the modular nature of the TM 500-Series allows you to make up the system that best fits your needs.

Machines using position servos often require very sensitive instruments with special analog circuits such as differential input amplifiers, filters, ramp generators, function generators, digital multimeters, power

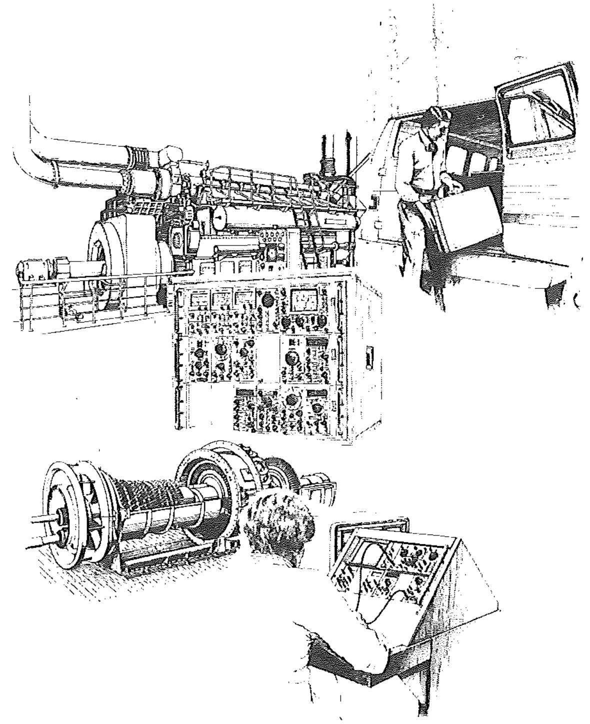


Figure 1-2. Various Applications with TM 500

supplies, and special purpose add point simulators. All of these are available as parts of various TM 500-Series test sets from Tektronix.

1-4. Mechanical Systems Measurements

Preventive maintenance is increasingly important as production processes become more closely linked into connected systems. Delivery times for even simple replacement parts often stretch to months and major subassemblies can take more than a year to produce; and often, the new parts cost five to ten times more than the original ones. Even where continuing operation is vital, redundant machinery is usually just too expensive or not available.

The way to avoid being surprised by sudden malfunctions is to conduct periodic performance monitoring, examine the trends these data indicate, and perform preventive maintenance. As part of a wide range of electronic instrumentation equipment, Tektronix offers several TM 500 Units designed to measure, qualify, and diagnose problems in mechanical systems. Some instruments may be used alone for jobs as simple as bearing monitoring, or several may be combined for inplace balancing equipment or sophisticated engine or turbine analysis systems. Some of the systems are enhanced by calculator or computer data reduction or control.

Mechanical measurement problems cover a wide range of parameters, and each situation may be very different, making custom instruments for each application almost a must. The TM 500 Family of modular test and measurement instruments is an almost ideal vehicle for this. Using TM 500 modularity, the right selection of instruments can be custom assembled for each job, with necessary changes for each new task made in seconds. Although the possibilities are virtually limitless, the following sections give some short descriptions of a few of the many TM 500 combinations that can be put together for mechanical measurement applications.

1-5. Multichannel and Transducer Data Acquisition

Multichannel data acquisition techniques are as varied as the applications. A few cases require multichannel acquisition and processing of one signal or transducer type, but most applications involve several signal types. The modular TM 500 Family and plug-in oscilloscopes allow implementation of a wide variety of systems solutions to multichannel data acquisition problems.

The key ingredients of transducer-based systems are: (1) transducer excitation, (2) signal processing, and (3) data display. Both active (self-generating) and passive transducers are common. Though active transducers require no electrical excitation source, passive transducers do. The TM 500 Family has a series of standard and modified power supplies available for transducer excitation. Both floating, grounded, and both fixed and precision adjustable power supply combinations are available in the PS 501-1 Series. Active transducers do not require excitation power, but do require special signal conditioning and processing. The TM 500 Signal Conditioning Modules include a family of special differential amplifiers with filters and an operational amplifier that may be component programmed to yield any desired signal processing characteristic.

Data display may take the form of either digital or multitrace oscilloscope patterns. The range of display sizes available run from the SC 501 (1.2x2.0 inches) to the 5100-Series (6.5 inches diagonally). In simple, multichannel, parallel acquisition, parallel display forms, banks of SC 501's have been used, each displaying one signal. In other applications, eight simultaneous displays have been shown on one 5111 with standard modules. Both digital voltmeters and digital counters may be used as digital data readout devices, as well as the digital printer of the calculator.

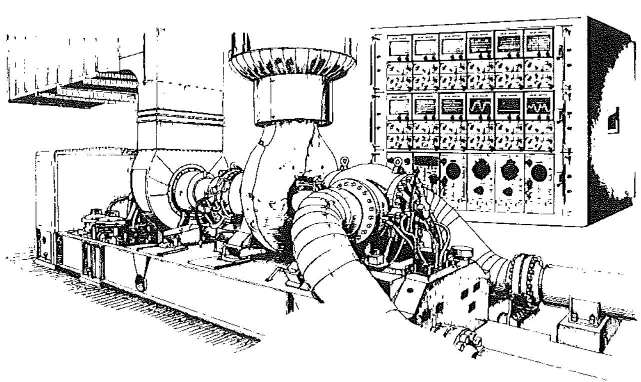


Figure 1-3. Multichannel Testing with TM 500

Section 2.

Section 2. Measurement Parameters

2-1. Introduction

Since this is a dynamic world, almost all applications of physical quantities require dynamic acquisition, measurement, and display of these quantities. Practical electronic measurements of physical quantities use transducers that transform either physical energy, or a change in physical dimension to electrical energy for processing and display. This section describes a series of transducers that are representative of the more commonly used units. Applications, specifications, dimensions, and accessories are listed in some detail.

This handbook is not intended to teach basic transducer theory, but to show proven solutions to common physical measurement problems. If you feel you need more data to understand the particular transducer or measurement problem, please consult the reference material sources listed at the end of each section.

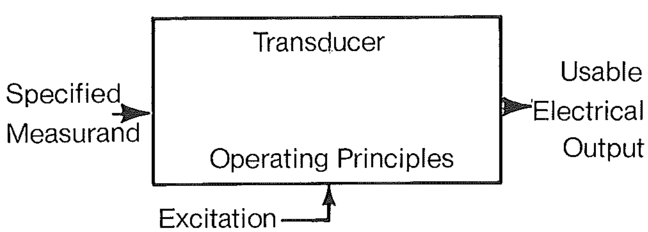


Figure 2-1. Transducer Symbolic Representation

2-2. Definition of Common Transducer Terms

TRANSDUCER—A device that provides a usable electrical output in response to a specified physical measurand (also called a sensor).

MEASURAND—A physical quantity, property or condition that is measured (i.e., pressure, force, length).

SENSITIVITY—The ratio of the scale in transducer output to a change in the value of the measurand (sometimes called scale).

THRESHOLD—The smallest change in the measurand that will result in a measurable change in transducer output (sometimes called resolution or dead zone).

OPERATING PRINCIPLES—The nature of: (1) the sensing principle, and (2) the transduction principle necessary to sense the measurand and produce an output signal.

EXCITATION—The external electrical voltage or current applied to a transducer to power its operation.

OUTPUT—The electrical signal form that is produced by a transducer, and that is a function of the applied measurand.

OVERLOAD—The maximum magnitude of measurand that can be applied to a transducer without causing an irreversible change in performance beyond the specified tolerance.

NATURAL FREQUENCY, DAMPED—The frequency of free (not forced) oscillations of the sensing element of a transducer in a specified installed environment.

NATURAL FREQUENCY, UNDAMPED—The natural frequency if no damping were present. NOTE: At this frequency, the output of a transducer lags a sinusoidally varying measurand by 90 degrees.

TIME CONSTANT—The length of time required for the output of a transducer to rise to approximately 63 percent of its final value as a result of a step change in the measurand.

STABILITY—The ability of a transducer to retain its performance throughout its specified operating and storage life.

CYCLING LIFE—The specified minimum number of full range excursions or specified partial range excursions over which a transducer will operate as specified without changing its performance beyond specified tolerances.

OPERATING LIFE—The specified minimum length of time over which the specified continuous and intermittent rating of a transducer applies without change in transducer performance beyond specified tolerances.

STATIC ERROR BAND—The error band applicable at room conditions and in the absence of any vibration, shock, or acceleration. NOTE 1: The maximum spread that occurs between the limits of the static error band, expressed as percent of full scale output. NOTE 2: Error band and error are defined as follows:
ERROR BAND—The band of allowable deviations of output values from a specified reference line or curve that are from causes attributable to the transducer, as measured over two consecutive calibration cycles.
ERROR—The algebraic difference between the indicated value and the true value of the measurand, usually expressed in percent of the output reading of the transducer.

REPEATABILITY—The ability of a transducer to reproduce output readings when the same measurand value is applied repeatedly, under the same conditions, and in the same direction. NOTE: Repeatability is expressed as the maximum difference between output reading; it is expressed specifically as "within X percent of full scale output."

TRANSFER FUNCTION—A mathematical, graphical, or tabular statement of the influence of a system or element on a signal or action at input or output terminals. NOTE: For a linear system, general usage limits the transfer function to the ratio of the Laplace transforms of the input and output in the absence of all other signals, and with initial conditions zero.

2-3. Parameter Measurements List

This section lists the 18 most common physical measurement parameters, the mathematical symbol of each, the unit in which each is specified, and the common methods of measurement and display. Particular emphasis is directed toward methods using established common physical principles available from several vendors rather than the proprietary sole-source items. In some cases, the functional ranges specified are achieved by several rather than one transducer. The following description of column headings explains in general what is included in each. In the cases where transducer part numbers are listed, these use the transduction principle listed but do not necessarily match the specifications listed or implied in the column of functional ranges and resolution.

Column Headings

1. MEASUREMENT PARAMETER
   The quantity to be measured is listed in capital letters with alternate terms listed in brackets.
2. SYMBOL
   The preferred symbol used in most physics and engineering activities.
3. S. I. UNITS
   The new Standard International Metric units (S. I.), as defined by NBS, are listed first, then the alternate units are listed in order of descending preference. English units are listed last in brackets. For brevity the more common abbreviated form of the nomenclature is used.
4. TRANSDUCTION PRINCIPLE
   The physical and electrical sensing form is listed for the more commonly used transducers. A more generalized term is often used instead of trade names. No order of preference is attempted. All items listed are generally available and represent the majority of installed units.
5. FUNCTIONAL RANGES
   The functional ranges of commercially available instruments are listed. These values do not indicate resolution, sensitivity, or the various factors making up the accuracy of the transducer. In some cases, the resolution, static error, or general accuracy are listed in brackets to allow some coarse evaluation of relative techniques.
6. TRANSDUCER DESCRIPTION
   This column explains some of the details of the transducer's operation or electrical signal pickoff. Where part numbers are listed, a representative transducer of this type is specified in detail in the next section of this handbook. This unit will be of the type but not necessarily the same specifications as listed in column 5.
7. SIGNAL CONDITIONING
   The excitation and signal conditioning requirements of each transducer type is listed here, with the part number of a typical type that will meet the requirements directly, or with the addition of common components of convenience. More detail on this equipment is included elsewhere in this handbook.
8. READOUT—DISPLAY
   The preferred display or readout equipment is listed for each transducer type. In many cases this is repetitive, but in others in which a group of common transducer types and signal forms are available, the displays are listed in order of preference. More detail on this equipment is listed elsewhere in this handbook.

TO OBTAIN → FROM (BELOW) MULTIPLY BY ↘	LBS. PER SQUARE INCH	PASCALS OR NEWTONS PER SQUARE METER	(TORR) MILLIMETERS OF MERCURY	INCHES OF WATER	INCHES OF MERCURY	MILLIBARS	ATMOSPHERES	OUNCES PER SQUARE INCH	GRAMS PER SQUARE CM	POUNDS PER SQUARE FOOT	DYNES PER SQUARE CM	KILO-PASCALS
LBS. PER SQUARE INCH	1	* 6.895×10^{3}	51.71	27.70	2.036	68.95	6.803×10^{-2}	16.00	70.31	144.0	6.895×10^{4}	6.895
PASCALS OR NEWTONS PER SQUARE METER	1.45×10^{-4}	1	7.502×10^{-3}	4.014×10^{-3}	2.952×10^{-4}	10^{-2}	9.869×10^{-6}	2.320×10^{-3}	1.0197×10^{-2}	2.088×10^{-2}	10	10^{-3}
MILLIMETERS OF MERCURY (TORR)	1.93×10^{-2}	* 133.3	1	0.5353	3.937×10^{-2}	1.33	1.316×10^{-3}	0.3094	1.360	2.785	1.333×10^{3}	0.1333
INCHES OF WATER	3.61×10^{-2}	* 2.491×10^{2}	1.868	1	7.355×10^{-2}	2.49	2.46×10^{-3}	0.5782	2.54	5.202	2.491×10^{3}	0.2491
INCHES OF MERCURY	0.4912	3.386×10^{3}	25.4	13.596	1	33.86	3.342×10^{-2}	7.851	34.5	70.70	3.386×10^{4}	3.386
MILLIBARS	1.45×10^{-2}	* 100	0.750	0.4014	2.952×10^{-2}	1	9.869×10^{-4}	0.2320	1.0197	2.088	10^{3}	0.1
ATMOSPHERES	14.70	1.0133×10^{5}	760	406.8	29.92	1.0133×10^{3}	1	2.351×10^{2}	1.033×10^{3}	2.117×10^{3}	1.0133×10^{6}	101.33
OUNCES PER SQUARE INCH	6.25×10^{-2}	4.31×10^{2}	3.232	1.729	0.1272	4.31	4.253×10^{-3}	1	4.394	9.00	4.31×10^{3}	0.431
GRAMS PER SQUARE CM	1.422×10^{-2}	* 98.07	0.7357	0.394	2.896×10^{-2}	0.98	9.678×10^{-4}	0.2276	1	2.0481	9.807×10^{2}	9.807×10^{-2}
POUNDS PER SQUARE FOOT	6.944×10^{-3}	* 47.88	0.3591	0.1922	1.414×10^{-2}	0.478	4.72×10^{-4}	0.1111	0.4883	1	4.788×10^{2}	4.788×10^{-2}
DYNES PER SQUARE CM	1.450×10^{-5}	10^{-1}	7.500×10^{-4}	4.0147×10^{-4}	2.953×10^{-5}	10^{-3}	9.869×10^{-7}	2.32×10^{-4}	1.0197×10^{-3}	2.088×10^{-3}	1	10^{-4}
KILO-PASCALS	0.145	10^{3}	7.502	4.014	0.2953	10	9.869×10^{-3}	2.320	10.197	20.88	10^{4}	1

*From NBS Circular

MEASUREMENT PARAMETER	SYMBOL	S.I. UNITS (ENGLISH UNITS)	TRANSDUCTION PRINCIPLE	FUNCTIONAL RANGES (RESOLUTION)	*TRANSDUCER DESCRIPTION PART NUMBER—ELECTRICAL SIGNAL	SIGNAL CONDITIONING TYPE NUMBER—DESCRIPTION	READOUT—DISPLAY TYPE NUMBER—DESCRIPTION
LINEAR DISTANCE	l	meters, m	Capacitance, incremental or differential	10^{-6} to 1 meter (10^{-7} m)	Differential bridge circuit, phase detector	Excitation—FG 503 Function Generator	DM 501 Digital Multimeter, DC VOLTS mode
(Displacement)	X	centimeters, cm	Inductive, eddy current, variable reluctance	10^{-4} to 10^{-2} meters (10^{-7} m)	Special circuitry—linearizing	Scale factor potentiometer—RC filter	DM 502 Digital Multimeter, DC VOLTS mode
(Dimension)	S	millimeters, mm					
(Position)		micrometers, μm	Strain gage, bonded, or semiconductor	10^{-5} to 10^{-1} meters (10^{-7} m)	PN 015-0164-00 Universal cell	PS 501-1 MOD 730E Transducer Power Supply	DM 501 MOD 718D Digital Multimeter
		(inches, in.)					
		(feet, ft.)	Linear Voltage Differential Transformer (LVDT)	10^{-3} to 5 meters (10^{-6} m)	PN 015-0168-00 Displacement transducer	Excitation—FG 503/AM 501 ac power supply	DM 501 Digital Multimeter
			Optical, photo electric, or Laser Interferometer	10^{-6} to 10^{4} meters (10^{-8} m)	Shadow mask or interference pattern effects	Vendor-supplied analog or digital circuitry	—
			Linear Potentiometer	5×10^{-3} to 1.5 meters (2×10^{-4} m)	Resistance voltage divider	Excitation—PS 503A Power Supply	DM 502 Digital Multimeter, DC VOLTS mode
			Linear (Digital) Encoders	10^{-1} to 10 meters (10^{-5} m)	Electrical or optical phase interference patterns	Vendor-supplied digital circuitry logic signals	DC 503 or DC 505A Universal Counters
LINEAR VELOCITY		meters per second	Inertial Mass—Magnetic field—self generating	2.5×10^{-4} to 2.5 meters/sec	PN 015-0166-00 and 015-0167-00 Vibration transducers	7A22 Differential Preamplifier	7313 Storage Oscilloscope 7B53A sweep unit
Speed		m/s	Pendulous Mass—Spring—LVDT	± 0.3 to ± 150 meters/sec (0.1% F.S.)	Displacement of pendulum measured by LVDT	Excitation (ac) FG 503/AM 501	DM 501 Digital Multimeter, AC VOLTS mode
	$\dot{X}$	kilometers per second	—Potentiometer	1 to 100 meters/sec (1% F.S.)	Wiper moved by pendulum	Excitation (dc) PS 503A	DM 502 Digital Multimeter, DC VOLTS mode
	V		Inductive—attached linkage	2.5×10^{-4} to 12.5 meters/sec (10^{-4} m/s)	Motion of magnetic core	Excitation (ac) FG 503/AM 501	DM 502 Digital Multimeter, AC VOLTS mode
			—non-contact	0.1 to 10 meters/sec (1% F.S.)	emf generated by induced magnetic field	R-C Filter	DM 502 Digital Multimeter, DC VOLTS mode
	$\dot{S}$		Optical—time differential	0.3 to 3×10^{4} meters/sec (1 millisecond)	Photo cell—light beam	—	DC 503 or DC 505A Universal Counter, TIME A→B
			Piezoelectric—integrated acceleration	10^{2} to 3×10^{3} meters/sec (0.01 m/s)	Integration of linear accelerometer	AM 501 Operational Amplifier—Integrator	5111 Storage Oscilloscope 5A18/5B10 plug-ins
LINEAR ACCELERATION	a	meters per	Seismic Mass—piezoelectric	2×10^{-3} to 10^{5} g (10^{-5} F.S.)	PN 015-0165-00 Accelerometer	5A22 Differential Preamplifier	5111 Storage Oscilloscope with 5B10 time base
	g	second per second	—piezoresistive	1 to 10^{3} g (10^{-4} F.S.)	Force from mass causes resistance change	both { PN 015-0169-00 Strain gage bridge	AM 502 Differential Amplifier
		m/s²	—strain gage	1 to 10^{3} g (10^{-4} F.S.)	Deflection of support causes resistance change	PS 501-1 MOD 730E Transducer Power Supply }	SC 502 Oscilloscope
	$\ddot{X}$	(feet per second per	—LVDT	1 to 100 g (0.3% F.S.)	Movement of mass measured by LVDT	Ac excitation FG 503/AM 503	SC 503 Storage Oscilloscope
		second, F/S²)	—inductive	1 to 10^{4} g (10^{-3} F.S.)	Movement of mass disturbs magnetic field	Linearizing electronics	5111 Storage Oscilloscope with 5A15N and 5B10N
			—capacitance	± 3 to ± 5×10^{3} g (10^{-4} F.S.)	Differential capacitance balance changed	Ac excitation FG 503 Function Generator	7313 Storage Oscilloscope with 7A22 and 7B50
			—potentiometer	2 to 200 g (0.5% F.S.)	Wiper moved by position change of mass	Dc excitation PS 503A	DM 502 Digital Multimeter
			Force balance servo	0.1 to 100 g (10^{-6} g)	Restoration current linear with force	± 15 volts from PS 503A Power Supply	DM 501 Digital Multimeter
ANGULAR DISPLACEMENT	θ	radians, r	Capacitor	5×10^{-6} to 3 radians (10^{-4} F.S.)	RF tuned oscillator circuit	RF Isolation Amplifier	DC 501 Digital Counter
		(degrees)	Inductive	10^{-3} to 2.5 radians (0.4% F.S.)	RF tuned oscillator circuit	RF Isolation Amplifier	DC 501 Digital Counter
		revolutions	Resistor	1 to 62 radians (10^{-4} F.S.)	10 turn potentiometer	PS 501-1 Instrument Power Supply	DM 501 Digital Multimeter
		(cycles)	Photo electric	10^{-4} to 6.2 radians (10^{-5} F.S.)	PN 015-0108-01 Rotary Function Generator	PS 501-1 MOD 730F RFG Power Supply	7313 Storage Oscilloscope with 7A18 and 7B53A
		(arc-seconds)	Strain gage	5×10^{-2} to 0.2 radians (0.2% F.S.)	Flat spring deflection	PN 015-0169-00 and PS 501-1 MOD 730E	DM 502 Digital Multimeter
			LVDT (rotary)	5×10^{-6} to 3 radians (10^{-5} F.S.)	Shorted turn differential transformer	Ac excitation FG 503/AM 501; phase detector	DM 501 MOD 718D Digital Multimeter
			Gyroscope	±0.1 to ±1 radian (0.5%)	Precession of gyro	Heater power plus ac excitation FG 503/AM 501	DM 502 Digital Multimeter
			Shaft Encoder, digital	10^{-5} to 6.2×10^{3} radians	Optical shadow mask—photo cells—logic circuits	+ 5 volts excitation from PS 501 or PS 503A	DC 503 or DC 505A Universal Counters
Inclinometer	θ	radians	Pendulum—Potentiometer	±0.5 radian (0.002 radian)	Pendulum displacement set pot wiper	Excitation PS 503A	DM 501 Digital Multimeter
		(grade)	Force balance—accelerometer—integrator	±0.6 radian (10^{-3} F.S.)	Current pulses to integrator nulls accelerometer	Excitation PS 501-1	DM 502 Digital Multimeter
		(degrees)	Liquid—resistor	±0.5 radian (0.02 radian)	Liquid shunts high resistance element	Excitation PS 503A	DM 502 Digital Multimeter
ANGULAR VELOCITY	θ	radians per	Generator, dc	4 to 6×10^{4} r/s (1% F.S.)	Permanent magnet stator and brushes	R-C low pass noise filter	DM 502 Digital Multimeter
(Tachometer)		second	, ac	1 to 6×10^{3} r/s (0.2% F.S.)	Permanent magnet rotor	—	DC 504 Digital Counter
		r/s	, drag cup	5 to 5×10^{3} r/s (1% F.S.)	Ac stator, slip rings, phase detector	Excitation (ac) FG 503/AM 501	DM 502 Digital Multimeter
		(rpm)					
			Photo electric or magnetic pulse wheel	10^{-2} to 5×10^{3} r/s (10^{-4} F.S.)	N pulses per revolution	+ 5 volt excitation from PS 501 or PS 503A and PG 501 Pulse Generator with R-C filter	DC 504 Digital Counter in RPM mode 5111/5B10/5A22 Storage Oscilloscope
ANGULAR ACCELERATION	$\ddot{\theta}$	radians per	Electromagnetic + differentiator	to 10^{4} r/s (10 r/s²)	Series pickup coils—diode circuit	No excitation required	DM 501 Digital Multimeter
		second per second	Force balance servo	1 to 3×10^{3} r/s² (10^{-5} F.S.)	Internal circuit balances mass	± 15 volt excitation PS 503A	DM 501 Digital Multimeter
		r/s²					
			Digital Shaft Encoder	10 to 10^{4} r/s² (1% F.S.)	Machine tool digital shaft encoder	PG 501 Pulse Generator plus 4 stage R-C network	SC 503 Storage Oscilloscope

*Note: Part numbers supplied are of the type but not necessarily the same specifications. See Section 2-4 for the exact specifications for these particular part numbers listed.

MEASUREMENT PARAMETER	SYMBOL	S.I. UNITS (ALTERNATE UNITS)	TRANSDUCER DESCRIPTION	FUNCTIONAL RANGES (RESOLUTION)	TRANSDUCER (OR ELECTRICAL PICKOFF) PART NUMBER—DESCRIPTION	SIGNAL CONDITIONING TYPE NUMBER—DESCRIPTION	READOUT/DISPLAY TYPE NUMBER—DESCRIPTION
PRESSURE	Pa, p	Pascal	Bellows—Potentiometer	0.1 to 100 psi (2% F.S.)	——variable resistance	PS 503A Power Supply	DM 501 or DM 502 Digital Multimeter, dc voltage
		Newton per					
		square meter	Capsule—Differential transformer—(LVDT)	10^{-3} mm Hg to 1000 psi (0.5%)	——ac voltage ratio	FG 503/AM 501 ac power supply	DM 501 or DM 502 Digital Multimeter, ac voltage
		N/m^2					
		(psi)	Diaphragm—Strain Gage	1 mm Hg to 1 psi (0.5%)	015-0161-00 (Strain gage) 0-3000 psig	both {PS 501-1 MOD 730E Transducer Supply	(1) TM 504/SC 502 Oscilloscope
		(mm Hg)		up to 10,000 psi (0.25%)	015-0162-00 (Strain gage) 0-300 psig	AM 502 or 5A22 or 7A22	(2) 7313 Oscilloscope, 7B53A, TM 504, DM 502
			Diaphragm—Piezoresistive	up to 10,000 psi (1% F.S.)	——variable resistor-bridge circuit	Excitation PS 503A Signal Processing AM 502	same as two alternates above
			Diaphragm—Piezoelectric	up to 10,000 psi (2% F.S.)	015-0117-00 (piezoelectric) 0-3000 psi	AM 502/5A22/7A22 plus shunt capacitor	5111m 7313 or SC 503 Storage Oscilloscope
			Diaphragm—Variable Capacitance	10^{-6} mm Hg to 20 psi (0.1% F.S.)	——differential capacitance or ac voltage	FG 503/AM 501 ac power supply	DM 501 or DM 502 Digital Multimeter
				up to 10,000 psi (.01% F.S.)	——		
			Diaphragm—Variable Inductance	0.1 to 5,000 psi (1% F.S.)	——ac or dc voltage from internal circuit	FG 503/AM 501 ac power supply	SC 502, 5110, SC 503 Oscilloscope
				(span)			
FLOW METERS		Cubic meter	Positive Displacement—Volumetric—liquid	0.5 to 2000 gpm (10:1)	——N pulses per gallon	DD 501 Digital Delay (÷ by N mode)	DC 503 Universal Counter
		per second	Positive Displacement—Volumetric—gas	0.01 to 300 cfm (100:1)	——N pulses per cubic foot per minute	DD 501 Digital Delay (÷ by N mode)	DC 504 Digital Counter
		m^3/sec	Differential Pressure—orifice	0.1 to 10,000 cfm (10:1)	——two strain gage pressure transducers}	both {2-PS 501-1 MOD 730E Transducer Supply	{Blank plug-in square root circuit or 2 display meters
		(sc cm)	$Q=K\sqrt{\frac{P2}{P1}}$ —Venturi	0.01 to 1000 cfm (100:1)	——two strain gage pressure transducers}	2-AM 502 Differential Amplifier	DM 502 Digital Multimeter
		(ft^3/min) (cfm)	—Pitot tube	0.001 to 100 cfm (5:1)	——two bellows—LVDT	PS 501-1 Power Supply	2-DM 502 Digital Multimeter (or Altimeter and Airspeed)
		(gpm)					
		(ccm)	Turbine—velocity—liquid	0.01 to 10,000 gpm (20:1)	——N pulses per gallon per minute	DD 501 Digital Delay (÷ by N mode)	DC 505A Universal Counter
			—gas	1 to 10,000 cfm (50:1)	——N pulses per cubic foot per minute	DD 501 Digital Delay (÷ by N mode)	DC 503 Universal Counter
			Magnetic—velocity	500 cc/min 100,000 gpm (1000:1)	——ac voltage excitation and output	AM 502 Differential Amplifier	DM 501 Digital Multimeter
			Variable area—float meter	50 cc/m to 300 gpm (12:1)	——dc-LVDT with dc excitation and output	PS 501-1 MOD 730E Transducer Power Supply	DM 502 Digital Multimeter—ac voltage
			—force meter	0.1 to 320 gpm (10:1)	——dc signal from internal electronics	PS 503 Power Supply	DM 502 Digital Multimeter—dc voltage
		Kilogram per second					
		Kg/s, (SCCM)	Thermal—mass flow	0.01 to 100,000 SCCM (200:1)	——dc signal	AM 502 Differential Amplifier	DM 501 Digital Multimeter—DC VOLTS
		(SCFM) (lb/min)	Differential Pressure—mass flow	1 to 5,000 lb/hr (6:1)	——strain gage differential pressure transducers	PS 501-1 MOD 730E and AM 502 amplifier	DM 502 Digital Multimeter—DC VOLTS
		(lb/hr)	Turbine—axial—momentum—mass flow	0.1 to 1000 lb/min (10:1)	——N pulses per lb per minute	DD 501 Digital Delay (÷ by N mode)	DC 503 Universal Counter
				(accuracy)			
TEMPERATURE	t	Degrees Celsius	Thermocouple—K—Chromel-Alumel	0-1250°C (±2.2°C)	——millivolt dc	junction compensation—ice point reference	DM 501 MOD 718D Digital Multimeter
		°C	J—Iron-Constantan	-0 to 750°C (±2.2°C)	——millivolts dc	junction compensation—ice point reference	DM 501 MOD 718D Digital Multimeter
		(°F)	B—Platinum-Rhodium	800 to 1700°C (±0.5%)	——millivolts dc	junction compensation—ice point reference	DM 501 MOD 718D Digital Multimeter
		(°K)	T—Copper-Constantan	-184 to 370°C (±1%)	——millivolts dc	junction compensation—ice point reference	DM 501 MOD 718D Digital Multimeter
		(°R)	RTD—Platinum	-270 to 650°C (0.02%)	3.92 milliohms per degree Celsius-Wheatstone bridge	AM 501 Operational Amplifier—Diff. Amp.	DM 501 Digital Multimeter—dc volts
			—Nickel	-75 to 150°C (0.2%)	6.7 milliohms per degree Celsius-Wheatstone bridge	AM 501 Operational Amplifier—Diff. Amp.	DM 501 Digital Multimeter—dc volts
			—Thermister	-75 to 260°C (0.5°C)	——incremental resistance	ohmmeter	DM 501 Digital Multimeter (Option 2)
			Semiconductor junction	-55 to 150°C (1.5°C)	P6058 for DM 501 or P6430 for DM 502	circuitry internal to DM 501 and DM 502	DM 501 or DM 502 Digital Multimeter (std)
			Pyrometer—radiation	315 to 4200°C (±5%)	——dc signal from internal circuits	——	——
			—Optical	700°C and up (±4%)	——dc signal from internal circuits	——	——
				(accuracy)			
VISCOSITY	η, (μ)	Newton-second	Falling—Ball	1 to 10,000 cp (±1%)	——manual time measurement	human observer-operator	DC 501 Digital Counter—MANUAL mode
Absolute-poise		per square meter	—Piston	0.1 to 1,000,000 cp (±0.1%)	——automatic time measurement	PS 503A Power Supply	DC 503 Universal Counter—TIME A→B mode
Dynamic-stoke		$N\text{-}s/m^2$					
		(dyn-sec/cm^2)	Capillary or Orifice (Saybolt)	0.5 to 100,000 cp (±0.25%)	——time for fixed force	PS 503A Power Supply	DC 503 Universal Counter—TIME A→B mode
		centipoise, cp					
			Rotating member	1 to 12 million cp (±0.5%)			
					Force measurement by rpm or Δt		DC 504 Digital Counter—RPM mode
				(accuracy)			
HUMIDITY		Relative Humidity	Animal hair—mechanical linkage	10% to 100% R.H. (±5%)	mechanical linkage to chart pen	——	——
		R.H.	Lithium chloride, electrical resistance	1.5% to 99% R.H. (±1.5%)	resistance and temperature	P6430 Temperature Probe	DM 502 Digital Multimeter
		Parts per million	Capacitance	0.1 to 10,000 ppm (1%)	ac bridge circuit-dc outputs signal	FG 503/AM 501 ac power supply	DM 501 Digital Multimeter
		ppm	Microwave	1% to 70% (1%)	R.F. power absorbent	circuitry internal to system	——
			Thermoelectric—optical servo	10 ppm to 100% R.H. (1%)	two resistive temperature sensors	internal calculations circuit	——

MEASUREMENT PARAMETER	SYMBOL	S.I. UNITS (ENGLISH UNITS)	TRANSDUCTION PRINCIPLE	FUNCTIONAL RANGES	TRANSDUCER DESCRIPTION PART NUMBER—ELECTRICAL SIGNAL	SIGNAL CONDITIONING TYPE NUMBER—DESCRIPTION	READOUT—DISPLAY TYPE NUMBER—DESCRIPTION
FORCE	F	Newton, N	Counter balance—Mass	10^{-8} grams to 10^{2} grams	micro balance up to standard scales	LVDT signal takeoff added 015-0168-00 below	DM 502 Digital Multimeter
F=ma		Kilogram-force	—electromagnetic	2×10^{-4} grams to 4×10^{7} grams	force balance servoloop nulling	Low pass filter	DM 501 Digital Multimeter
		dynes					
			Deflection—Strain Gage	5×10^{-4} grams to 4×10^{8} grams	strain gage installed on steel spring	PN 015-0169-00 and PS 501-1 MOD 730F	DM 501 MOD 718D Digital Multimeter
		(lb-f)	—LVDT	10^{-2} grams to 4×10^{6} grams	LVDT coupled by lever arm to load	Excitation PS 501-1 Power Supply	DM 501 Digital Multimeter, AC VOLTS mode
			—Piezoresistive	1×10^{-4} grams to 10^{2} grams	deflection of mechanical linkage	Excitation PS 503A Power Supply	DM 501 MOD 718D Digital Multimeter
			—Capacitive	1 gram to 2 kilograms	differential capacitance distance	Excitation FG 503/AM 501/transformer	DM 501 Digital Multimeter, AC VOLTS mode
			—Inductive	1 to 4,000 kilograms	deflection of load ring	ac carrier-oscillator-phase detector	DM 502 Digital Multimeter
			—piezoelectric	1 gram to 4×10^{7} grams	compression washer	AM 502 Differential Amplifier (charge mode)	5111 Storage Oscilloscope with 5A18N/5B10N
TORQUE	T	Newton-Meter	Torsional Windup—Strain Gage	10^{-4} N × m to 10^{5} N × m	strain gage with slip rings installed on shaft	PN 015-0169-00 and PS 501-1 MOD 730E	DM 501 Digital Multimeter MOD 7180
		N × m	—LVDT (Torsional Variable D.T.)	10^{-1} N × m to 10^{4} N × m	Torsional Variable Differential transformer	Excitation FG 503/AM 501 ac power supply	DM 502 Digital Multimeter
		dyne-cm	—Photo-electric encoder	10^{-2} N × m to 10^{2} N × m	Optical measurement of shift between two disc:	Lamp power PS 503A	DC 505A Universal Counter
		(lb-ft)	—Permeability change	10^{2} N × m to 10^{6} N × m	magnetic properties of shaft change with load	vendor-supplied circuitry	7623 Multimode Storage Oscilloscope
		(oz-in)	Dynamometer	10^{-2} N × m to 10^{4} N × m	installed load absorbing	vendor-supplied with particular design	7313 Bistable Storage Oscilloscope
VIBRATION—DISPLACEMENT	D peak to peak	millimeters, mm	Linear Displacement Transducers (DC-LVDT)	± 5 millimeters	PN 015-0168-00 Displacement Transducer	Excitation PS 501-1 MOD 730E Power Supply	DM 502 Digital Multimeter
(Distance)	d peak	(inches, in)					
(Amplitude)			Integrated linear velocity transducer signals	± 0.6 millimeters	PN 015-0166-00 Vertical Vibration	(none required)	5111 Storage Oscilloscope 5A18N/5B10N
				± 0.6 millimeters	PN 015-0167-00 Horizontal Vibration	(none required)	7313 Storage Oscilloscope 7A18/7B53A
			Double integrated accelerometer signals	± 10 millimeters	PN 015-0165-00 Accelerometer	2-AM 501 Operational Amplifier	SC 502 Oscilloscope
VIBRATION—VELOCITY	V zero to peak	millimeters per second	Linear velocity transducers, seismic	± 50 millimeters per second	PN 015-0166-00 Vertical Vibration	(none required)	5111 Storage Oscilloscope 5A18N/5B10N
				± 50 millimeters per second	PN 015-0167-00 Horizontal Vibration	(none required)	7313 Storage Oscilloscope 7A18/7B53A
		mm/s	Integrated accelerometer signals	± 1 meter per second	PN 015-0165-00 Accelerometer	AM 501 Operational Amplifier	SC 502 Oscilloscope
		(inches per second)					
		(ips)					
VIBRATION—ACCELERATION	G, g, a	g's	Linear accelerometers-piezoelectric	0.01 to 1000 g's	PN 015-0165-00 Accelerometer	AM 502 Differential Amplifier	SC 502 Oscilloscope
		meters per second per second					
VIBRATION-TORSIONAL			Time interval variations during rotation of each revolution.	0 to 30 degrees misalignment	Rotary shaft encoder (machine tool)	Excitation PS 503A (+5 volts)	5111 Storage Oscilloscope 5A20N/5B10N
					(512 + bits per revolution)	Pulse shaping-PG 501 plus R-C networks	
			Strain gage—inertial mass	0 to 10 degrees misalignment	strain gage with slip rings installed on shaft	PN 015-0169-00 and PS 501-1 MOD 730E	DM 501 Digital Multimeter
SOUND (Microphone)				(Variation)			
		dBm	Piezoelectric	−10 to 160 dB ± 2 dB		AF 501 Bandpass Filter	DM 501 Digital Multimeter, AC VOLTS mode
		dBv	Capacitance	10 to 150 dB ± 1 dB		AM 501 Operational Amplifier	DM 502 Digital Multimeter, dB mode
			Variable reluctance	85 to 135 dB ± 3 dB		AM 501 Operational Amplifier	SC 502 Oscilloscope

2-4. Transducer Descriptions and Specifications

The following list provides numbers and brief applications information on transducers and accessories available through the Tektronix parts system.

PART NUMBER	PARAMETER/APPLICATION
015-0165-00	Acceleration
015-0116-00	Vibration (engine)
015-0166-00	Vibration, vertical velocity and displacement
015-0167-00	Vibration, horizontal velocity and displacement
015-0162-00	Pressure, 300 psig (strain gage)
015-0161-00	Pressure, 3000 psig (strain gage)
015-0117-00	Pressure, 3000 psig (engine)
015-0164-00	Force, displacement (strain gage)
015-0168-00	Displacement (LVDT)
015-0119-00	Reference mark (rpm)
015-0108-01	Rotary function generator (angular position)
015-0169-00	Strain gage adapter
015-0171-00	Strain gages
015-0172-00	Strain gage cement kit

Following are brief descriptions of the items in the preceding list.

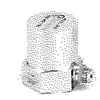
ACCELEROMETER,
PN 015-0165-00

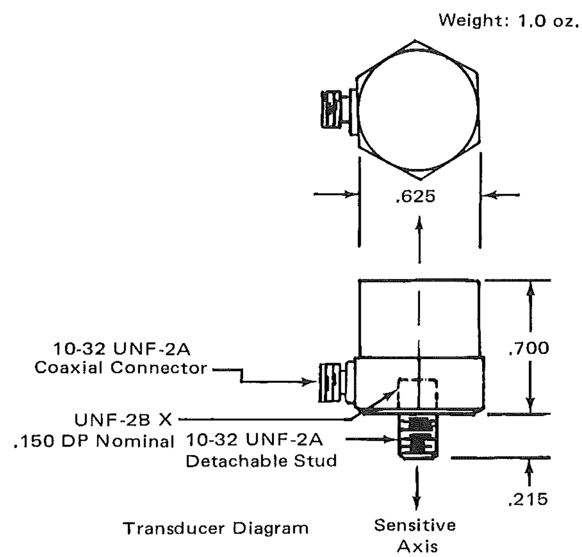
This unit is a small, very sensitive motion sensor that has many applications in education and industry. It is often used as a high frequency vibration pickup with the AM 502, 5A22, or 7A22 High Gain Amplifiers. Its high frequency range and high sensitivity make it applicable for machinery noise measurement and many ultrasonic applications. The basic output signal is approximately 10 mV per g. It is a dynamic device without a dc or static mode of operation. The basic equation of motion ($X = X_o + Vt + \frac{1}{2}at^2$) indicates that the accelerometer can be a basic motion measurement device. Integration of the accelerometer vibration signal gives the velocity of the vibration. A second integration gives the displacement of the vibration.

The accelerometer is "the" general purpose transducer for vibration measurement. It is a piezoelectric device with a high output signal scale factor and high output capacitance. The high output capacitance allows the use of standard voltage amplifiers instead of special-purpose charge amplifiers. Also, it minimizes the errors caused by cable capacitance and variations in capacitance caused by cable flexure during the tests. A careful design tradeoff was made between frequency response and ease of use. The specifications for this transducer are given below. Applications are listed in the parameter table, and the recommended application zones are shown in the nomograph (see Figure 3.5). Two zones on the vibration nomograph are shaded out for the 015-0165-00 Accelerometer: the upper right corner and the lower left corner. The upper area represents conditions in excess of 1000 g's that require special cabling and installation techniques.

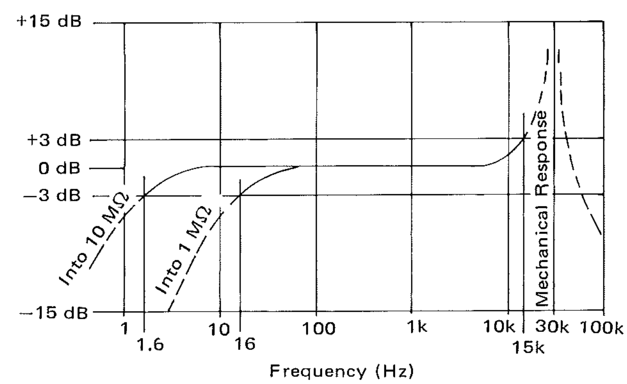
The lower area represents signals below 10 μV that will be masked by local interference signals, noise, and thermal conditions even with the special low noise cable. The specified 20-ft cable (PN 012-0211-00) is made of low noise, high temperature coax with a microdot connector at one end (for the accelerometer) and a BNC connector at the other (for the oscilloscope).

This unit is shipped with a data sheet, a calibration sheet, and a certificate of traceability.





Transducer Diagram



Frequency Response

Specifications

Acceleration Range	10,000 g's
Accuracy	5% (2% Linearity)
Nominal Sensitivity	≈ 12 pk-mV/pk-g
Nominal Charge Sensitivity	2 picocoulombs/g
Nominal Capacity	≈ 10,000 pF
Frequency Response	See graph
Resonant Frequency	30 kHz
Operating Temperature Range	−74°C to +120°C
Physical Data	303 stainless steel, with a #10-32 tapped hole for mounting (stud supplied) 1.1 oz

Figure 2-2. Acceleration Transducer and Specifications

ENGINE VIBRATION TRANSDUCER,
PN 015-0116-00

This unit is a special-purpose accelerometer specifically designed to pick up the primary noises of rotating machinery. The basic sensor is a piezoelectric crystal with a cantilever weight. The unit has an unsuppressed high-Q resonance near 11 kHz. This resonance will respond to very low level signals over a wide ultrasonic range. It will also act to spread out high level shocks that might have passed too fast to be noticed on the oscilloscope. The design sacrifices signal linearity and frequency response for sensitivity to machinery noises. It is housed in a cast aluminum body with a magnetic mounting system.

This unit should be used for engine and rotary process machinery applications. Use the 015-0165-00 Accelerometer for signal applications requiring high accuracy or wide frequency ranges.

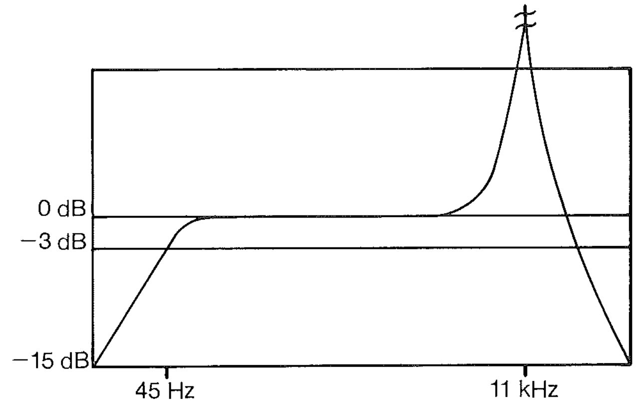


Figure 2-4. Frequency Response Diagram (1-MΩ Load)

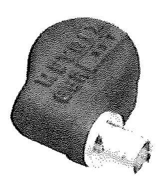


Figure 2-3. Vibration Transducer

ENGINE VIBRATION TRANSDUCER SPECIFICATIONS

Sensitivity (transducer alone)	6 mV/g
Transducer with 20-ft coax	4.5 mV/g
Maximum Acceleration	1000 g's
Temperature Range	40°C to +150°C
Resonant Frequency	≃ 11k Hz
Nominal Capacitance	≃ 3,500 pF
Weight	2.5 oz

VIBRATION TRANSDUCERS, VERTICAL (PN 015-0166-00) AND HORIZONTAL (PN 015-0167-00)

These units are primarily used to measure machine vibration velocity and displacement for safety and reliability testing; but may be used for inplace balancing of machinery, for structural vibration analysis, for location of sources of vibration, to check the effectiveness of vibration isolators on machinery, and to measure the effect of one machine on another (i.e., one punch press on another punch press, or on a milling machine, or between milling machines).

These vibration transducers are inductive, dual-coil, seismic geophones, or simply seismic transducers. The basic element of the transducer is a magnetic seismic mass suspended on a sealed capsule between two coils. The velocity of motion of the frame with respect to the mass will produce a voltage proportional to the velocity. Normal operation is above the resonance frequency of 8.5 Hz.

There are two separate units, one for vertical motion and one for horizontal motion. Each unit has essentially no output sensitivity to motion at 90° to its axis. Passive circuit components are included to dampen the resonance frequency effects and to electrically integrate the signal into an absolute motion or displacement signal. Both signals, velocity and displacement, are brought out through BNC jacks on the case of the instrument. Mounting is by a 10-32 NF threaded hole in one end of each unit.

Normal operation is in the area indicated in the vibration transducer application zones nomograph (see Figure 3-5). The low frequency limit is normally just below the resonance (10 Hz) and the high frequency limit (L/R)—3d B point is well above a point at which the phase shift is still small. An upper g limit (30 g's) is imposed by the seismic mass travel limits. The units are so sensitive that some have been used for burglar alarms or earthquake detectors.

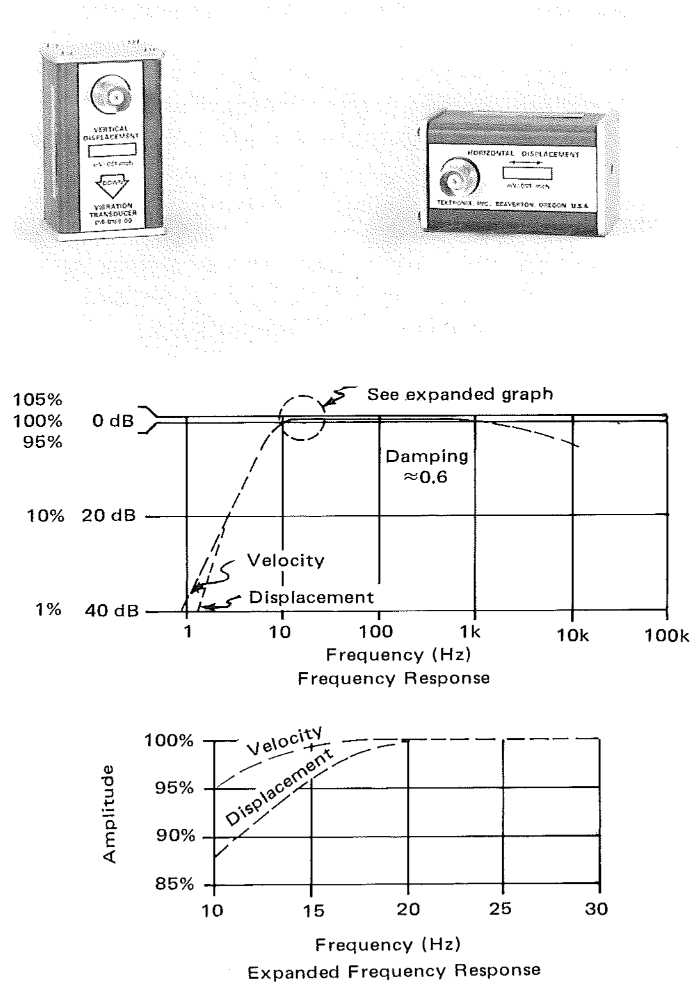


Figure 2-5. Vibration Transducers, Vertical and Horizontal

VIBRATION TRANSDUCER SPECIFICATIONS, VERTICAL AND HORIZONTAL

Coil Resistance	840 Ω
Coil Inductance	0.125 H
Voltage Output (Nominal)	
Velocity	550 mV/inch sec.
Displacement	10 mV/.001 inch
Frequency Response	See graph
Displacement Range	0.050 inch p-p
Accuracy	5%
Operating Temperature Range	−40°C to −71°C
Weight	5.8 oz.

STRAIN GAGE PRESSURE TRANSDUCERS
(PN 015-0162-00) 300 psig and (PN 015-0161-00) 3000 psig

These pressure transducers are used for pump, compressor, and process pressure measurements. A stainless steel case provides for use in most gaseous and fluid operations, but not with combustion processes such as gasoline engines because of the very high shock waves associated with pre-ignition or engine "knock." The units can be used wherever static or dynamic (low frequency) operations are involved or where higher accuracies are required.

The high frequency limit is imposed by the fluid volume and its maximum flow rate, i.e. the velocity of sound in the fluid or gas for the path length and the resultant acoustic resonances.

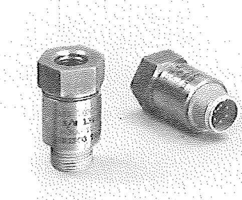
Connection to the pressure line is through a threaded fitting. Each industry and company has favorite types of fittings. For that reason, a recessed standard thread adaptable to most systems is used. Adapter nipples are available at most plumbing stores, aircraft service companies, automotive supply houses, Imperial Eastman Corp., or Whitney Corp. The pressure connection lines should seal tightly and be very short.

The electrical connection should be through dual-twisted-pair shielded cable of a type similar to PN 012-0209-00.

These pressure transducers use four bonded strain gages electrically connected as four active arms of a Wheatstone bridge circuit. The four gages are located on a diaphragm, two circumferentially oriented for temperature compensation and two radially oriented to sense deflection of the diaphragm under pressure. A shunt calibration resistor is also mounted internal to the pressure transducers.

The resistor simulates approximately a half scale pressure signal to allow for calibration of the electrical circuits without a pressure source. The model PS 501-1 MOD 730E Transducer Power Supply includes the null balance circuits for this transducer, the power source, and the circuit to activate the calibration resistor.

CAUTION: Care should be exercised when inserting the adapter that it does not contact the sensing diaphragm.This will damage the transducer and cause errors.The shoulder to tip length of the adapter should not exceed 7⁄16 inch. If it does, use space washers to reduce the length and prevent damage to the transducer.



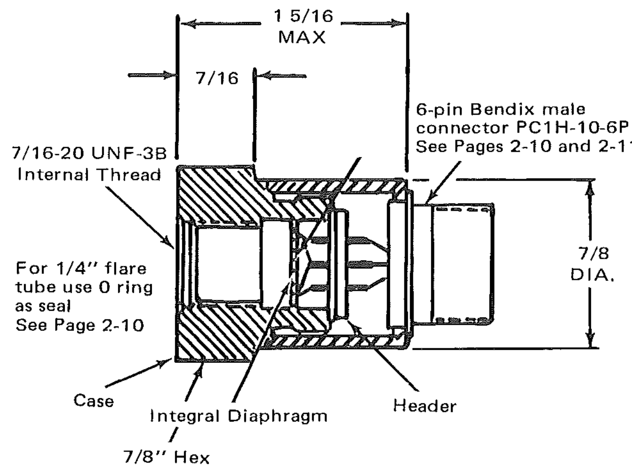


Figure 2-6. Pressure Transducer

PRESSURE TRANSDUCER SPECIFICATIONS

INPUT	
Measured Fluids	Fluids compatible with 17-4 PH stainless steel
Pressure Range	300 and 3000 psig
Excitation	15 V maximum
Resistance	350 Ω nominally
OUTPUT	
Voltage	3.0 mV/V (nominally) FS
Source Impedance	350 Ω nominally
PERFORMANCE	
Combined Linearity and Hysteresis	Within 1% FS
Repeatability	Within 0.25% FS
Pressure Overload	1.5 X FS
Zero Balance	Within 5% of FS
Mechanical Resonance Frequency	
300 psig	24 kHz
3000 psig	65 kHz
Acceleration Error	
300 psig	Less than 0.003% FS/g
3000 psig	0.001% FS/g maximum
ENVIRONMENT	
Operating Temperature Range	+55°C to +120°C
Compensated Temperature Range	−20°C to +85°C
MECHANICAL	
Material	17-4 PH stainless steel
Fitting (thread size)	7⁄16-20 UNF-3B
Connector	6-pin Bendix PC1H-10-6P

DYNAMIC PRESSURE TRANSDUCER, PN 015-0117-00

This high sensitivity piezoelectric pressure transducer is designed for dynamic pressure measurement applications such as engine cylinder pressure measurement on a large diesel engine or surge testing of a hydraulic system. The practical frequency response limits on the transducer are imposed by the length of the air column connecting the pressure source and the internal diaphragm of the transducer; i.e., the incremental pressure change will travel at a speed somewhat less than the speed of sound. In systems with short connections to a cylinder, this is approximately equivalent to 6000 RPM or 1000 RPM with the cooling adapter (PN 015-0118-00).

The cooling adapter is often required to keep the transducer body temperature (at the pressure connection threads) at or below 150°C. This unit will also tolerate the effects of preignition explosions (or knock), with the attendant shock waves as high as 9000 psi, without degradation of the calibration as would happen with a strain gage transducer. The sensitivity of approximately 200 pC per psi is two orders of magnitude greater than other common units.

The transducer sensitivity is specified both in terms of charge sensitivity and voltage sensitivity. Most practical applications require operation into the 1 meg ohm input of an oscilloscope. Best performance is achieved through the use of a shunt capacitor to standardize the deflection sensitivity, to enhance low frequency performance and to minimize cable length effects.

Voltage sensitivity of the transducer with a shunt capacitor is given by the following equations:

$$E=\frac{Q}{C_s}$$

Where: E=volts sensitivity
Q=coulombs of change
C=farads of capacitance

For a typical pressure transducer of sensitivity 230 pico coulombs per psi and a 0.23 micro farad capacitor.

$$\frac{230\ \text{pc/psi}}{0.23\mu\text{fd}}=\frac{2.3\times10^{-10}}{2.3\times10^{-7}}=1 \text{ millivolt per psi}$$

The lower frequency response point (−3db) will be found with the following equation:

$$f_{LF}\quad\frac{1}{2\pi R_{in} C_s}$$

$$\frac{1}{6.28\times1\ \text{meg ohm}\times C}=\frac{1.59\times10^{-7}}{2.3\times10^{-7}}=0.69 \text{ Hz}$$

This value is good down to 165 RPM (4×41.4)

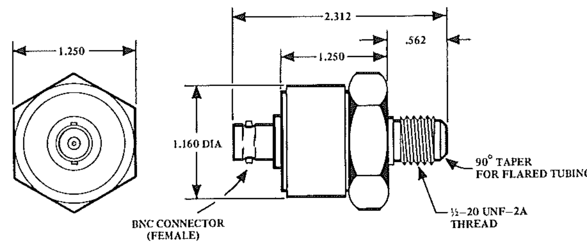


Figure 2-7. Dynamic Pressure Transducer

PRESSURE TRANSDUCER SPECIFICATIONS

Pressure Range	0 to 3000 psi
Sensitivity	200 pC/psi (nominal charge sensitivity) 25 mV/psi (nominal volts sensitivity) 7000 pF (nominal capacitance)
Accuracy	Within 5%
Maximum Overload Pressure	300%
Temperature Range	−40° to +150°C (cooling adapter extends range above +150°C)

UNIVERSAL FORCE CELL, PN 015-0164-00 AND ACCESSORIES

This unit is a basic universal transducing cell made with four 350-Ω unbonded strain gages making four active arms of a Wheatstone bridge circuit. This particular unit operates only in the compression mode. The basic unit takes 60 g (grams) of force to deflect the 0.12 mm of standard range. Thus, it can be used for either deflection or force measurements. Additional load ranges may be achieved by adding "load cells," which are heavy spring-like devices. The universal cell measures the deflection of these heavy springs under load to obtain larger force ranges. The load buttons are available for 0.2 kg to 450 kg (0.5 to 1000 lb) with the 22.5 kg (50-lb) unit supplied as a standard accessory with the basic load cell. When the load cell is attached, its internal mechanical zero adjustment screw can be used to bias the load cell for both tension and compression operation.

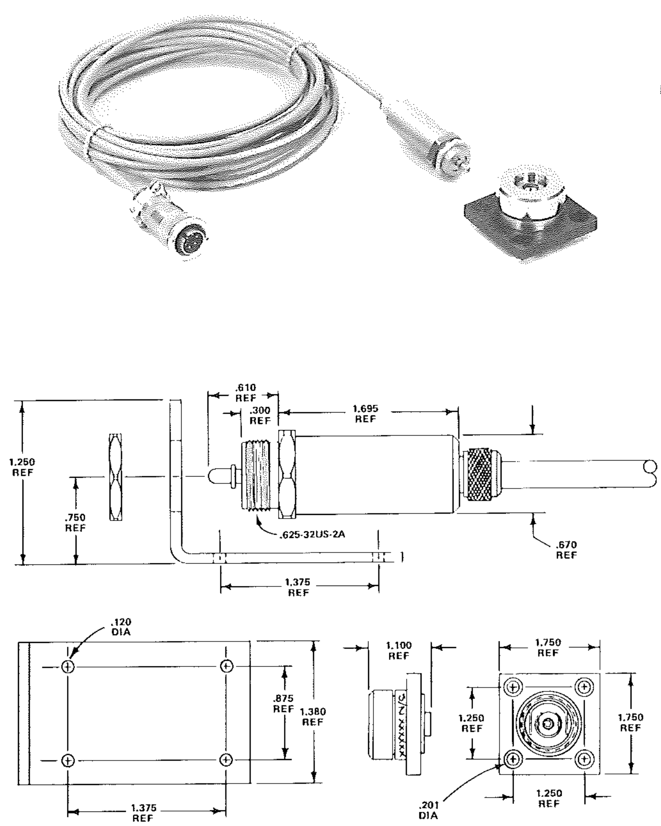


Figure 2-8. Low Force Transducer

LOW FORCE TRANSDUCER SPECIFICATIONS

Force Range—Universal Cell	50 g (0.1 lb) compression only
Load Range (with accessory load cell)	22.5 kg (50 lb) compression or tension
Displacement Range	0.12 mm
Accuracy	0.5% FS (worst case) linearity and hysteresis
Thermal Shift Sensitivity	0.01% FS/°F (maximum)
Thermal Shift Zero	0.01% FS/°F (maximum)
Bridge Resistance	350Ω (nominal)
Excitation Voltage	5 V nom (7.5 V maximum)
Output Signal Full Scale	60 to 80 mV nominal (16 mV/V excitation, 12 mV/V excitation with the load cell)
Operating Temperature	−50°C to +85°C
Electrical Connection	20 ft shielded cable with Bendix PC06A-10-6 P connector
Self Calibration	Internal half scale resistor (≃ 11 kΩ)

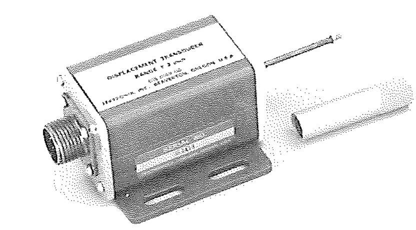
DISPLACEMENT TRANSDUCER, PN 015-0168-00

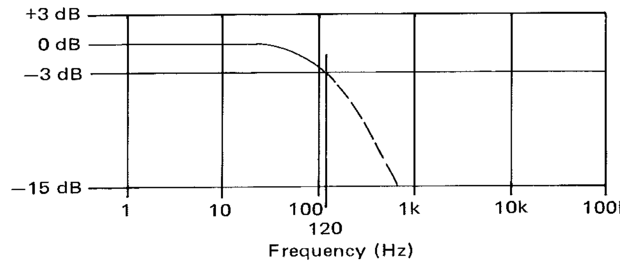
The displacement transducer is an integrated package, consisting of a precision linear variable differential transformer (LVDT), a solid state oscillator, and a phase-sensitive demodulator. When the transformer core is displaced axially, an output voltage change directly proportional to the displacement is produced. Also, the output voltage scale factor is linearly changed by the input voltage so that the unit in effect multiplies the sensed displacement, times the input dc voltage.

This particular unit was designed to measure the movement of switching elements in thermal switches, slide switches, pushbutton switches, cam switches, and other short travel devices. The moving element is controlled by a 1-72 UNF threaded rod 2 inches long. Zero output is obtained when the rod extends about 1.750 inches from the plastic end face. A motion of plus and minus 0.2 inch (5 mm) provides an output signal of plus and minus 4 V at approximately 7.5 V excitation. As the scale factor changes with excitation voltage, a typical unit provides 20 mV per 0.001 inch at 7 V excitation and 1 V per mm at 8.5 V. (CAUTION: Do not exceed 11 V excitation.) At these excitation levels, it is possible to resolve 0.000005 inch with the DM 501 or DM 502.

Absolute accuracy is dependent upon the mounting situation and high accuracy can be achieved only by calibration in place with a high order micrometer and gage blocks. Accuracy of a raw unit will be better than 0.002 inch with the supplied calibration. The best application of the unit is in areas of incremental variations or deviations of one part from the next. In this type of application, repeatability of 0.0001 inch over long periods and 0.00005 inch for short periods can be expected. A similar unit has been operating in space for over 12 years with a resolution of 6/1,000,000 and in a machine shop for 10 years at 0.0001-inch accuracy.

Each transducer package consists of a transducer and a 0.040-inch feeler gage. A six-conductor cable, PN 015-0209-00, is required for interconnection to the PS 501-1 MOD 730E Transducer Excitation Power Supply.





Typical Frequency Response

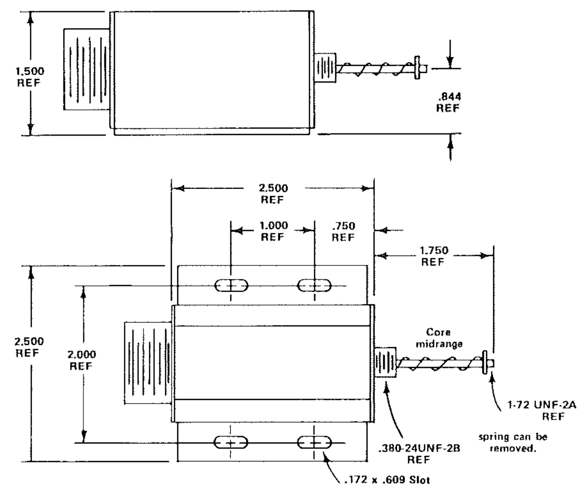


Figure 2-9. Displacement Transducer

DISPLACEMENT TRANSDUCER SPECIFICATIONS

Displacement Range	±4.0 mm (calibrated and usable within a range of ±0.2 inch)
Accuracy	2% (1% linearity)
Input power	−11 Vdc maximum: 1 V/mm (at 8.5 V excitation)
Output ≃ 3 V minimum	20 mV /0.001 inch (at 7.5 V excitation)
Frequency Response	See figure 3-5
Operating Temperature Range	−54°C to +60°C
Connector	Bendix PC02A-10-6P (mates with Bendix PC06A-6S)

REFERENCE MARK (OR VELOCITY) PICKUP, PN 015-0119-00

This electromagnetic velocity pickup is often called a reference marker, an RPM sensor, a pip coil, a TDC marker, and many other things. The electrical output of this permanent magnet, magnetic field sensor is dependent upon the velocity and magnetic properties of items passing through its field. Normal signals are achieved by such items as cotter keys, screw heads, or machined notches in an iron shaft moving near the pickup. The device may be used to create a reference time signal for RPM, event timing, and mechanical phase calibration or synchronization. Each transducer is complete in itself and may be used with any BNC cable.

The primary use of this unit is to provide a top dead center (TDC) reference for engine analyzer (EAS) applications. It is also very useful as a signal source for the DC 504 in RPM measurements, as an external trigger source for oscilloscopes in mechanical vibration studies, in rotary machine dynamic balancing, and in friction drives and belts to measure slippage by applying the two signals to a DC 503. This same two-sensor technique can be used to verify performance of a hydraulic transmission, or to check a gear ratio in a complex enclosed gear box. This transducer will synchronize almost all TEKTRONIX Oscilloscope sweep units, which allows portable scopes to be used to maintain office copy machines, teletype terminals, line printers, or almost any electromechanical machinery.

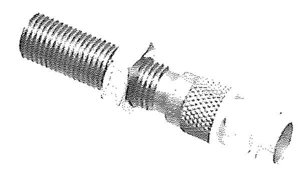


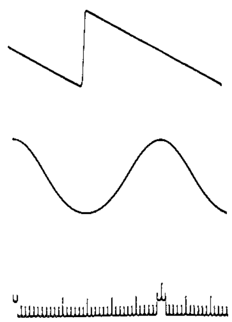
Figure 2-10. Reference Mark Transducer

REFERENCE MARK TRANSDUCER SPECIFICATIONS

Output Voltage	At least 15 V p-p at 1000 ips and clearance gap of 0.005 inch using 20-pitch, 30-tooth ferrous metal gear
Coil Resistance	90 Ω to 110 Ω
Coil Inductance	24 mH to 40 mH
Temperature Range	−54°C to +107°C

ROTATIONAL FUNCTION GENERATOR,
PN 015-0108-01

The rotational function generator (RFG) supplies three separate electrical signals timed to the mechanical rotation of its shaft. These three waveforms are shown in Figure 2-11 and are used to supply the necessary control and timing signals for piston engine analysis.



A sawtooth ramp for displays related to crankangle.

A sinewave with approximately 6% second harmonic content to provide piston volume as a function of crankshaft rotation (r/l = 1/4).

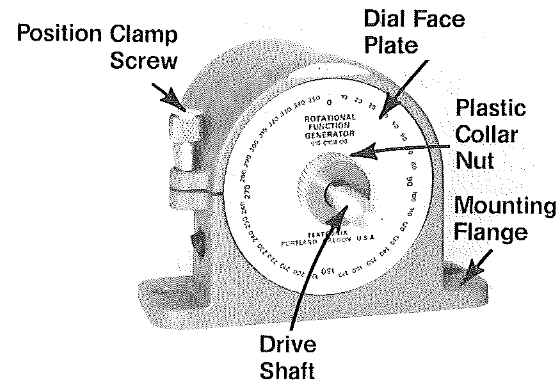
Crankangle markers in 10°, 60°, and 360° increments.

Figure 2-11. Rotational Function Generator Waveforms

The ramp signal is the source voltage for the horizontal or X axis when operating the oscilloscope in an X-Y mode instead of the normal Y-T time base mode. This mode of operation displays rotation (or angle) on the X axis and is essential to the analysis of many machines subject to reciprocating motion, torsional vibration or cyclic loads non linear with time.

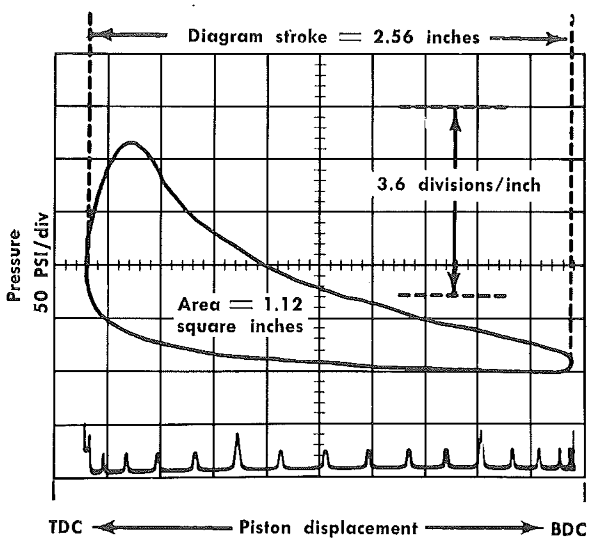
The second signal is a modified sinewave also used with the X-Y mode for piston engine IHP (indicated horsepower) or P-V analysis by simulating piston displacement (or volume) along the horizontal axis. The third signal is a series of rotational angle markers that are used in engine analysis to establish timing.

The various markers are displayed in ruler form on one vertical channel to establish a calibrated mechanical rotational angle oriented scale along the horizontal or X axis. A top dead center (TDC) mark is obtained from a magnetic pickup, PN 015-0119-00, sensing a marker on the flywheel. This magnetic pickup is connected to a second vertical channel and is superimposed on the RFG trace. The RFG body is aligned by loosening the alignment lock screw and positioning the TDC pedestal to the TDC marker from the pip coil. This alignment sets up the sawtooth sweep with the TDC mark at screen center. The RFG volume signal is also aligned to this reference cylinder. By use of the angular reference dial on the front, the RFG may be aligned to any other cylinder in subsequent tests.



The RFG-generated volume signal simulates the piston displacement for every point in the cycle. The signal shown in the illustration simulates a connecting rod to crank radius of 4 to 1, which adds 6.35% second harmonic to the motion sinewave. This signal is used to generate the volume (V) horizontal axis for a P-V diagram such as shown in Figure 2-12. The ratio picked represents an optimum-minimum (+2.08%—2.28%) error curve for the various common engines. This does not including the Wankel, double-opposed piston, elliptic, or the external combustion chamber, which all require special units. Computer generated correction curves are available for standard ratios.

The RFG signals are generated by a photo-optical system. The power for the RFG is normally supplied from the PS 501-1 MOD 730F Rotary Function Generator power supply. This power supply also contains circuitry to offset the three signals and to allow expansion of any portion of these signals. This additional adjustable gain control allows operation with many X-Y oscilloscopes.



3.6 div/inch × 50 PSI/div = 180 PSI/inch

180 PSI/inch ÷ 2.56" diagram stroke = 70.3 PSI/inch^2

70.3 PSI/inch^2 × 1.12 inch^2 area = 78.7 PSI MEP

IHP = PLAN/33,000

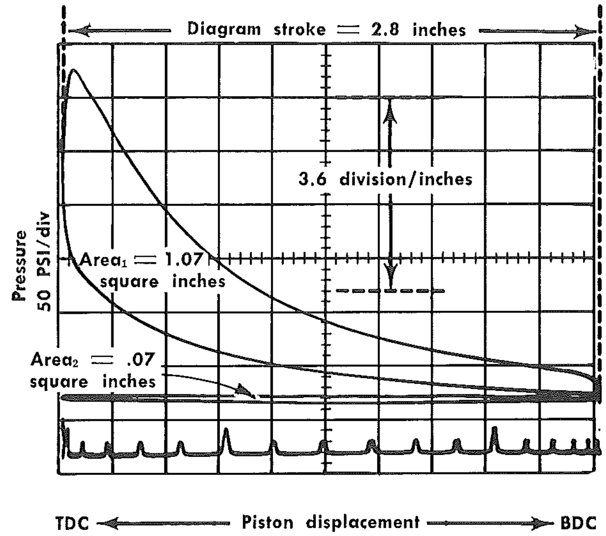
IHP = 78.7 × 1 × 78.5 × 600 ÷ 33,000 = 112.3 HP

(A) Example 1. PV diagram of a 2-cycle engine operating at 600 RPM, with accompanying horsepower calculation; piston stroke = 1 foot; cylinder cross sectional area = 78.5 sq. in.

*Note: The area inside the oscilloscope trace was measured with a Keuffel and Esser model 62-0000 compensating polar planimeter with a resolution of 0.01 square inch. Initial operation followed the calibration procedure on page 17 of the K & E manual and the photo measurement technique used the same set up to insure accuracy and ease of operation.

Figure 2-12. P-V Diagram for Two-Cycle Engine

The P-V diagram forms the basis of (IHP) evaluation of a piston engine. Figures 2-12 and 2-13 show the calculation method, using a planimeter,* to obtain the IHP of cylinders of a two-cycle and a four-cycle engine.



3.6 div/inch × 50 PSI/div = 180 PSI/inch

180 PSI/inch ÷ 2.8 inches diagram stroke = 64.3 PSI/inch^2

1.07 inch^2 ($Area_1$) — .07 inch^2 ($Area_2$) = 1.0 inch^2

64.3 PSI/inch^2 × 1.0 inch^2 ($Area_1$ — $Area_2$) = 64.3 PSI MEP

IHP = PLAN/33,000

IHP = 64.3 × 1 × 78.5 × 600/2 ÷ 33,000 = 45.9 HP

(B) Example 2. PV diagram of a 4-cycle engine operating at 600 RPM, with accompanying horsepower calculation; piston stroke = 1 foot; cylinder cross-section area = 78.5 sq. in.

Figure 2-13. P-V Diagram for Four-Cycle Engine

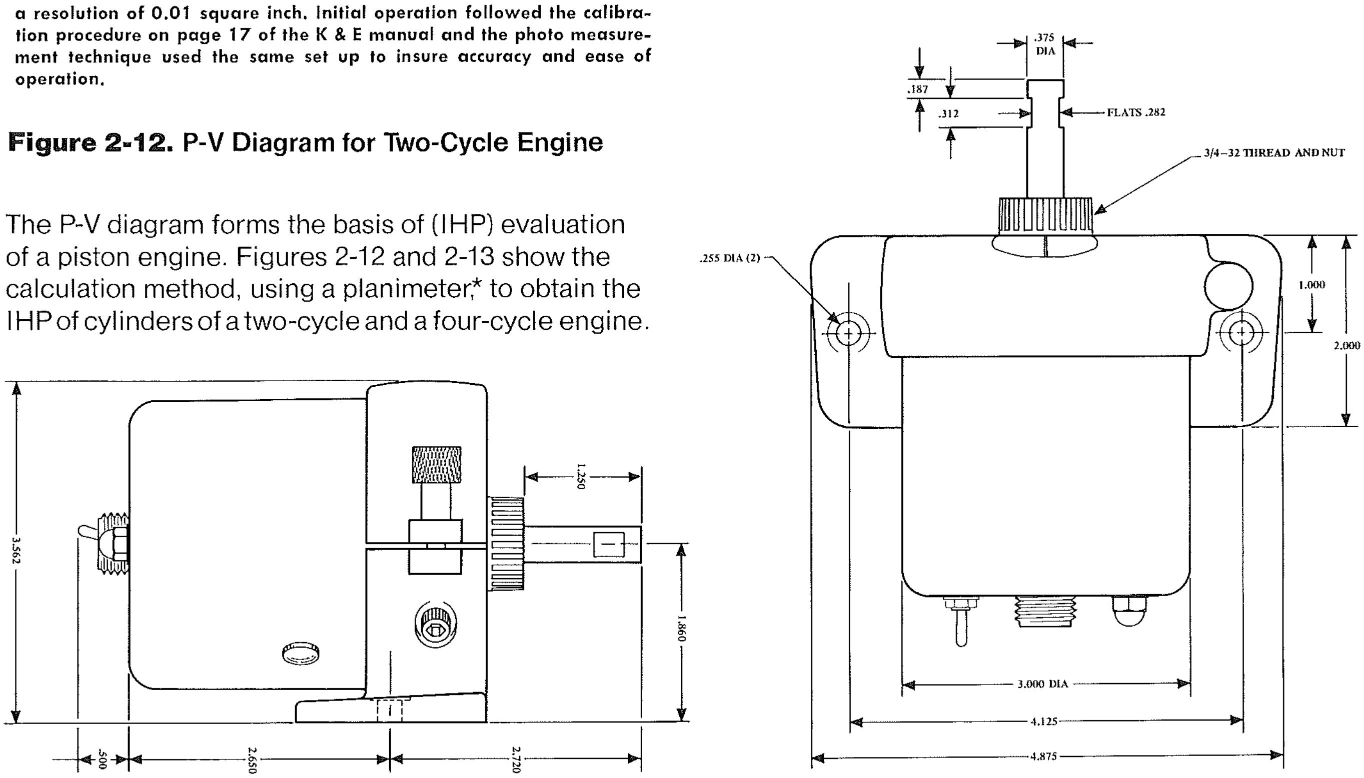


Figure 2-14. Rotational Function Generator

ROTATIONAL FUNCTION GENERATOR SPECIFICATIONS

Output Signal Amplitude	
Sine wave	Between 200 and 500 mV p-p.
Sawtooth	Between 200 and 500 mV p-p.
Degree Markers	At least 30 mV as measured at tallest marker (delivered to a high impedance circuit)
Output DC Level	
Sine wave and Sawtooth	−2.25 ±0.4 V
Degree Markers	5 V ± 1 V
Source Impedance	
Sine wave and Sawtooth	1.5 kΩ ±5%
Degree Markers	2.1 kΩ ±20%
Voltage Requirement	−11 V to −13 V
Maximum RPM	20,000
Maximum Cable Length	300 ft
Degree Marker Angular Accuracy	Within 1°
Shaft Load, Axial and Radial	10 lb max
Weight	21 oz
Accessory Cables	20 ft PN 015-0140-00 50 ft PN 015-0140-01

The RFG is connected to the engine with either a shaft coupling, a timing belt, or a 2 to 1 gearbox. The RFG shaft is ⅜ inch in diameter and can be connected to various size stub shafts by solid, bellows, flexible, Oldham, or spring couplings. These are available from Winfred M. Berg Inc., Sterling Precision Products, Renold Inc., Rembrant Inc., Kolock Products Inc., Stafford Mfg. Corp., General Thermodynamics Corp., Helical Products Co., and Huco Engineering Industries. One of the more ingenuous techniques developed by a customer to attach the RFG to a running machine uses a timing belt. These are available from Gates Rubber Co., Uniroyal Industrial Products Div., Stock Drive Products Div. of Designatronics, Inc., Butler Precision Belting, Winfred M. Berg Inc., and PIC Design Div. of Benrus. In some applications in which the RFG is used on a four-stroke-cycle engine, it is desirable to use a 2 to 1 reduction gearbox to display two revolutions on one sweep in the X-Y mode. This can be achieved with either a 2 to 1 timing belt pulley ratio or a 2 to 1 gearbox. These gearboxes are available from Browning Mfg. Div. of Emerson Electric, Winsmith Speed Reducers, Sterling Power Systems Inc., PIC Design Div. of Benrus Inc., Gear Specialist Inc., and Boston Gear.

STRAIN GAGE ADAPTER, PN 015-0169-00
STRAIN GAGES (5), PN 015-0171-00
STRAIN GAGE CEMENT KIT, PN 015-0172-00

This combination makes up a complete strain gage system for structural or strength of materials evaluation. The system is applied primarily in educational or research activities where it is used to measure or prove most physical stress, strain, bending, loading, deflection, and structural resonance theories or conditions. The strain gage adapter shown in Figure 2-15 provides for connecting 1, 2, or 4 strain gage arms into a Wheatstone bridge circuit. Power for the gages is obtained through an attached 1.8 m (6 ft) cable from the PS 501-1 MOD 730E transducer power supply. The adapter has a variable shunt calibration resistor that simulates 1000 microstrains to a 120 Ω gage when the dial is set to the proper gage factor and the small red CAL button on the transducer power supply is pressed. The adapter may be used with 1, 2, or 4 arm 120 Ω gages or with 4 arm 30 to 5000 Ω gages.

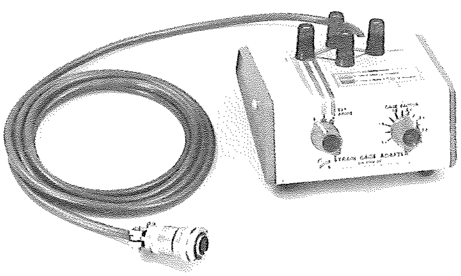


Figure 2-15. Strain Gage Adapter

The strain gages in Figure 2-16 are each 120 Ω and are made from constantan alloy for temperature self-compensation. The sensing length is 125 mils and each gage has preattached soft copper leads.

STRAIN GAGE SPECIFICATIONS

Resistance	120Ω ±0.15%
Gage material	Constantan alloy
Gage factor	≃ 2.1 ±0.5%
Active gage length	0.125 inch
Range	30,000 microstrains
Accuracy	1% at calibration temperature
Backing material	Polyimide
Operating Temp. Range	−40°C to +120°C with RTV cement
Thermal expansion	6 ppm/°F
Mounting size	0.125 X 0.062 inch

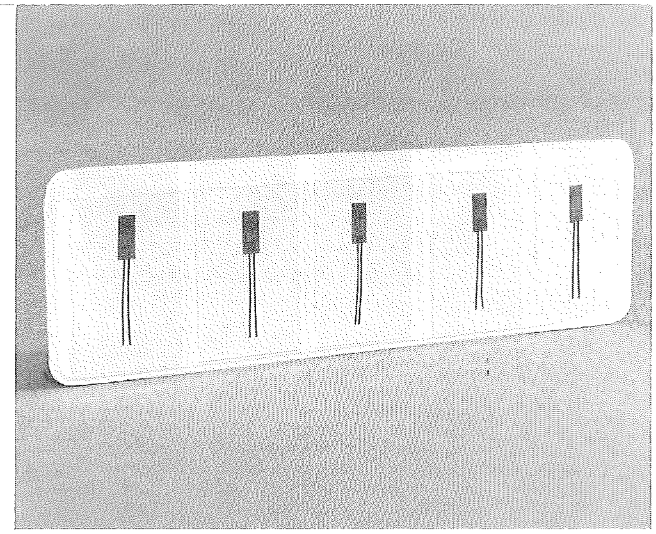


Figure 2-16. Strain Gage

The strain gage cement kit (Figure 2-17) provides the instructions and materials for mounting and connecting the gages. It includes epoxy cement for attachment, RTV clear silicon rubber for coating and lead attachment terminals and insulators.

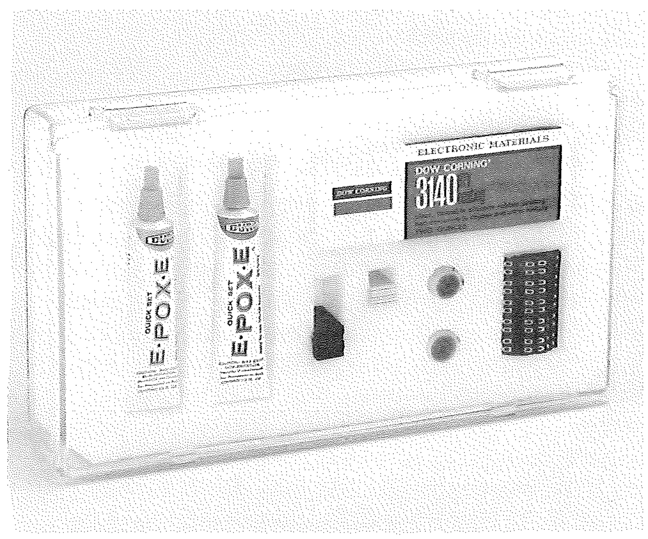
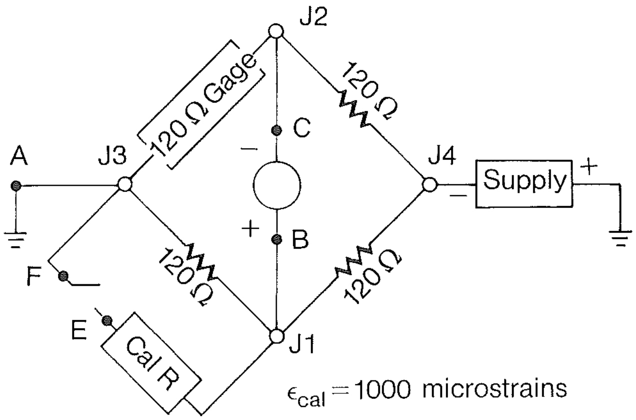


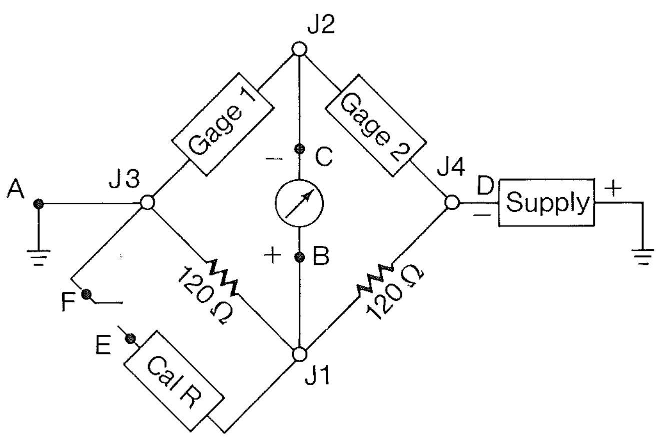
Figure 2-17. Strain Gage Cement Kit



$\epsilon_{cal} = 1000$ microstrains

$\epsilon_{actual} = \epsilon_{reading}$

Figure 2-18. Use of Strain Gage Adapter, One External Arm



$\epsilon_{cal} = 1000$ microstrains

Figure 2-19. Use of Strain Gage Adapter, Two External Arms

$\epsilon_{cal} = 1{,}000$ microstrains

Gage resistance (R) may be any value, but the two must be equal to preserve linearity and balance. In order to increase sensitivity, gages must be attached to measure opposites (i.e., tension versus compression strains).

$\epsilon_{reading} = \epsilon_{arm\ 1} - \epsilon_{arm\ 2}$

$$\epsilon_{actual} = \frac{\epsilon_{reading}}{Km}$$

Km = 2 if gage 1 and 2 measure equal but opposite strains

OR

Km = 1 + Poisson's ratio for the material being measured if Poisson strain is being measured by one of the gages.

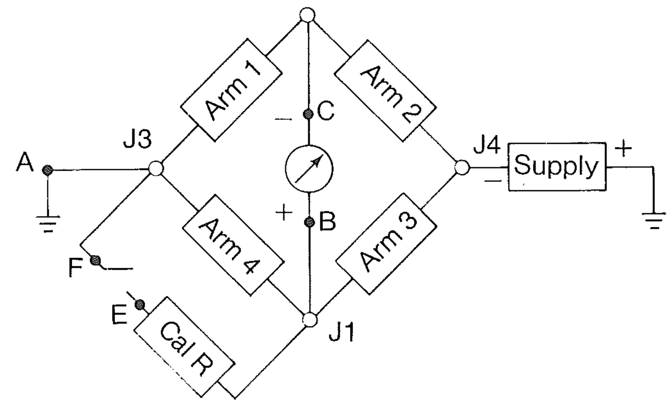


Figure 2-20. Use of Strain Gage Adapter, Four External Arms

The arms may exhibit any resistance but should be nearly equal (1 to 2 and 3 to 4 within 1% preferred).

$$\epsilon_{cal} = 1000 \times \frac{120}{R_{ext}} \text{ microstrains}$$

$$\epsilon_{actual} = \frac{\epsilon_{reading}}{Km}$$

Km depends on how many arms have active strain gages included, and if Poisson's ratio applies (see Two External Arms).

$\therefore \epsilon_{reading} = \epsilon_{arm_1} - \epsilon_{arm_2} + \epsilon_{arm_3} - \epsilon_{arm_4}$

MISCELLANEOUS NOTES ON STRAIN GAGE SELECTION, INSTALLATION, OPERATION, AND CALIBRATION

1. A quick setup and display or readout calibration method that is quite handy for 120Ω single arm gages uses the 120Ω resistors of the strain gage adapter to complete the bridge. Then the adapter box dial is set to the gage factor printed on the package. Finally, the gage supply voltage is set for an even number of divisions to represent 1000 microstrains. The system is then calibrated to read strain directly. NOTE: Do not exceed 6 V on the bridge for most metal-mounted applications. Read the reference material for higher accuracy or special applications.
2. If strain gages with resistance other than 120 Ω are used in arm 4, the calibration strain (ϵ_{cal}) is no longer 1000 microstrains.
3. In the 1 ext arms position, only 120 Ω strain gages may be used.
4. In the 2 ext arms position, any value of strain gage resistance may be used with $\epsilon_{cal}=1000$ microstrains because it shunts the 120 Ω resistors in arm 4.
5. In the 4 ext arms position, any value gage resistance may be used if

$$\epsilon_{cal}=1000\times\frac{R_{ext}}{120}$$

6. The strain sensitivity may be increased by using two or more strain gages if the gages are properly connected to the strain gage adapter. If a beam is subjected to forces causing bending, legs one and two of the adapter should be used with one gage measuring tension and the other compression by mounting one gage on top and one on the bottom. Since the sensitivity is doubled, the actual strain will be half the strain voltage reading. Calibration of the strain gage supply voltage will still be for a total of 1000 microstrains on one gage.
7. For two gages, both in tension or both in compression, opposite legs of the bridge must be used. The switch on the adapter box must be turned to the 4 ext arms position. This removes all the internal 120 Ω resistors from the bridge. The cal resistor remains across the R_4 position. Fixed temperature-stable resistors, equal in value to the two gage resistances, must then be inserted in the open legs. With 120 Ω resistors in the bridge, ϵ_{cal} is still 1000 microstrains, but, since the sensitivity has been doubled, the strain voltage reading must be halved to obtain the actual strain.
8. When four gages are used for more sensitivity, those measuring like strain must be in opposite legs. Also the Poisson strains (strains at right angles to the applied force such as the necking down of a specimen subject to tension) have a magnitude of Poisson's ratio times the tensional or compressive strains. Thus, when two gages are measuring tensional strains and two gages are measuring Poisson strains, the strain reading must be divided by $1+1+(2\times\simeq 0.3)$ (Poisson's ratio for the material) to obtain the actual strain.
9. During the tests, do not exceed the elastic limit of the material to which the gage is applied.
10. Do not exceed the gage strain limits.
11. Power dissipation in strain gages: Determine the voltage drop across the gage and check strain gage data sheets to make certain that the voltage doesn't exceed that recommended by the gage manufacturer. Use 2 V on plastics, 3 V in dynamic tests, and 4 V on metal static tests if the proper information is not available.
12. Output voltage of the strain gage bridge
    a. Modules of elasticity—strain relationships

$$Em=\frac{\Upsilon}{\epsilon}=\frac{\text{(stress)}}{\text{(strain)}}$$

$$\Upsilon=\frac{P}{A}\ \text{(stress)}=\frac{\text{(force)}}{\text{(area)}}$$

$$\epsilon=\frac{P}{A\ Em}\ \text{(strain)}=\frac{\text{(force)}}{\text{(area) (modules of elasticity)}}$$

$$\epsilon=\frac{\Delta l}{l}\ \text{strain}=\frac{\text{(change in length)}}{\text{(length)}}$$

    b. Wire resistance—strain relationships

$$R=\frac{\rho l}{A}\ \text{(resistance)}=\frac{\text{(specific resistance) (length)}}{\text{(area)}}$$

$$A=\frac{\pi D^2}{4}$$

$$\frac{\Delta R}{R}=\frac{\Delta l}{l}+\frac{\Delta\rho}{\rho}-2\frac{\Delta D}{D}$$

$$\frac{\Delta D/D}{\Delta l/l}=-\mu\ \text{(poisson's ratio)}=\frac{\text{(unit change in diameter)}}{\text{(unit change in length)}}$$

$$\frac{\Delta R/R}{\Delta l/l}=1+2\mu+\frac{\Delta\rho/\rho}{\Delta l/l}=\text{G.F. (gage factor)}$$

$$\Delta R=R\ (\text{G.F.}\times\epsilon)$$

    C. Electrical Signal—strain relationship
    Wheatstone bridge equation of equal resistance legs.

$$E_{out}=\frac{Ein}{4}\left[\frac{\Delta R_1}{R_1}-\frac{\Delta R_2}{R_2}+\frac{\Delta R_3}{R_3}-\frac{\Delta R_4}{R_4}\right]$$

    Strain gage bridge output

$$E_o=\frac{Ein}{4}\times\text{G.F.}\times\epsilon\times N\quad \text{where N=number of active legs}$$

2-5. Conversion Factors, Static.

The changeover to the standard international metric system (SI) of units has forced everyone to become conversion factor conscious. Good tables of conversion factors are available from the following publi-tions.

Handbook of Chemistry and Physics.
Chemical Rubber Publishing Co. Page F215.

Reference Data for Radio Engineers.
Howard W. Sams Co. Pages 3-6.

IEEE Standard 268-1973.

NBS Special Publication 286.
Units of Weight and Measure.

The following short list of basic conversion factors are the most commonly used in instrumentation of physical quantities.

Symbol	Given	Multiply by	To obtain	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	30.48	centimeters	cm
yds	yards	0.9144	meters	m
mi	miles	1.609	kilometers	km
		AREA		
in^2	square inches	6.452	square centimeters	cm^2
ft^2	square feet	0.09290	square meters	m^2
		VOLUME		
fl oz	fluid ounce	29.57	milliliters (or cubic cm)	m or cm^3
gal	gallons	3.785	liters	l
		FORCE		
oz (f)	ounces-force	0.2780	newtons	N
lb (f)	pounds-force	4.448	newtons	N
kg (f)	kilograms-force	9.807	newtons	N
dyn	dyns	10^{-5}	newtons	N

The following chart shows the various terms for pressure used in different scientific disciplines and the appropriate conversion factors.

2-7. Reference Material List

The following is a short list of sources for more detailed information on transducers.

ISA Transducer Compendium. 3 volumes.
ISA, Pittsburgh, Pennsylvania.

Measurements and Control Handbook.
Measurements and Data Corp., Pittsburgh, Pennsylvania.

Control Equipment Master.
Chilton, Radnor, Pennsylvania.

Handbook of Measurement and Control.
Schaevitz Engineering, Camden, New Jersey.

Dynamic Transducer Catalog.
Columbia Research Laboratories, Woodlyn Pennsylvania.

Fundamentals of Temperature, Pressure and Flow Measurement, 2nd Edition by Robert P. Benedict
Wiley-Interscience, New York, N.Y.

Section 3.

Section 3. Vibration Test Methods and Equipment

3-1. Introduction

This section presents information relative to the measurement, display, and analysis of vibrations in common industrial situations. Background information, including terms, conversion factors, formulae, and nomographs is presented first. Then basic measurement hardware configurations are shown.

The control of vibration is the primary reason for vibration measurement. This control may take one of three general forms: (1) reduction at the source, (2) isolation, or (3) reduction of the response.

Reduction of vibration in rotating machinery is most readily achieved by either balancing or counterbalancing. In automobile engines, individual masses are designed into the crankshaft to offset or counterbalance the inertial effects of the connecting rods and pistons. In applications using rotary compressors, fans, blowers, or drive shafts, it is common to add or remove material to achieve a balanced rotating element. Several techniques for balancing are described in the application notes and reference literature. Additional equipment and techniques are described later in this section.

Careful engineering designs, that control clearances and balance of magnetic flux of rotating members in electric motors, will reduce noise generation.

Careful dimensional analysis of designs to prevent or control contact between moving parts also sharply reduces noise at its source. The best and most successful design is one that eliminates vibration and noise generation.

Isolation of the source of shock or vibration by foundation design and vibration isolators will reduce effects on other machinery and personnel. Sensitive equipment requires special care and isolation to remove small shocks such as footsteps.

Response to outside shock and vibration signals can sometimes be reduced. One very successful method of minimizing signal frequency vibration effects is to alter the natural frequency of a sensistive device so that it is not frequency related to the interference source. Also, it is sometimes possible to move the interference source frequency. Another method of response alteration, used in instances where multiple frequencies are involved, is the use of energy absorbers. This is quite common on household appliances and automobiles. Additional auxiliary masses or foundations may be added to reduce the coupling of energy between units. Unsymmetrical mountings and structural member configurations also reduce coupling. This method is used with engine mounts and frame design in automobiles and trucks.

Once vibrations are understood, measured, and quality criteria established, many methods for control are available.

3-2. Shock and Vibration Concepts

Vibration is usually defined as any oscillation (usually undesired) in a mechanical system. It may be characterized by both amplitude and frequency. It is assumed that the time history of any vibration may be expressed as a series of sinusoidal waves of simple harmonic form. In practice, vibration in only the most simple structures exhibit something that is recognizable as a sine wave or series of sine waves. These are called "periodic" waveforms or vibrations; that is, each part of the signals has an integral multiple relationship to the fundamental frequency, and a repetitive pattern. Vibration situations in which there is no integral relationship among the vibration frequency components are defined as complex vibrations.

Text books often describe vibration of machines or structures in terms of simplified models based on spring-mass systems and in terms of "free" or forced vibrations. In these simple ideal systems, the free vibration is performed by the system when excited only by an initial impulse. This is called transient vibration and may be mathematically analyzed. In practical machinery, the conditions for "forced vibrations" exist because there is a continuous input of energy to excite and sustain vibrations. This sustaining energy has a characteristic frequency that appears in the vibration signal. The relationships of this input frequency and the characteristic frequencies of the device, structure, or machine determines the principal characteristics of the observed vibrations. A great deal of further information on the analysis and causes of vibrations are available from the literature listed in the reference section at the back of this handbook.

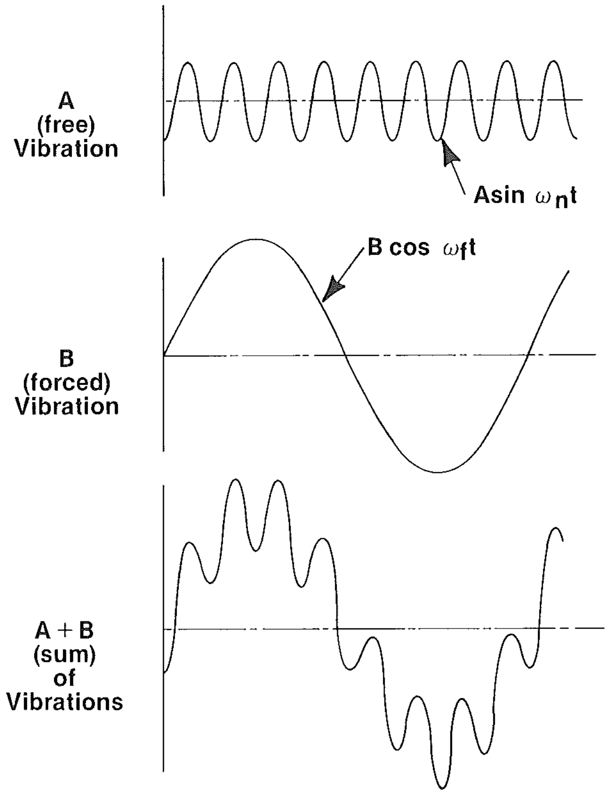


Figure 3-1. Vibration Waveforms

3-3. Conversion Factors

Conversion factors, equations, and definitions are basic parts of the work of an engineer. The following are those most commonly used in vibration work.

Harmonic motion definitions:

rms value	=0.707 X peak value (one way from zero)
rms value	=1.11 X average value
peak value	=1.414 X rms value
peak value	=1.57 X average value
average value	=0.637 X peak value
average value	=0.90 X rms value
peak-to-peak value	=2 X peak value
crest factor	=peak value ÷ rms value

Angular Acceleration Conversion Chart

Multiply Number of → / by / to Obtain ↓	Radians per second per second	Revolutions per minute per minute	Revolutions per minute per second	Revolutions per second per second	Degrees per second per second
Radians per second per second	1	1.745×10^{-3}	0.1047	6.283	0.01745
Revolutions per minute per minute	573.0	1	60	3600	10
Revolutions per minute per second	9.549	1.667×10^{-2}	1	60	0.1667
Revolutions per second per second	0.1592	2.778×10^{-4}	1.667×10^{-2}	1	2.778×10^{-3}
Degrees per second per second	57.30	0.1	6	360	1

Angular Velocity Conversion Chart

Multiply Number of → / by / to Obtain ↓	Degrees per second	Radians per second	Revolutions per minute	Revolutions per second
Degrees per second	1	57.30	6	360
Radians per second	1.745×10^{-2}	1	0.1047	6.283
Revolutions per minute	0.1667	9.549	1	60
Revolutions per second	2.778×10^{-2}	0.1592	1.667×10^{-2}	1

Linear Acceleration Conversion Chart

Multiply Number of → by ↘ to Obtain ↓	Centimeters per second per second	Feet per second per second	Kilometers per hour per second	Meters per second per second	Miles per hour per second	"G's" Gravity	Inches per second per second
Centimeters per second per second	1	30.48	27.78	100	44.70	980	2.54
Feet per second per second	3.281 $\times 10^{-2}$	1	0.9113	3.281	1.467	32.2	8.33 $\times 10^{-2}$
Kilometers per hour per second	0.036	1.097	1	3.6	1.609	35.28	9.14 $\times 10^{-2}$
Meters per second per second	0.01	0.3048	0.2778	1	0.4470	9.8	2.54 $\times 10^{-2}$
Miles per hour per second	2.237 $\times 10^{-2}$	0.6818	0.6214	2.237	1	21.92	5.68 $\times 10^{-2}$
"G's" Gravity	1.02 $\times 10^{-3}$	0.0311	2.83 $\times 10^{-2}$	0.102	4.56 $\times 10^{-2}$	1	2.59 $\times 10^{-3}$
Inches per second per second	0.3937	12	10.94	39.37	17.6	386	1

Linear Velocity Conversion Chart

Multiply Number of → by ↘ to Obtain ↓	Centimeters per second	Inches per second	Feet per second	Meters per second	Feet per minute	Miles per hour	Kilometers per hour
Centimeters per second	1	2.54	30.48	100	0.508	44.7	27.77
Inches per second	0.3937	1	12	39.37	0.2	17.6	10.94
Feet per second	3.28 $\times 10^{-2}$	0.0833	1	3.2808	1.666 $\times 10^{-2}$	1.466	0.91
Meters per second	10^{-2}	2.54 $\times 10^{-2}$	0.3048	1	5.08 $\times 10^{-3}$	0.447	0.2778
Feet per minute	1.969	5	60	196.9	1	88	54.6
Miles per hour	2.237 $\times 10^{-2}$	5.68 $\times 10^{-2}$	0.682	2.237	1.136 $\times 10^{-2}$	1	0.6214
Kilometers per hour	3.6 $\times 10^{-2}$	9.14 $\times 10^{-2}$	1.098	3.60	1.828 $\times 10^{-2}$	1.6093	1

Energy, Work and Heat Conversion Chart

Multiply Number of → by to Obtain ↓	British thermal units	Centimeter-grams	Ergs or centimeter-dynes	Foot-pounds	Horsepower-hours	Joules or watt-second	Kilogram-calories	Kilowatt-hours	Meter-kilograms	Watt-hours
British thermal units	1	9.297×10^{-8}	9.470×10^{-11}	1.285×10^{-3}	2545	9.470×10^{-4}	3.969	3413	9.285×10^{-3}	3.409
Centimeter-grams	1.076×10^{7}	1	1.020×10^{-3}	1.383×10^{4}	2.737×10^{10}	1.020×10^{4}	4.269×10^{7}	3.671×10^{10}	10^{5}	3.671×10^{7}
Ergs or centimeter-dynes	1.055×10^{10}	980.7	1	1.356×10^{7}	2.684×10^{13}	10^{7}	4.190×10^{10}	3.6×10^{13}	9.807×10^{7}	3.6×10^{10}
Foot-pounds	778.3	7.233×10^{-5}	7.367×10^{-8}	1	1.98×10^{6}	0.7376	3087	2.655×10^{6}	7.233	2655
Horsepower-hours	3.929×10^{-4}	3.654×10^{-11}	3.722×10^{-14}	5.050×10^{-7}	1	3.722×10^{-7}	1.559×10^{-3}	1.341	3.653×10^{-6}	1.341×10^{-3}
Joules or watt-seconds	1055.9	9.807×10^{-5}	10^{-7}	1.356	2.684×10^{6}	1	4190	3.6×10^{6}	9.807	3600
Kilogram-calories	0.2520	2.343×10^{-8}	2.386×10^{-11}	3.239×10^{-4}	641.3	2.386×10^{-4}	1	860.0	2.343×10^{-3}	0.8600
Kilowatt-hours	2.930×10^{-4}	2.724×10^{-11}	2.778×10^{-14}	3.766×10^{-7}	0.7457	2.778×10^{-7}	1.163×10^{-3}	1	2.724×10^{-6}	0.001
Meter-kilograms	107.7	10^{-5}	1.020×10^{-8}	0.1383	2.737×10^{5}	0.1020	426.9	3.671×10^{5}	1	367.1
Watt-hours	0.2933	2.724×10^{-8}	2.778×10^{-11}	3.766×10^{-4}	745.7	2.778×10^{-4}	1.163	1000	2.724×10^{-3}	1

Power Conversion Chart

Multiply Number of → by to Obtain ↓	British thermal units per minute	Ergs per second	Foot-pounds per minute	Foot-pounds per second	Horsepower	Kilograms-calories per minute	Kilowatts	Metric-horsepower	Watts
British thermal units per minute	1	5.689×10^{-9}	1.285×10^{-3}	7.712×10^{-2}	42.41	3.969	56.89	41.83	5.689×10^{-2}
Ergs per second	1.758×10^{8}	1	2.259×10^{5}	1.356×10^{7}	7.460×10^{9}	6.977×10^{8}	10^{10}	7.335×10^{9}	10^{7}
Foot-pounds per minute	778.0	4.426×10^{-6}	1	60	3.3×10^{4}	3087	4.426×10^{4}	3.255×10^{4}	44.26
Foot-pounds per second	12.97	7.376×10^{-8}	1.667×10^{-2}	1	550	51.44	737.6	542.5	0.7376
Horsepower	2.357×10^{-2}	1.340×10^{-10}	3.030×10^{-5}	1.818×10^{-3}	1	9.355×10^{-2}	1.340	0.9863	1.340×10^{-3}
Kilogram-calories per minute	0.2520	1.433×10^{-9}	3.239×10^{-4}	1.943×10^{-2}	10.69	1	14.33	10.54	1.433×10^{-2}
Kilowatts	1.758×10^{-2}	10^{-10}	2.260×10^{-5}	1.356×10^{-3}	0.746	6.977×10^{-2}	1	0.7355	10^{-3}
Metric horse-power	2.390×10^{-2}	1.360×10^{-10}	3.072×10^{-5}	1.843×10^{-3}	1.014	9.485×10^{-2}	1.360	1	1.360×10^{-3}
Watts	17.58	10^{-7}	2.260×10^{-2}	1.356	746.0	69.77	1000	735.5	1

3-4. Definition of Common Shock and Vibration Terms

Following are some of the terms common to the shock and vibration fields. A complete list is available from the American National Standards Association.

ACCELERATION—A vector quantity that specifies the time rate of change of velocity.

AMPLITUDE—The maximum value of a sinusoidal quantity (peak).

ANGULAR (CIRCULAR) FREQUENCY—In radians per unit time, the frequency multiplied by 2π (6.2832).

ANGULAR MECHANICAL IMPEDANCE (ROTATIONAL MECHANICAL IMPEDANCE)—The impedance involving the ratio of torque to angular velocity. (See Impedance.)

BALANCING—A procedure for adjusting the mass distribution of a rotor so that vibration of the journals, or the forces on the bearings, at once-per-revolution are reduced or controlled.

BEATS—Periodic variations that result from the superposition of two simple harmonic quantities of difference frequencies (f_1 and f_2), and that involve the periodic increase and decrease of amplitude at the beat frequency ($f_1 - f_2$).

BROADBAND RANDOM VIBRATION—Random vibration having frequency components distributed over a broad frequency band. (See Random Vibration.)

COMPLEX VIBRATION—Vibration with sinusoidal components that are sinusoids not harmonically related to one another. (See Harmonic)

COMPLIANCE—The reciprocal of stiffness.

COULOMB DAMPING (DRY FRICTION DAMPING)—The dissipation of energy that occurs when a particle in a vibrating system is resisted by a force. The force magnitude is constant and independent of displacement or velocity. The force direction is opposite to the velocity direction of the particle.

COUPLED MODES—Modes of vibration that are not independent but that influence one another because of energy transfer from one mode to the other.

CRITICAL DAMPING—The minimum viscous damping that will allow a displaced system to return to its initial position without oscillation (or overshoot).

CRITICAL SPEED—A speed of a rotating system that corresponds to a resonant frequency of the system.

CYCLE—The complete sequence of values of a periodic quantity that occurs during a period.

DAMPED NATURAL FREQUENCY—The frequency of free vibration of a damped linear system. Free vibrations may be considered periodic in the limited sense that the time interval between zero crossings in the same direction is constant, even though successive amplitudes decrease progressively. The frequency of the vibration is the reciprocal of this time interval.

DAMPING—The dissipation of energy with time or distance.

DEGREES OF FREEDOM—The minimum number of independent coordinates required to define completely the positions of all parts of the system at any instant in time. In general, it is equal to the number of independent displacements that are possible.

DISPLACEMENT—A vector quantity that specifies the change of position of a body or particle and is usually measured from the mean position or position of rest. In general, it can be represented as a rotation vector, translation vector, or both.

DYNAMIC VIBRATION ABSORBER (TUNED DAMPER)—An auxiliary mass-spring system that tends to neutralize vibration of a structure to which it is attached. The basic principle of operation is vibration out-of-phase with the vibration of such structure, thereby applying a counteracting force.

EQUIVALENT SYSTEM—A system that may be substituted for another for the purpose of analysis. Many types of equivalence are common in vibration and shock technology: (1) equivalent stiffness, (2) equivalent damping, (3) torsional system equivalent to a translational system, (4) electrical or acoustical system equivalent to a mechanical system, etc.

EXCITATION (STIMULUS)—An external force (or other input) applied to a system that causes the system to respond in some way.

FORCED VIBRATION (FORCED OSCILLATION)—Oscillation of a system with the response imposed by the excitation. If the excitation is periodic and continuing, the oscillation is steady state.

FOUNDATION (SUPPORT)—A structure that supports the gravity load of a mechanical system. It may be fixed in space, or it may undergo a motion that provides excitation for the supported system.

FRACTION OF CRITICAL DAMPING (DAMPING RATIO)—For a system with viscous damping, the ratio of actual damping coefficient C to the critical damping coefficient C_c.

FREE VIBRATION—Vibration that occurs in the absence of forced vibration.

FUNDAMENTAL MODE OF VIBRATION—The mode having the lowest natural frequency.

g(GRAVITY)—The acceleration produced by the force of gravity, which varies with the latitude and elevation of the point of observation. By international agreement, the value 980.665 cm/s^2=386.087 inch/s^2=32.1739 ft/s^2 has been chosen as the standard acceleration because of gravity.

IMPEDANCE—For mechanical impedance, the ratio of a force-like quantity to a velocity-like quantity when the arguments of the real (or imaginary) parts of the quantities increase linearly with time. Examples of force-like quantities are: force, sound pres-pressure, voltage, and temperature. Examples of velocity-like quantities are: velocity, volume velocity, current, and heat flow. Impedance is the reciprocal of mobility.

JERK—A vector that specifies the time rate of change of acceleration, the third derivative of displacement with respect to time.

LINEAR SYSTEM—A system with response proportional to excitation for every element in the system. This definition implies that the dynamic properties of each element in the system can be represented by a set of linear differential equations with constant coefficients, and that, for the system as a whole, superposition holds.

MODE OF VIBRATION—In a system undergoing vibration, a characteristic pattern assumed by the system in which the motion of every particle is a simple harmonic with the same frequency. Two or more modes may exist concurrently in a multiple-degrees-of-freedom system.

MULTIPLE DEGREES OF FREEDOM—A system for which two or more coordinates are required to define completely the position of the system at any instant.

NATURAL FREQUENCY—The frequency of free vibration of a system. For a multiple-degrees-of-freedom system, the natural frequencies are the frequencies of the normal modes of vibration.

NOISE—Any undesired signal. By extension, noise is any unwanted disturbance within a useful frequency band, such as undesired signal waves in a transmission channel.

NORMAL MODE OF VIBRATION—A mode of vibration that is uncoupled from (that is, can exist independently of) other modes of vibration of a system. The term "classical normal mode" is sometimes applied to the normal modes of a vibrating system characterized by vibration of each element of the system at the same frequency and phase. In general, classical normal modes exist only in a system having no damping or having particular types of damping.

RANDOM VIBRATION—Vibration with instantaneous magnitude not specified for any given instant in time.

SELF-INDUCED (SELF-EXCITED) VIBRATION—Vibration that results from conversion, within the system, of monoscillatory excitation to oscillatory excitation.

SHEAR WAVE (ROTATIONAL WAVE)—A wave in an elastic medium that causes an element of the medium to change its shape without a change of volume.

SHOCK ABSORBER—A device that dissipates energy to modify the response of a mechanical system to applied shock.

SIMPLE HARMONIC MOTION—A motion such that the displacement is a sinusoidal function of time; sometimes designated merely by the term "harmonic motion."

SINGLE DEGREE OF FREEDOM SYSTEM—A system for which only one coordinate is required to define completely the configuration of the system at any instant.

SNUBBER—A device used to increase the stiffness of an elastic system (usually by a large factor) whenever the displacement becomes larger than a specified value.

STANDING WAVE—A periodic wave having a fixed distribution in space that is the result of interference of progressive waves of the same frequency and kind. Such waves are characterized by the existence of nodes, or partial nodes, and antinodes that are fixed.

STIFFNESS—The ratio of change of force (or torque) to the corresponding change in translational (or rotational) deflection of an elastic element.

SUBHARMONIC—A sinusoidal quantity having a frequency that is an integral submultiple of the fundamental frequency of a periodic quantity to which it is related.

SUBHARMONIC RESPONSE—The periodic response of a mechanical system exhibiting the characteristic of resonance at a frequency that is a submultiple of the frequency of the periodic excitation.

SUPERHARMONIC RESPONSE—A term sometimes used to denote a particular type of harmonic response that dominates the total response of the system, and frequently occurs when the excitation frequency is a submultiple of the frequency of the fundamental resonance.

TRANSFER IMPEDANCE—Between two points, the impedance involving the ratio of force to velocity when force is measured at one point and velocity at the other point.

TRANSIENT VIBRATION—Temporarily sustained vibration of a mechanical system. It may consist of forced or free vibration, or both.

UNCOUPLED MODE—A mode that can exist in a system concurrently with and independently of other modes.

UNDAMPED NATURAL FREQUENCY—The frequency of free vibration resulting from only classic and inertial forces of the system.

VELOCITY—A vector quantity that specifies the time rate of change of displacement with respect to a reference frame. If the reference frame is not inertial, the velocity is often termed "relative velocity."

VIBRATION—An oscillation wherein the quantity is a parameter that defines the motion of a mechanical system.

WHITE NOISE—A noise the power spectral density of which is substantially independent of frequency over a specified range.

A more complete list is available in the reference material sources listed at the end of each chapter.

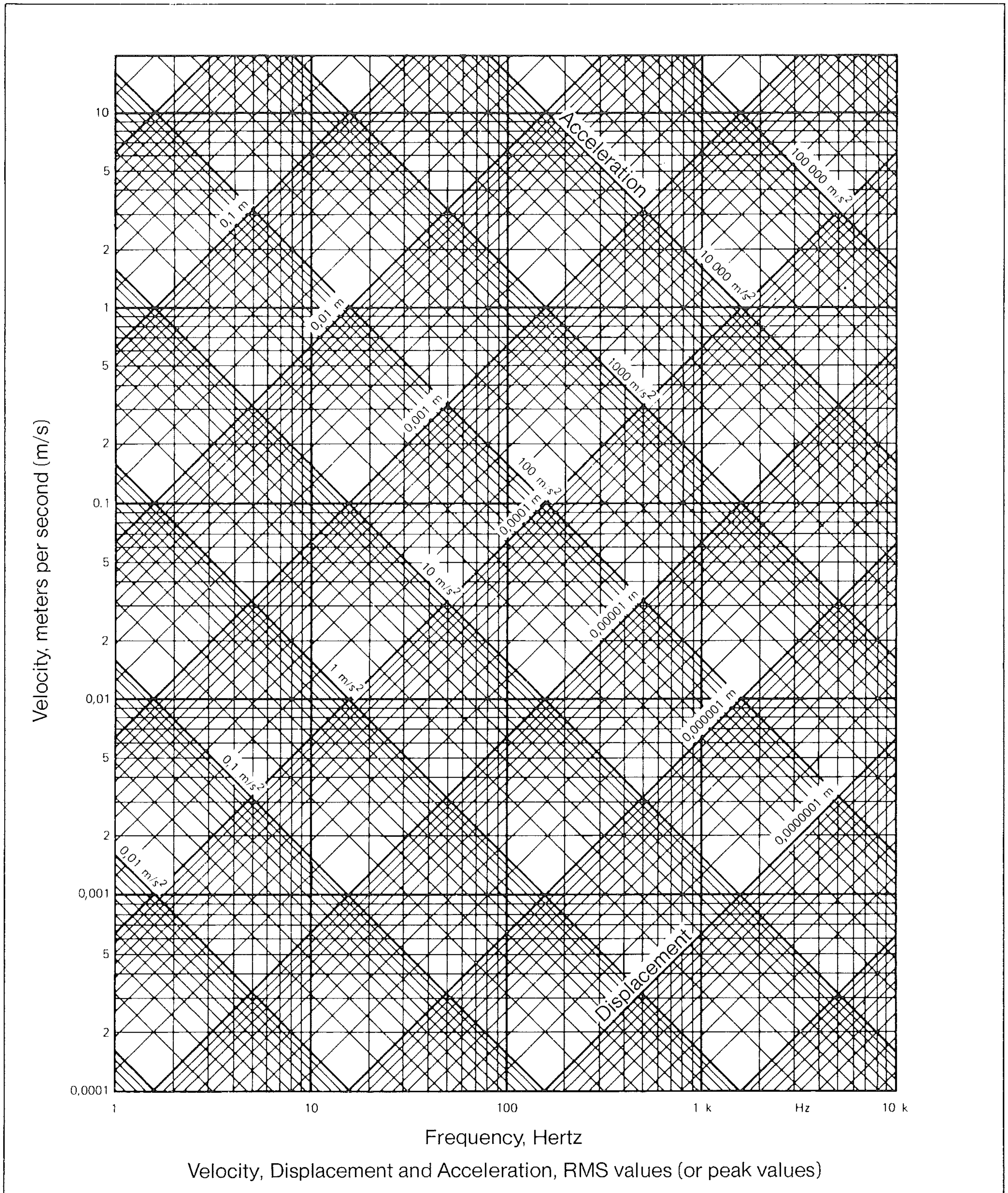


Figure 3-2. Vibration Frequency Nomograph

3-5. Mathematical Definitions

The following is a short summary of some of the basic mathematics used in defining vibration:

Linear quantity

Linear displacement	x
Force	F
Spring constant	k
Damping constant	c
Mass	m

Spring Force $F = K(x_0 - x_1)$

Damping Force $F = c\,(x_0 - x_1)$

Inertial Force $F = m\ddot{x}$ $(F = ma)$

Rotational quantity

Angular displacement	α
Torque	T (or M)
Spring constant	kr
Damping constant	cr
Moment of inertia	I

Spring Torque $M = k_r\,(\alpha_2 - \alpha_1)$

Damping Torque $M = c_r\,(\dot{\alpha} - \dot{\alpha}_1)$

Inertial Torque $M = I\,\ddot{\alpha}$

Free vibration without damping

$m\ddot{x} + kx = 0$ (spring force) + (displacement force)=0

$$X = A \sin \sqrt{\frac{k}{m}}\,t + B \cos \sqrt{\frac{k}{m}}\,t$$

$$\omega_n = \sqrt{\frac{k}{m}} \text{ angular natural frequency}$$

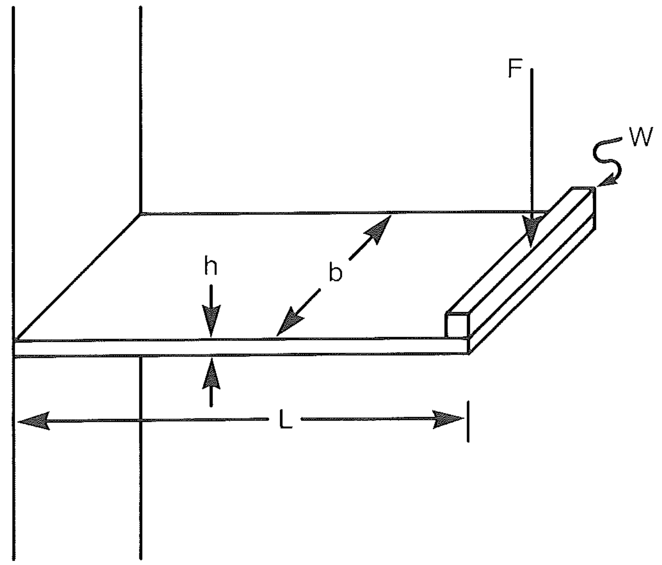
$$\tau = \frac{2\pi}{\omega_n} \text{ period of one cycle}$$

$$f_n = \frac{1}{\tau} = \frac{1}{2\pi}\sqrt{\frac{kg}{W}} \text{ where: } W = mg \text{ (weight)}$$

This equation for natural frequency applies to a simple undamped single-degree-of-freedom system such as a single spring and a single weight or mass. If this weight is located directly above the spring, the spring will deflect as the result of the force of gravity as shown by the following equation:

$$\delta = \frac{W}{k} = \frac{mg}{k}$$

Application of these basic formulae to a simple canti-levered bar with a weight (W) at its end is shown.



Static deflection X_0 for Force F

$$X = \frac{FL^3}{3EI}$$

Where E=Modulus of elasticity x 30 x 10^6 lb/in^2 for steel

I=Moment of inertia ($bh^3/12$) for this shape member

Spring constant

$$k = \frac{F}{X} = \frac{3EI}{L}$$

Natural frequency when F=W

$$f_n = \frac{1}{2\pi}\sqrt{\frac{3EI_g}{WL^3}} \text{ Hz}$$

$$f_n = \frac{1}{2\pi}\sqrt{\frac{36E_g}{Wbh^3L^3}} \text{ Hz}$$

$$f_n \approx 1.03 \times 10^5 \sqrt{\frac{1}{Wbh^3L^3}} \text{ Hz}$$

3-6. Machine (Vibration) Signature Analysis.

Equations describing functional mechanical systems require consideration of many additional factors such as damping, several resonant elements, and coupling between these elements. Therefore, the descriptive equations are quite complex. Accordingly, the practice of machinery signature analysis was developed.

Machinery signature analysis is usually based on the patterns of a properly operating machine of like kind in a like application. Because of the extreme complexity of vibration signatures, or any machine performance signatures, most of the emphasis is placed on the "trend analysis" method of machine signature analysis. In this method of analysis, careful records are kept for a large number of machine characteristics recorded at definite time intervals. When these data are plotted versus time, many "condition trends" become obvious and maintenance plans may be developed to prevent catastrophic failures. When vibra tion signatures of machines, structures, bearings, etc. are taken, effort should be made to identify and record the source of the large signal components. These components will change in ratio when the machine conditions change because of both forced and free vibrations. Free vibration components will change when machine dimensions change as, for instance, when a casting cracks. When an element of a machine performs differently, the forced vibration content will change. If prior analysis of the machine has been made, these changes will point the way to the causes of the performance change, thereby providing necessary data. Some companies have very successfully used these data to establish minimum stress operating points for machinery and have greatly extended operating life and minimized operating costs. The Vibrations Severity Guide shown in Figure 3-3 is a typical chart used for this purpose. The implementation of a signature analysis program requires: (1) data on the machine and its use, (2) data acquisition equipment, and (3) a planned data reduction and analysis program. It is to the second item that this handbook is directed. The key elements are transducers, transducer excitation, transducer signal processing, data display, and data recording.

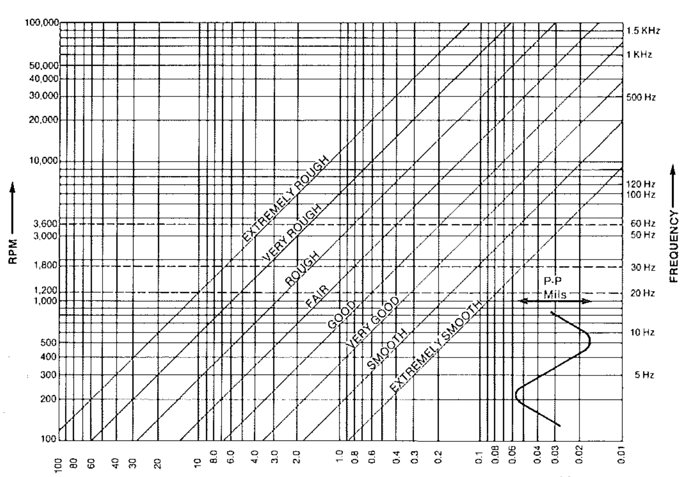


Figure 3-3. Rotating Machine Vibrations Severity Guide

3-7. Transducer Selection

Selection of the "right" transducer type is a compromise among several factors and no single type is best for all applications. Three basic types are used: (1) displacement, (2) velocity, and (3) acceleration. The graph shown in Figure 3-4 depicts the relationship between these transducer output signals when attached to a constant velocity (0.3 in/sec) mass. The limit values indicated are generally accepted industry standards, not the limits of the transducers. The displacement range is often broken into ranges by the types of displacement transducers. The lower frequency part of the displacement range applies to the contact type displacement transducers, the resonant mass transducers, or the seismic transducers. The noncontact or eddy current displacement transducer is used primarily in the upper frequency range, often in competition with accelerometers. The middle range of frequencies is the domain of the velocity transducers by tradition and the high frequency range, well into the ultrasonic, is dominated by the accelerometer.

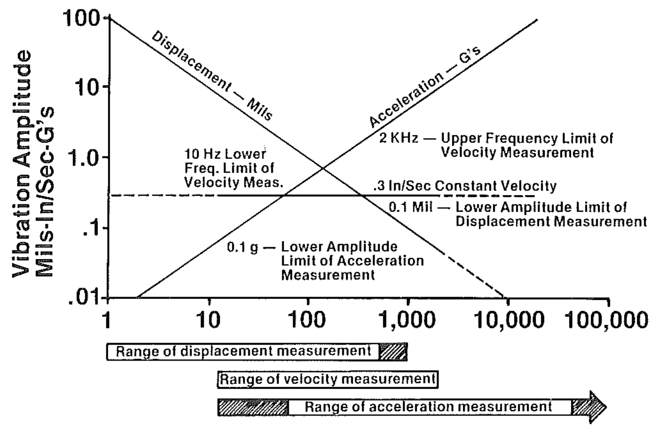


Figure 3-4. Transducer Output Signal Relationships

The shading on the nomograph of Figure 3-5 shows the operating zones of two specific transducers. This nomograph illustrates the relationships of velocity (left vertical scale for horizontal lines), frequency (lower horizontal scale for vertical lines), displacement (diagonal lines running from lower left to upper right) and acceleration (diagonal lines running from lower right to upper left. The displacement units are inches peak to peak. If other units are required, use the conversion factor listed earlier in this section. The acceleration units are peak g, and the velocity units are ips peak. Vibration quality figures are listed on the left side of the velocity scales. These values are obtained from data in the reference material listed at the back of this section.

The transducer shading shows the preferred operating zones for the PN 015-0165-00 Accelerometer, the PN 015-0166-00 Vertical Velocity and Displacement Transducer, and the PN 015-0167-00 Horizontal Velocity and Displacement Transducer previously discussed in the transducer section. The two dark areas in the lower left and upper right designate zones of caution for the accelerometer. Operation of the accelerometer over 1000 g's requires careful attachment and cabling. Operations below 0.001 g at levels below 10μ volt are subject to noise and cable pick up problems if extreme care is not taken.

There are four zones of forbidden operation or caution for the seismic transducers. The first zone is the region below 10 Hz. The resonance of the seismic transducers is approximately 8 Hz and normal operation is above the resonance. The electrical phase shift, because of the inductance of the pickup coil, imposes a high frequency limit somewhere above 1 or 2 kHz.

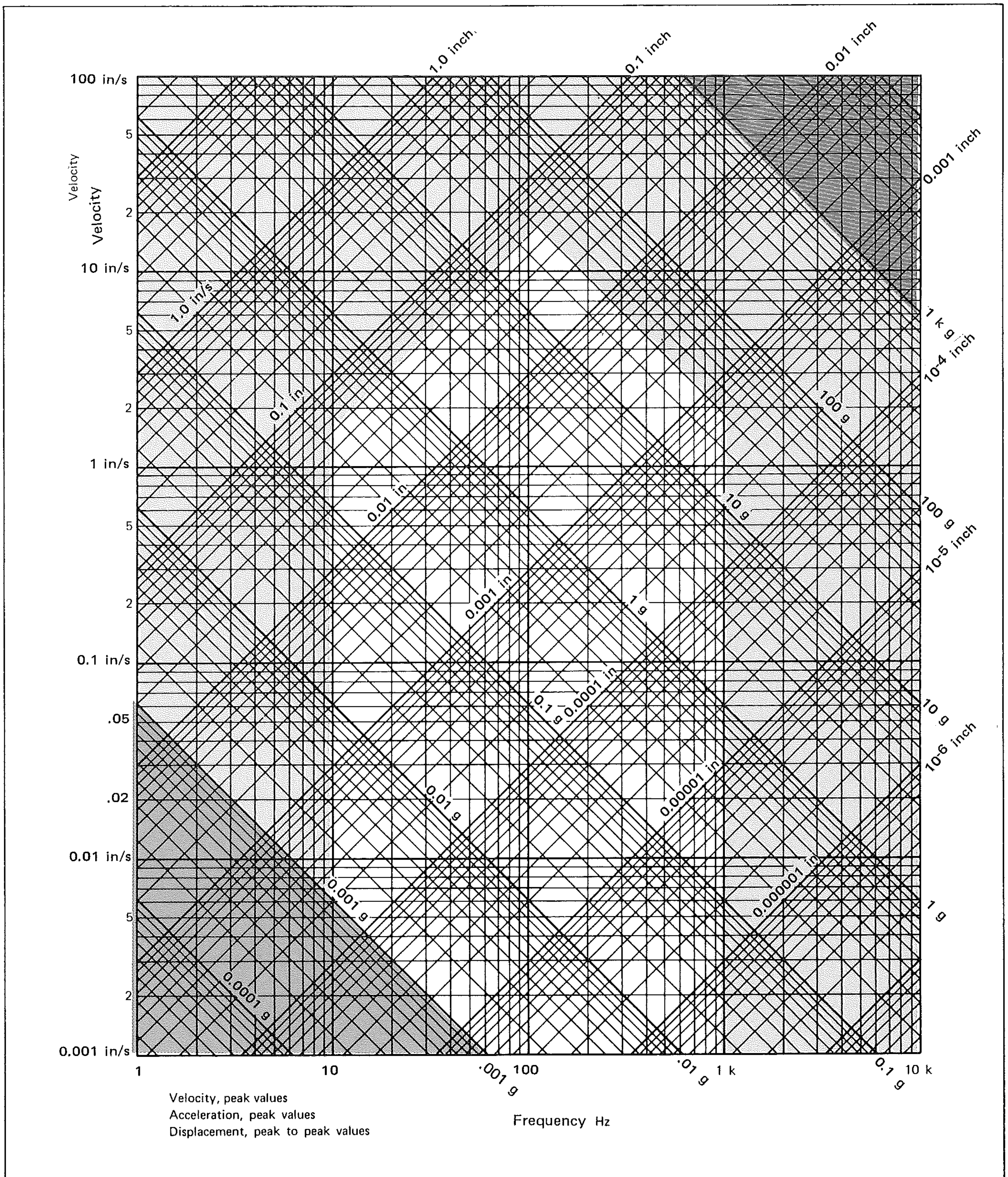


Figure 3-5. Vibration Transducer Application Zones

If the excursion of the seismic mass is too great (over 0.05 inch), both the velocity and displacement signals will flatten out on the peaks and result in an erroneous indication. The physical mounting method on the transducer limits its application to below 30 to 50 g's. As discussed earlier, general rules of application dictate choosing the accelerometer for higher frequency signals (higher g signal amplitudes), and velocity transducers for lower frequency applications. The dividing line is somewhere in the 50 to 100-Hz (3000 to 6000 RPM) region, but the decision is usually based on signal level and environmental factors.

3-8. Rotary Machinery Vibration Sources

The following 12 categories are considered to be the major causes of rotary machine vibrations, the symptomatic noises, and resultant failures.

1. IMBALANCE. This is the usual cause of machine vibrations at the rotational (X1 RPM) frequency. Two common forms of imbalance are important: (A) *Static Imbalance*—This causes a free rotational force because of the displacement of the center of gravity from the rotational axis. (B) *Dynamic Imbalance*—A free mechanical couple because the principal inertial axis is not coincident (not parallel) to the bearing or rotational axis. These imbalances may be caused by nonsymmetrical parts, mechanical distortion (due to damage, loading effects, or temperature differentials), uneven wear, corrosion, eccentricity, nonhomogenous materials, migration of materials, or shifting of parts.
2. MISALIGNMENT. The misalignment of couplings or bent shafts can create axial bearing loads and vibrations at 1X, 2X, or 3X RPM frequencies and 1X RPM radial vibrations. This misalignment of couplings creates torsional vibration in the shaft and resultant signals of 2X, 4X, and 6X RPM frequencies.
3. OUT OF ROUND. Eccentric or out-of-round gears, pulleys, wheels, or tires will cause 1X RPM vibration. This is another form of imbalance conditions.
4. RESONANCES. Excitation of machine natural structural resonance frequencies by operation near this frequency or near one of its harmonics. This type operation supplies the necessary excitation to cause excessive vibration with only slight imbalance.
5. LOOSE PARTS. Loose mountings, loose parts, excessive bearing clearances, and excessive gear clearances create impact-type vibrations at twice (2X) the running frequency. Excessive gear clearances also create vibrations at tooth frequencies of NX RPM, where N equals the number of teeth in either gear or any whole mathematical relation of the two teeth frequencies.
6. BAD BEARINGS. Bad bearing conditions including lack of lubrication, rough sleeve bearings, out-of-round journals, scored balls or rollers in antifriction bearings, and oil whip. The first items create high frequency signals and the last item, caused by instability of the oil film at high speed or lightly loaded sleeve bearings creates signals below the rotational speed (1X RPM) frequency.
7. RECIPROCATING PARTS. Reciprocating parts including pistons, connecting rods, cross heads, geneva movements, escapements, etc. create vibrations at multiples of the running speed with mechanical rotational phase-time relationships.
8. IMPACTS. The metal to metal contact of valves seating, cams hitting pushrods, punch presses, even footsteps create a high frequency, sharply rising, slowly damped characteristic vibration signal with definite time relations.
9. RUBBING. The contact friction-excited vibrations of rubbing parts such as clutches, electrical brushes, etc. or friction hysteresis effects such a stick slip on machine tool slides which create a chatter effect.
10. MECHANICAL WEAR OR DESIGN. Worn gears, the wrong tooth profile, or unplanned resonances contribute a range of unplanned vibrations and problems. Adjacent machine interaction crosstalk and beat frequency effects cause some unusual low frequency signals. Operation of adjacent engines such as aircraft engines, at slightly different frequencies, will create strong very low frequency interactions in all types of machines.
11. HYDRAULIC AND AERODYNAMIC. The effects of nonlaminar flow, turbulence, cavitation, standing waves, flutter, surface waves, water hammer, uneven blade loading on pumps, fans or propellers and tunnel structural members or pipes create low to 1X RPM frequency effects.
12. ELECTROMAGNETIC. The induced magnetic fields in magnetic materials (iron, steel, nickel alloys, etc.) in addition to transformer or motor cores cause twice line frequency vibrations (120 Hz) to flow in all adjacent structural parts. Dynamic interaction of this frequency with slip speed times the number of poles in an electric motor will create a beat effect at low frequencies.

These are the most common causes of the machine-associated vibrations that warrant measurement.

3-9. Vibration Measurement Systems

The primary reason for making vibration measurements is to obtain data upon which decisions can be made. Vibration readings alone are of no value—they need to be combined with other information in order to have a firm basis for decisions. Accordingly, basic information about the machine being measured is required. All operating conditions should be noted, and the particular measurement method and equipment should be selected for specific machine properties evaluations. As the variety of installed machinery is almost beyond imagination, so are the possible tests. The following examples are selected from the most productive, the simpler, and those which require a minimum of equipment and special training. The previous list of 12 items represent the most common causes. Example 1 shown below will detect rubbing (9) and marginally (1), (2), (4), and (12). Example 2 shown below will detect bad bearings (6) and marginally (1), (2), (4), and (12). In Section 3-10 the examples shown will detect imbalance (1), resonance (4), bad bearings (6), impacts (8), hydraulic and aerodynamic (11), and electromatic (12). Misalignment (2) is best measured by the technique described in Section 3-11.

If your specific need is not shown, you may make up a TM 500 system from the individual modules and tailor it directly to your needs. Details on the electronic modules are given in the rear of this book and in the TM 500 Modular Test and Measurement Instruments catalog. Details on the transducers are given in Section 2 of this book.

Example 1. Machinery Journal Vibration Measurement
Many rolling mills, raw materials processors, or even office copy machines have drive shafts of various forms supported by journals. As shown in Figure 3-6, five different measurements may be made with four transducers connected to four different signal conditioning modules mounted in a TM 504 Mainframe. Progressing from left to right in the photo, the AM 502 Differential Amplifier is connected to an accelerometer to measure the bearing noise level. The AF 501 Operational Amplifier (bandpass filter) is connected to a horizontal vibration transducer mounted in two different positions to obtain two different vibration signals. The DC 504 Counter/Timer is connected to the reference mark pickup to measure the RPM or rotational period of the shaft. The PS 501-1 Mod 730F Rotary Transducer Supply is connected to the rotary function generator to supply a rotationally controlled sawtooth sweep signal for the oscilloscope displaying the vibration data. This is applicable where there are rotational angle related loads.

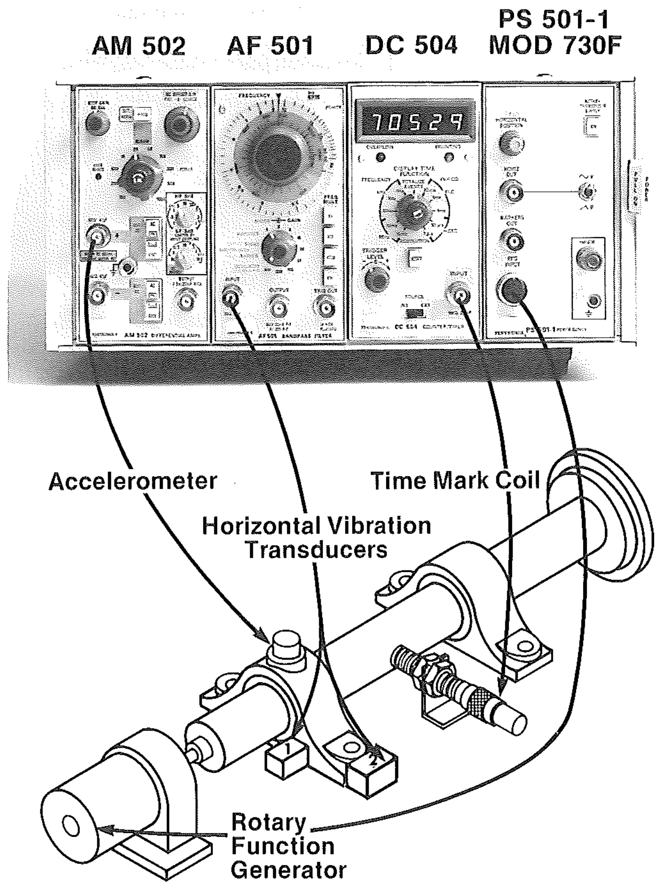


Figure 3-6. Typical System to Make Journal Vibration Measurements

Journal vibration signal analysis is somewhat more of an art than a science, but several basics have emerged. Sleeve bearings produce only a small amount of high frequencies in normal operation because the shaft rides on a lubricant film. The large signals that are generated by galling are coincident with or occur after the failure and provide very little warning in advance of catastrophic failure. But these signals are sharp and strong indicators of dangerous failures. Ball or roller antifriction bearings normally produce a very small amount of high frequency vibration signals. There is both a linear and a nonlinear theory of bearing vibration frequencies. Several common elements in each theory point out that there are signals related to the size of the inner race, the outer race, and the ball. The predominant signals are not synchronous with the driving shaft rotational speed. Experience has shown that bearing conditions can be evaluated by looking in certain characteristic regions with an accelerometer, a filter, and an oscilloscope.

Early tests established that a "good" signal was broadband, noiselike with an amplitude of less than 1/2 g, or 5 mV p-p (this was done with a 10 mV/g accelerometer and an oscilloscope display). If this level went above 5 mV, but was still less than 10 mV, the bearing was spray cleaned and relubricated. If the noise level went down, all was considered to be in good order. If the noise level did not reduce to below 5 mV, the bearing was marked for further investigation. This investigation included checking for load changes, balance, installation conditions of the bearing, and any possible external factor that could have caused the signal increase. If no cause was found and cleared, the bearing was tagged for replacement or continuous monitoring for either vibration or temperature. A plot of the signal level versus time often predicts the impending bearing failure.

Newer techniques bring more equipment to bear on the nature of the frequency components of the signal and its shift with time. One method uses the average amplitude of the ultrasonic components of the signal while suppressing the lower frequencies. This technique can be implemented using the 7L5 Spectrum Analyzer. A reference typical good bearing signal is stored in register "A" and used as a comparison standard for all subsequent units. This method, like the oscilloscope "grass" method, is somewhat subjective and it is difficult to establish mathematical correlation for the displays. But, it has been very successful in the industrial environment.

Another new technique establishes the frequency and amplitude level for the 5 to 7 principal frequency components of the "grass" signal at some standard condition. This is achieved either with a spectrum analyzer or a simple filter such as the AF 501 Bandpass Filter. One of these frequency components will be at the rotational speed of the machine and indicates the level of imbalance of the machine. Most factors that cause bearing failures have been proven to either cause a shift in the frequency-amplitude ratios of these principal frequency components, or to introduce new components. This higher level of information allows a more precise prediction of the bearing conditions and causes of impending failures and accounts for the sudden rash of FFT (Fast Fourier Transforms) machinery analyzers.

Example 2. Bearing Vibration Demonstration System
Basic instruction in bearing noise signatures and analysis is expedited by the use of a simple demonstration system such as shown in Figure 3-7. Two bearings are mounted in support posts A and B of the fixture and driven by a shaft connected to a sewing machine motor. The sewing machine motor noises are isolated by soft shaft couplings and vibration isolation mountings. The bad bearing is mounted in post A and the good bearing is mounted in post B. A 10-32 threaded stud is placed on each post to connect the PN 015-0165-00 Accelerometers. A small length of magnetic material is taped to the shaft between the motor and post B. This magnet creates a strong signal in the PN 015-0119-00 Reference Mark Transducer which synchronizes the SC 502 Oscilloscope sweep with the rotational speed of the shaft. The weight of this magnet also creates a X1 (times 1) RPM imbalance signal that is detected by the transducer when it is located at post B.

Several forms of measurements can be made with the modules shown. The cable connections shown are just one of many possible combinations. The DC 504 Counter may be internally switched to the RPM mode (÷6) and used to measure the shaft speed from the reference mark transducer. The connections shown use the DC 504 Counter in normal mode to measure the predominant frequencies passing through the AF 501 Bandpass Filter. The accelerometer signal is applied to channel 2 of the SC 502 Oscilloscope and to the input of the AF 501. The output signal from the AF 501 is connected to channel 1 of the SC 502 and to the input of the DM 502 Digital Multimeter operating in the AC VOLTS DB mode. The AF 501 operates in three different modes during the bearing noise demonstration tests. The first mode is the AMPLIFIER mode during which the gain and reference dB levels are established. With an accelerometer sensitivity of 10 mV/g and an SC 502 channel 2 sensitivity of 10 mV/div. the display scale factor is 1 g/div. This

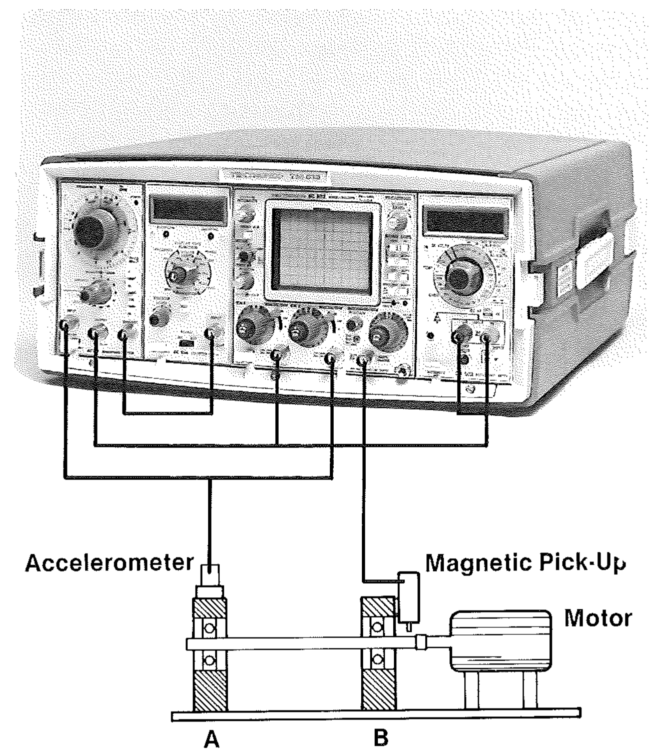
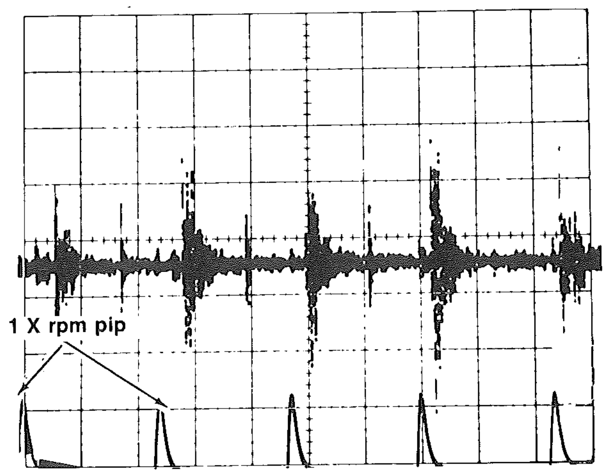


Figure 3-7. Bearing Vibration Demonstration System

level is far too low to obtain a useful reading from the DM 502. But, if the gain of the AF 501 is set at 100, the resultant 1 V/g, a typical reading of −30 dB or below for a good bearing. If this reading were above an established criterion (e.g., −26 dB), the next test phase is used.

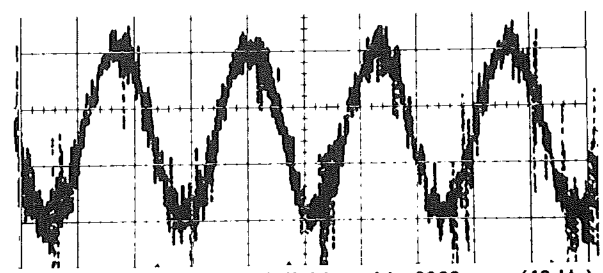
A form of qualitative analysis can be performed by following the methods outlined. The AF 501 dial is set to the RPM obtained from the DC 504, connected to the reference mark transducer. Then the AF 501 is switched to the BROAD filter mode. If the DM 502 reading drops sharply, the total signal contains significant signals other than the X1 imbalance signal. A sharper decrease should also be observed in the NARROW filter mode. Set the AF 501 gain at 100 to 500, the filter to NARROW, and the DM 502 on AC VOLTS-DB. Now tune the AF 501 through the frequency range above the rotational speed to locate and measure the principal noise frequencies.

A second method of antifriction bearing noise analysis uses the AF 501 and SC 502 to obtain oscilloscope displays that are interpreted by the operator. Figure 3-8 shows these displays as obtained from the bearing vibration demonstration system. The reference magnetic pickup is connected to channel 2 of the SC 502 instead of the accelerometer signal, to give a visual reference. Figure 3-8 (a) shows the unfiltered vibration pattern on the top trace and the timing mark on the bottom trace. The picture shows a series of noise bursts that are stable and phase locked to the rotational speed. The first phase of the test isolated the X1 RPM component of about 0.16 g at 48 Hz. This was achieved by a setting of 5 mV per div with a gain of 10. A check of the g and frequency values on the chart of Figure 3-5 indicates a good balance (0.15 ips) of 1 mil displacement. The vibration severity is almost in the rough zone of Figure 3-3. Further exploration with the AF 501 found a sharp signal at 3.35 kHz and at 24 kHz. An educated guess chose the lower frequency to be related to the inner race, in part, because it seemed to stay stable with rotational position. A second guess chose the higher frequency to be related to one or more balls of the bearing, again in part because the signals did not hold stable in timing and were not exactly repetitive. A far larger number of known samples are required before any hard and fast rules can be made. Optical examination of this bearing did find marks that could have caused these noises. However, caution is necessary in optical examination, because marks can be made in the disassembly process. Most bearing manufacturers have a good optical evaluation service that can supply the correlation data on bad bearings.

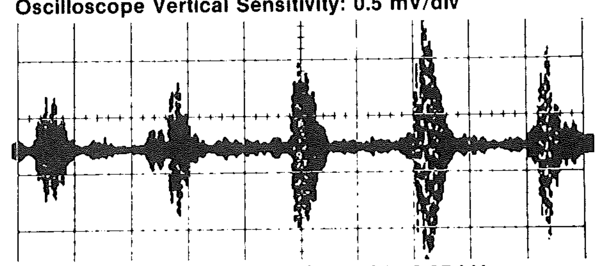


Unfiltered Vibration Pattern

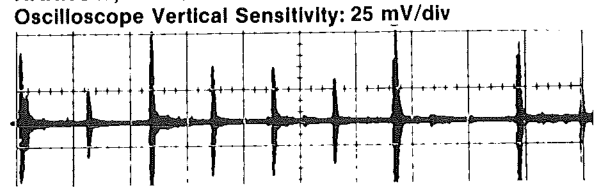
Oscilloscope Sweep Rate: ≈10 ms/div
Vertical Sensitivity: 100 mV/div



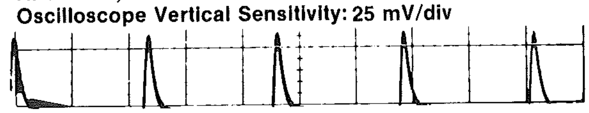
NARROW; FREQUENCY dial tuned to 2900 cpm (48 Hz)
Oscilloscope Vertical Sensitivity: 0.5 mV/div



NARROW; FREQUENCY dial tuned to 3.35 kHz
Oscilloscope Vertical Sensitivity: 25 mV/div



NARROW; FREQUENCY dial tuned to 24 kHz
Oscilloscope Vertical Sensitivity: 25 mV/div



Filtered Vibration Pattern

AF 501 MODE switch set to BANDPASS FILTER narrow
Oscilloscope Sweep Rate: ≈10 ms/div

Figure 3-8. Bearing Signature Waveforms

3-10. Dynamic Balancing

Almost all rotating machinery is balanced by either static or dynamic methods during production. Relatively slow operating machinery is often only statically balanced by using the forces of gravity to slowly rotate the part on knife edges, single point suspensions, or pendulous suspensions. Often simple air bubble level gauges are used as indicators.

Dynamic balancing is achieved by spinning the part, detecting the imbalance and applying the required corrections. Most methods use some form of indicating system to show relative magnitude and location in the form of rotational angle or phase. Dynamic balancing is usually performed in two or more planes over the significant parts of the operating speed range. The equipment used is usually in one of two classes: (a) stationary or (b) portable.

In the case of the stationary balancer rotary parts are taken from the installed machinery, placed in the balancer and run from below the first resonance or critical above this first resonance. The imbalance magnitude measurement transducers used in the past cover a wide range of electromechanical, optical, dial indicator gauges, force transducers and vibration transducers. The phase or angle measurement devices are stobe lights, pencils, blinking lights, mechanical contacts, resolvers, synchros, wattmeters, shaft encoders and magnetic position pick-ups. Balance weights or removal of material have been used in a trial and error approach. In the case of automotive engine crankshafts, extra iron tabs are "cast on" and ground off during balance.

A demonstration unit for rotary equipment balancing is shown in Figure 3-9. This is an instructional unit that allows the demonstration of both static and dynamic imbalance conditions. The slender shaft, with two inertial wheels, allow simulation of both single-plane and two-plane balancing problems. The bearing support structures are semi-rigid, which allows structural sensitivity to imbalance and easy measurement of the effects of interaction of the two planes. Both vertical and horizontal vibration transducers (PN's 015-0166-00 and 015-0167-00) may be mounted, though the horizontal units will yield the largest signal. The timing reference is obtained by the use of an electromagnetic pickup (PN 015-0119-00). Details of this unit and its operation are given in the application notes on balancing, listed at the end of this section.

The Model 5111 Storage Oscilloscope is used to simultaneously display three signals: (1) the left bearing vibration, (2) the right bearing vibration, and (3) the timing reference signal. When the oscilloscope trace is triggered by the magnetic pickup signal, and the second occurrence of this signal is aligned with the ninth horizontal division, the horizontal scale factor is 40° per division. If it is aligned with the eighth division, the scale factor is 45° per div. Three very simple plug-in units are used with this oscilloscope to give the signal sensitivity required. This is typical of the equipment added to in-place balancing fixtures to increase versatility and accuracy.

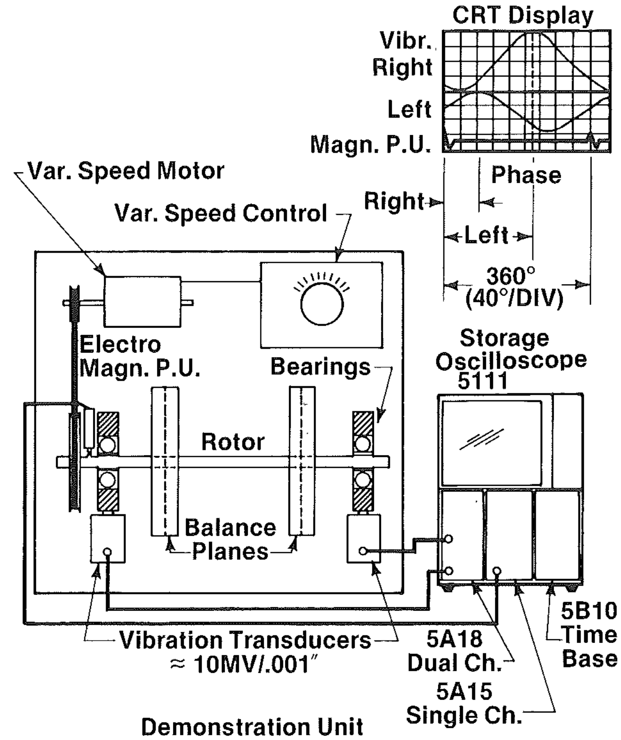


Figure 3-9. Rotary Equipment Balancing Demonstration Unit

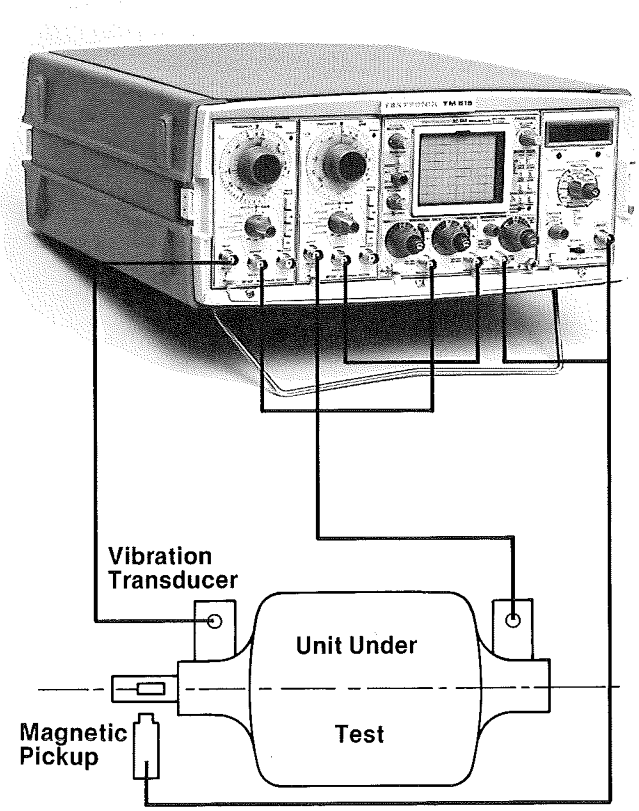


Figure 3-10. Portable In-Place Balance Test Set

In the case of the portable balancers, the equipment is taken to the machine to be balanced. This equipment usually consists of portable instruments, vibration transducers, and a reference mark pickup. The procedures used are somewhat more restrictive and formalized. In most cases, this procedure has three steps with measurements at each pair of support bearings. The first step is in the "as is" condition, the second is with weight added to one end, and the third is with weight added at the other end. Details of these methods using graphic techniques, hand calculations, calculators, or computers are given in the application notes listed at the end of this section. Figure 3-10 shows a typical portable balance test set used for in-place balancing. The transducer signals are routed through AF 501 Bandpass Filters to clean up the signal and remove the effects of other machinery in the area. The reference mark pickup senses a cotter key and is connected to both the DC 504 Counter/Timer and the EXT TRIG jack of the SC 503 Oscilloscope. When the first internal mode switch of the DC 504 is placed in the lower position, a divide-by-6 circuit is activated and the DC 504 display is in RPM. Initially the AF 501 Bandpass Filters are operated in the amplifier mode and their signals are routed to channels 1 and 2 of the SC 503 Oscilloscope. When the test RPM is reached, as indicated on the DC 504, the AF 501 FREQUENCY dial is turned to that speed and then switched to the BROAD BANDPASS FILTER mode. Most background and extraneous noise signals will be eliminated from the oscilloscope traces. In rare cases, it will be necessary to switch to the NARROW BANDPASS FILTER mode to remove the noise. If critical narrow band operation is required, the AF 501 dials can be very accurately set by switching to the OSCILLATOR mode, temporarily connecting the output to the counter. The oscillator frequency measured is the exact center of the bandpass of the narrow filter mode.

The following components make up a complete portable in-place balance test set as depicted in Figure 3-10.

ITEM	QUANTITY	TYPE	DESCRIPTION
1	1	TM 504	Mainframe
2	1	SC 503	Storage Oscilloscope
3	2	AF 501	Bandpass Filter
4	2	015-0167-00	Horizontal Vibration Transducer
5	1	015-0166-00	Vertical Vibration Transducer
6	1	015-0119-00	Magnetic Reference Transducer
7	3	012-0136-00	20-foot Coaxial Cable
8	3	012-0118-00	8-inch Coaxial Cable

Fasteners supplied by firms other than Tektronix will be required for mounting the transducer to your machine. Mounting details are given in the reference material at the end of this section.

3-11. Torsional Vibration Measurement

Torsional vibration is present in all rotating machinery. This type of vibration is difficult to detect directly. Torsional vibration is the periodic change in angular position, velocity, or acceleration of a mass. It may be specified in terms of frequency or in relationship to the rotational speed of the shaft.

Torsional vibration is usually defined in terms of the increasing and decreasing of the rotational velocity of a shaft in a cyclic manner. The crankshaft of a reciprocating engine is subject to torsional vibration caused by each compression stroke and each power stroke of the engine decelerating and accelerating the crankshaft. Almost all reciprocating engines or pumps are subject to torsional vibration. Sometimes this torsional vibration is equated with the smoothness of operation of a rotating system. Most ac electric motors give off a stepping pulse torque that is related to the slip of the motor from synchronous speed (i.e., 1800 RPM). The individual interactions of the stationary and rotary blades in a steam or gas turbine create torsional torque pulses that can cause substantial stresses in the drive shaft and couplings when the turbine is used as a prime mover for a large inertial mass such as an alternator rotor. Excessive torsional vibration causes material fatigue failures, fractured shafts, worn couplings, excessive wear on gears, short life for bearings, and excitation of other system mechanical (and structural) resonances.

There are various ingenuous ways to measure torsional vibration. Most mechanical and electrical torsional vibration transducers use a spring-mass system, with a very low torsional resonance frequency. The spring is a flexible torsion bar, a helix spring, or sometimes the attraction force of a permanent magnet. A typical system is shown in Figure 3-12.

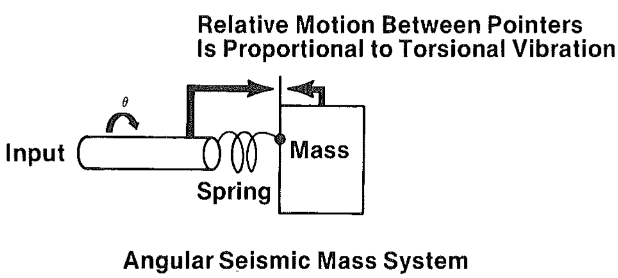


Figure 3-12. Angular Seismic Mass System

When the torsional vibration frequency of the input shaft is higher than the resonant frequency of the transducer spring-mass system, the mass is isolated from the torsional vibration. The mass stands still and becomes the reference point for measuring the amplitude of the torsional vibration. Some of the spring-mass type of transducers use sliprings to transfer the electrical signal from the rotating tranducer; others have a stationary sensing circuit.

For measuring the relative motion between the input shaft and the mass, the same basic principles as commonly used for linear displacement transducers are employed. Typical transduction methods used are: self-generating inductive, linear variable differential transformers (LVDT), and strain gage on beam. There are also some transducers using neither springmasses nor sliprings.

A standard machine tool rotary shaft encoder of the photoelectric type can be used to sense shaft position, shaft speed, and torsional vibration, without adding any springs, seismic masses, or sliprings. Figure 3-13 shows the encoder hooked up to a U-joint vibration calibrator. The pulses from the encoder trigger a pulse generator to produce pulses with constant time duration. The following low pass filter and integrator circuits convert the pulses to an average voltage that is proportional to the speed of the shaft (the ac component) and the torsional vibration angle (the ac component). The shaft speed or vibration is measured by switching the oscilloscope input to either the dc or ac position.

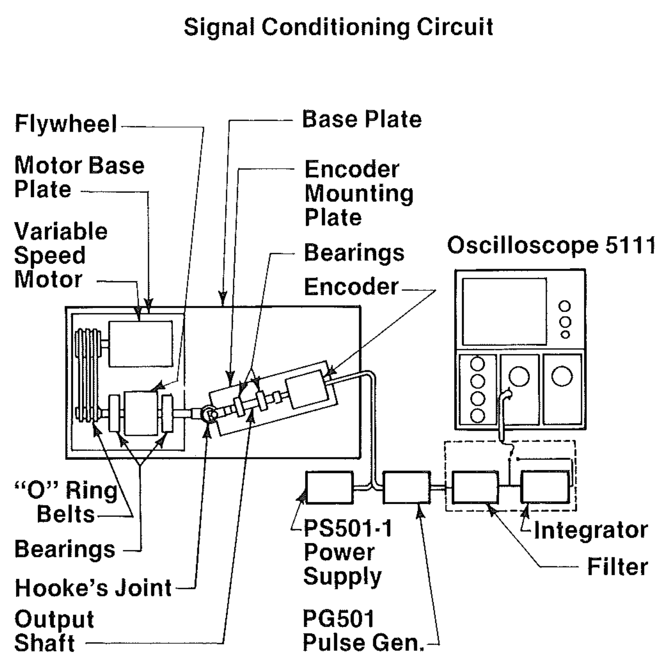


Figure 3-13. Photoelectric Shaft Encoder Used as a Torsional Vibration Transducer

Using the circuit shown in Figure 3-14, an encoder with 500 pulses/rev and 5V, 20μs pulses from the pulse generator produced a sensitivity of 1 mV/deg of torsional vibration, and a 0.8 mV/RPM dc signal for shaft-speed measurement. Filter characteristics determine the frequency limits of this system. With the filter shown, the output is proportional to angular vibration between 3 and 100 Hz. Replacing the 7.5 kΩ resistors with 1 kΩ resistors brings the maximum frequency up to 750 Hz, but also increases the noise-to-signal ratio. Figure 3-15 shows a Bode plot of the circuit.

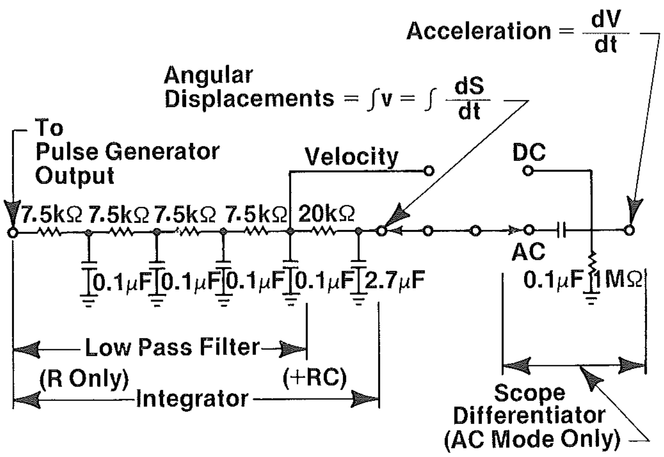


Figure 3-14. Filter-Integration Circuit

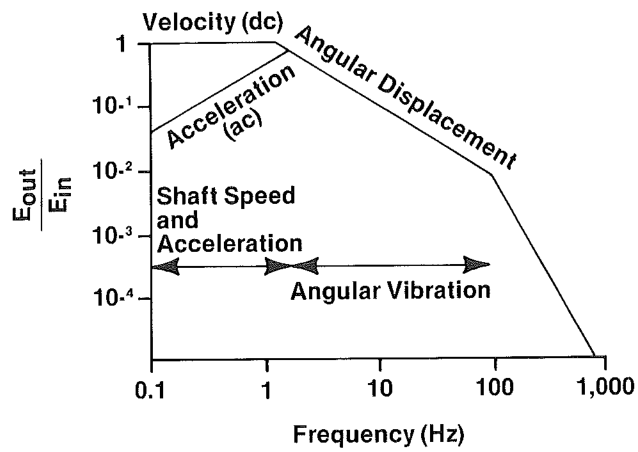


Figure 3-15. Bode Plot of Filter-Integration Circuit

Figure 3-16 shows an oscilloscope display of the speed and angular acceleration of an electric motor-flywheel system when turned on and off using the same encoder as a sensor. The oscilloscope displays speed when dc coupled, and low frequency angular acceleration (less than 3 Hz) when ac coupled.

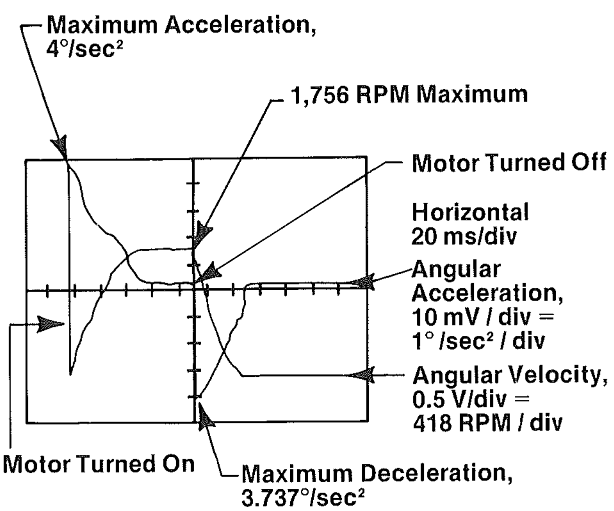


Figure 3-16. Torsional Vibration Transducer Systems Response

The maximum amplitude is limited only by the acceleration capabilities of the encoder. The pulse frequency capability of the encoder determines the maximum RPM and the resolution. With 500 pulses/rev, the maximum was about 10,000 RPM for the encoder used. Calculated sensitivities were verified with a U-joint used as a torsional vibrator. This is shown in Figure 3-17.

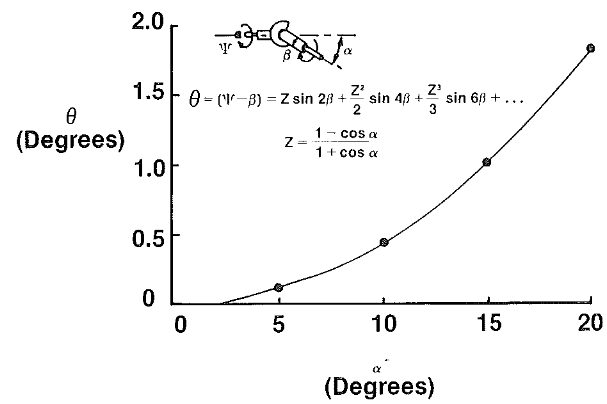


Figure 3-17. Angular Vibration of U-Joint

A complete portable torsional vibration test set is shown in Figure 3-18. The standard PS 501-1 Power Supply is covered by the filter-integrator circuit constructed on a front-panel circuit board adapter kit (PN 013-0152-00). The encoder power (+5 V) is obtained from the PS 501-1. The N-pulse output lead of the encoder is corrected to the TRIG IN jack of the PG 501. The TRIG OUT jack of the PG 501 is connected to the filter-integrator. The once a revolution output lead is connected to the DC 504 Counter/Timer (internally switched to the RPM mode) for speed indication. When the SC 502 Oscilloscope is used, the velocity signal from the filter may be connected to channel 1 and the angular displacement signal from the integrator may be connected to channel 2. Channel 1 is normally switched to the dc input condition for the velocity signal and to the ac input condition for the acceleration. The acceleration is derived by using the input circuit of the oscilloscope as a differentiator. Additional data are available from the technical papers and application notes on torsional vibration listed in the reference section.

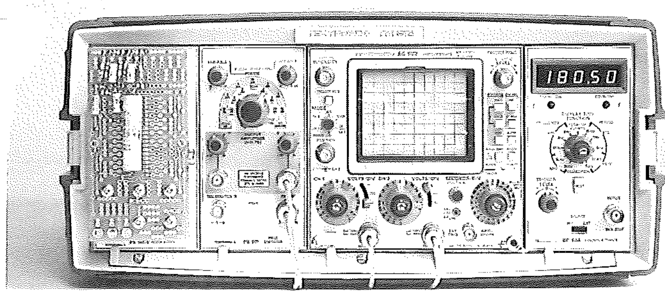


Figure 3-18. Portable Torsional Vibration Test Set

ITEM	QUANTITY	TYPE	DESCRIPTION
1	1	TM 515	Mainframe
2	1	SC 503	Storage Oscillo-scope
3	1	PS 501-1	Power Supply
4	1	PG 501	Pulse Generator
5	1	DC 504	Digital Counter
6	1	013-0152-00	Adapter kit

3-12. Shock, Impulse, and Transient Testing

Shock, impulse, and transient testing of the mechanical characteristics of devices is important in establishing the expected performance of products. Shock is usually defined as a sudden acceleration of a system by the application of a transient force of relatively short duration. No steady state or periodic component is present in the transient signal, which distinguishes it from vibration. The very short time duration of the shock pulse distinguishes it from random vibration, which is aperiodic.

A variety of different signal waveforms is used to create the shock pulse. The more common pulses are listed and discussed below.

SQUARE WAVE—A square wave excitation pulse, that has a risetime of 2 to 5% of its width, is often specified for extreme shock testing. The sharper the leading and trailing edges, the higher the frequency content of the resultant shock. Very high energy requirements are also imposed by very square pulses.

TRAPEZOID—To reduce the excitation power requirements and to limit the frequency bandwidth characteristics of the shock, a trapezoidal waveform with controlled rise and fall times is sometimes used.

TRIANGULAR—The limit case of the trapezoidal waveform is the triangular waveform. This is seldom used as more than a starting point for the trapezoidal waveform because of the very light shock effects.

NOTE: Each of these three pulses has characteristics that can create nulls in the shock spectrum. This property could hide a damaging resonance and, for this reason, these pulses are being used less in specifications than heretofore.

SAWTOOTH—Both the ramp up and ramp down sawtooth pulses have no holes in the response spectrum. The ramp up signal, with a fall time of 25% or less of its rise time, yields the best possibility for a consistent response spectrum, according to some shock and vibration experts.

NOTE: All of the above waveforms are generated by the PG 505 Pulse Generator. The leading edge slope and the falling edge slope of the output are variable from less than 1 μs to greater than 20 ms. The pulse width is variable from less than 5 μs to greater than 0.5 s. The pulse interval is variable from 10 μs to greater than 1 s and may be externally or manually triggered for one-shot operations. This combination of controls allows the generation of square, trapezoidal, triangular, and sawtooth waveforms of any desired characteristics. The PG 505 also has an external control or output delayed mode, which allows "one-shot" operation or synchronized multi-axis shock excitation.

HALF SINE PULSE–This is one half of a sinewave signal, which mathematically might be better stated as a cosine pulse. This is often chosen for mathematical analysis reasons or for its constant initial velocity characteristics.

VERSED SINE PULSE—This is a combination of a positive pedestal and a complete cosine wave, the period of which is from −180 degrees to +180 degrees and exactly coincides with the pedestal width. The peak amplitude is twice the pedestal amplitude. This combination creates a smooth single pulse similar to the cosine-squared pulse, which starts at zero with an increasing slope to a pulsed half sinewave and then flares out for a low velocity, with no overshoot, at zero.

SINE PULSE TRAIN—This is a series of sinewaves that are gated on for a specified period. The purpose of this multiple wave excitation is to impart a large amount of energy of a specified frequency, to simulate the effects of specific external excitations.

NOTE: These three waveforms may be obtained from a combination of the PG 505 Pulse Generator and the FG 501 or by use of the FG 504 Function Generators alone. The PG 505 TRIG OUT signal is applied to the connector of the FG 501 to control the on time of the function generator sinewave oscillator signal. The pedestal effect is obtained by use of the PHASE control, which sets the starting point of the sinewave output. The PULSE DURATION controls of the PG 505 determine the sinewave on time. It can be any interval from one half sinewave to multiple sinewaves. When the start signal for the sinewave is at −90 degrees, and the duration is equal to one cycle, a cosine pulse is achieved.

Some shock spectrum holes can also result from these waveforms. This can be avoided by using a very narrow-type pulse signal, the spectral characteristics of which are very much higher than any of interest in the test subject. An alternate method is to use the swept sinewave measurement technique and thereby excite all possible resonance frequencies. The RG 501 Ramp Generator can be connected to the VCF IN connector of the FG 501, thereby generating a continuous sweep of frequencies over a range of up to 3 decades, at any desired rate.

3-12.1. Signal Sources

A number of basic signal sources are available to supply the excitation for external power amplifiers and shake tables. Figure 3-19 shows the range of common signal generators. The SG 502 Oscillator supplies very pure sinewaves over a range of amplitudes. This type signal is used to verify the exact frequency of a resonance or the effect of a specific single frequency. It has a 5 V squarewave output signal to drive a digital counter. The second type signal source is represented by the RG 501 Ramp Generator. This unit produces very linear increasing amplitude signals with very short reset times. Standard units may be adjusted from 10 μs to 10 s duration and, with modification, to over 100 s. These units are usually used to supply a sweep control voltage to frequency sources or displays. The third signal source is the function generator. These come in all levels of complexity and usually can generate sine, triangular, square, and sawtooths of both ramp up and ramp down. Some units like the FG 501 Function Generator also may be gated, synchronized, phase shifted, or frequency swept. The fourth signal generator type is illustrated by the PG 505 Pulse Generator. Pulse generators usually supply a train of pulses of controlled period, rate and amplitude. The PG 505 adds the features of external delay ramp control and adjustable rise and fall times. These adjustable times allow generation of square, trapezoid, triangular, and controlled-slope sawtooth waveforms. The separate adjustment of the rise time and fall time of the pulses allows a tailoring of the pulses or sawtooth waveform to fit the application.

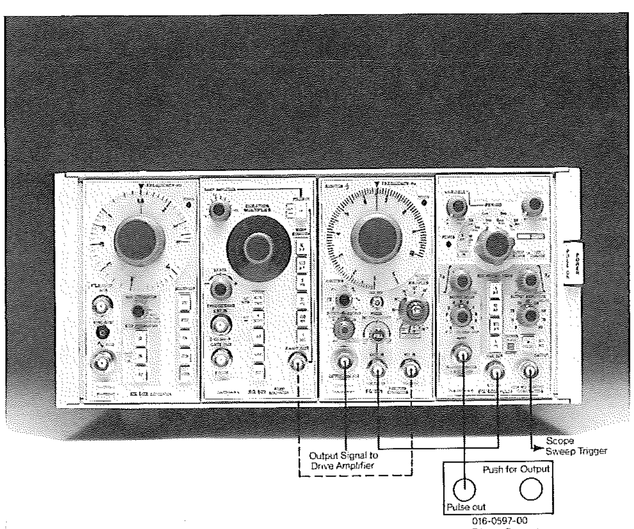


Figure 3-19. Basic Signal Sources

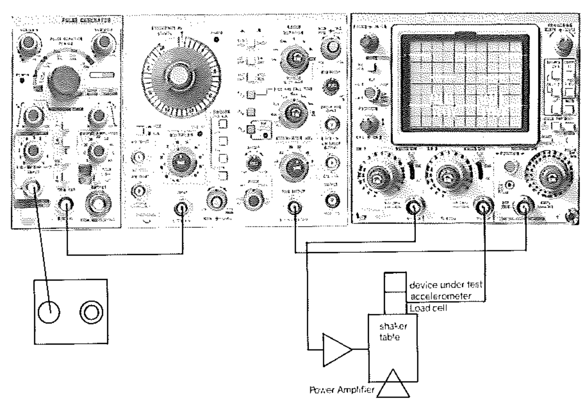
ITEM	QUANTITY	TYPE	DESCRIPTION
1	1	TM 504	Mainframe
2	1	SG 502	Oscillator
3	1	RG 501	Ramp Generator
4	1	FG 501	Function Generator
*5	1	PG 505	Pulse Generator
6	1	016-0597-00	Trigger Generator, manual

3-12.2. Power Amplifiers

Each mechanical drive mechanism or shake table imposes specific requirements for its power amplifier. In addition to the requirement to increase the power level of the signal, the power amplifier system must be impedance matched to the drive coil. This often takes the form of a complex impedance to minimize more than the effects of the coil; it can include the shake table magnetics, structure, and fixturing. In some units, internal feedback transducers are included to minimize extraneous (free) signals that appear in the shock signal to the device under test and destroy the accuracy and repeatability of the test data. A great deal of care must be used to ensure that the test fixtures and table only impart the desired impact to the test sample. The addition of a load cell in the mechanical loop is an excellent method of obtaining accurate impulses and usable data.

3-12.3. Signal Generating Systems

Figure 3-20 shows a complete waveform generating package that can be added to any conventional shake table drive system. The FG 504 combines and extends the features of the RG 501 and FG 501.



ITEM	QUANTITY	TYPE	DESCRIPTION
1	1	RTM 506	Mainframe
2	1	PG 505	Pulse Generator
3	1	FG 504	Function Generator
4	1	SC 503	Storage Oscilloscope
5	1	DC 503	Digital Counter
6	1	016-0597-00	Trigger Generator, Manual

3-13 Reference Material

3-13.1 Textbooks

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Spartan, 1972.

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Mechanics of Vibrations.
Wiley, 1952.

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Applied Mechanics Dynamics.
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Mechanical Engineers Handbook.

Thompson, W. T.
Mechanical Vibrations.
Prentice-Hall.

Timoshiuko, S.
Vibration Problems in Engineering.
Van Nostrand, 1955.

3-13.2 ISA Standards

S2. 11-1969
Shock and Vibration Transducer Calibration Tests.

S2.2-1959
Shock and Vibration Transducer Calibration Methods.

3 International Standards

IEC 68-2-6 (1970)
Vibration Testing (sinusoidal).

IEC 68-2-27 (1972)
Shock Testing.

ISO R.495
Test Codes for Machine Noise.

ISO R.532
Loudness Level Calculation.

ISO R1680
Rotating Machine Airborne Noise.

ISO D1940
Balance Quality of Rotating Rigid Bodies.

ISO D2041
Vibration and Shock Terminology.

ISO D2372
Mechanical Vibration 10-200 RPS (1972).

ISO D2373
Mechanical Vibration Shaft 80 to 400 mm High.

ISO IS3945
Mechanical Vibration Large Machines 10-200 RPS (1975).

ISO IS2954
Instruments, Vibration Rotating or Reciprocating Machines (1973).

3-13.4 National Electrical Manufacturers Association Standards

MG1-12.05
Dynamic Balance of Motor 1971.

MG1-12.06
Method of Measuring Motor Vibrations (1971).

MG1-20.52
Balance of Machines 1969

MG1-20.53
Methods of Measurement 1969.

3-13.5 Military Standards

MIL-STD-167-I (ships)
Mechanical Vibrations of Shipboard Equipment.

MIL-STD-810-D
Environmental Test Methods.

3-13.6 Torsional Vibration

Chapter 38 of Harris and Crede, op cit.

Machine Design Magazine, page 142,
April 18, 1975 issue.

Verhoef, W.
Torsional Vibration Measurement Techniques.
Proceedings of the 23rd International Instrumentation Symposium ISA (code A36), Pittsburgh, Pennsylvania.

3-13.7 Machine Balancing

Application Note 75A1.0
Balancing Rotating Machinery.

McDuff, J. N.
A Procedure for Field Balancing Rotating Machinery.
Sound and Vibration, July, 1967

Chapter 39, Harris and Crede, op cit.

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A Quick Balancing Method for Rotating Machinery.
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Maxwell and Sanderson.
Site Balancing of a Large Flexible Rotor, etc.
Proceedings of 5th Turbomachinery Symposium, 1976 Texas A&M

Gunter, Barrett, and Allaire.
Balancing of Multi-mass Motors.
Proceedings of 5th Turbomachinery Symposium, 1976 Texas A&M

3-13.8 Papers on Vibration Problem Analysis from the Proceedings of the Texas A&M Turbomachinery Symposium. Editor, Dr. Meherwan P. Boyce.

1st-1972
Sohare, John S.
Turbomachinery Analysis and Protection

Genter, Edgar J.
Rotor-Bearing Stability.

Borhaug and Mitchel.
Application of Spectrum Analysis to Machinery.

2nd-1973
Wachel, Von Nimitz and Szenasi.
Case Histories of Specialized Turbomachinery.

3rd-1974
Schauzenbach, George P.
The Installation and Application of Sensors for Turbomachinery Monitoring.

4th-1975
Mitchell, John S.
Examination of Machinery by External Vibrations.

Von Nimitz, Walter W.
Low Frequency Vibration of Centrifugal Plants.

Bently, D. E.
Forward Subrotative Speed Resonance Action of Rotating Machinery.

5th-1976
Sparks and Wachel.
Pulsation in Liquid Pumps and Piping Systems.

Landou and Counter.
Axial Vibration Characteristics of Metal-Flexing Couplings.

Section 4.

Section 4. Machinery Analysis Systems

4-1. Introduction

This section describes test sets configured for machinery maintenance and performance analysis. The primary emphasis here is on the hardware, its use and its interactions. Operating procedures for the equipment are covered in the manuals supplied with the equipment. The details of specific applications will be covered in application notes where appropriate, and the measurement theory has been previously covered or is in the reference literature.

4-2. Analysis Systems

The prime mover, power source, or simply the engine driving any system requires careful and systematic maintenance. The basic ingredients of this preventive maintenance are much the same for piston engines, gas turbines, steam turbines, and for the associated auxiliary equipment. A number of papers with useful techniques and data are listed at the back of this section. The ramification of certain items of hard-won knowledge should be understood by anyone planning a diagnostic and instrumentation system. Some of these are:

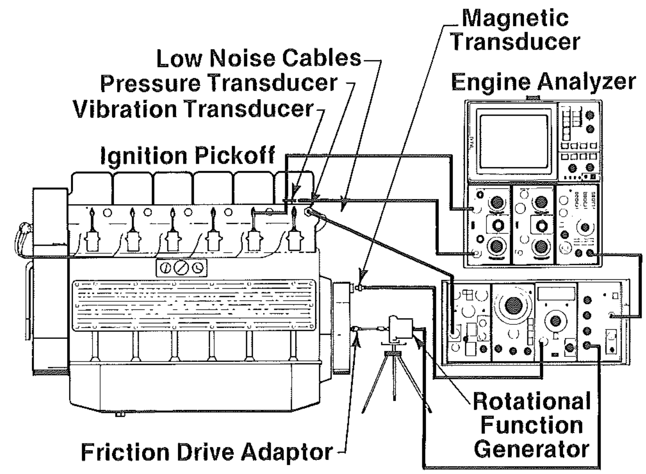
1. The costs for systems may vary over wide ranges of several orders of magnitude (i.e., $200 to $2,000,000 each).
2. Costs, in general, are inversely proportional to the degree of participation of the diagnostic system operator in the data acquisition and reduction.
3. In manual systems, the transducer acquisition and calibration usually represent the highest ongoing cost to ensure reliable information.
4. In automatic systems, the data reduction elements represent the highest acquisition and maintenance cost.
5. Maintenance systems data are meaningful and useful only if there is a predesignated procedure to act on the information derived.
6. The accuracy of diagnostic data is a direct function of the equipment maintenance action feedback frequency and accuracy.
7. The cause of most failures can be traced to improper maintenance, installation or operation.
8. Most failures occur shortly after changes in operating conditions; i.e., load.
9. The highest yield of useful data is from just a few well-placed sensors.
10. The information that is most needed during the analysis of an equipment failure is the data you did not take, those readings you did not record, or the quantities you did not plot in a meaningful form.

After these words of discouragement, I would be remiss if I did not quote the very large economic benefits that are received from nearly every preventive maintenance program. Many natural gas pipelines receive returns on investments in preventive maintenance as high as $225 cost savings per dollar invested, in less than three years. In one case, the increased throughput and station efficiency yielded an additional $3,000,000 in billing, brought about by increased compressor efficiency. These results are obtainable with careful planning, well thought out procedures and minimal equipment outlays. Which specific single measurement is most meaningful is very much dependent upon the specific machine type, but high on all lists is vibration. More machine conditions are shown in this signal than any other. But, with all of those data goes the question as to which parts of the data are meaningful to a specific application. The answer to this is obtained by experience, manufacturers' data, and further interactive relationships of vibration levels and frequencies versus location, operating conditions, and timing of machine functions. Conservative designs on larger systems include some form of monitoring and alarm trip levels. Cautious operators will initially set these levels too low. Then, after several false alarms, they will usually move the trip level adjustments above the damage or danger level, negating the purpose of the monitor system. This has been experienced in vibration, temperature, flow, pressure and level monitoring systems. The best methods found to avoid this problem are through the use of periodic calibration and maintenance of the transducers by an instrumentation specialist, and through the immediate verification of any alarm by measurements with auxiliary test equipment. In most cases, the equipment previously described will fulfill this requirement very well but, in some cases, specialized application-oriented measurement systems are required. The Engine Analyzer System and the Portable Analyzer for Reciprocating Machinery described here are examples of these systems.

4-3. Engine Analyzer System

The piston engine analyzer system (EAS) described below was developed for the large (600 horsepower and greater), mixed fuel engines used in refineries and on natural gas pipelines. A necessary feature of the engines is the installation of Kiene cocks (type V10) or pressure relief ports using the truncated Whitworth thread to enable connection of the PN 015-0118-00 Cooling Adapter for the PN 015-0117-00 Piezoelectric Pressure Transducer. Without this feature, it is necessary to install special pressure taps on each cylinder. In sparkplug ignition engine applications, special sparkplug pressure taps and transducers are available directly from: (1) PCB Piezotronics in Buffalo, New York; (2) Sundstrand Data Control in Redmond, Washington; (3) Vibro-Meter in Torrance, California; (4) Metrix Instruments in Houston, Texas; or (5) Endevco in San Juan Capistrano, California. The use of the pressure transducer is explained in the earlier transducer section, and the complete system is described in Figure 4-1.

This basic engine analyzer system can be assembled in several ways. The portable system described later in this section, for use with reciprocating machinery, is one implementation. The following illustration and photo depict the 7000-Series Engine Analyzer System. This system is made up of the following components and is shown in Figure 4-2.



DISPLAY	APPLICATION
Pressure-Time P-T	*Observe many combustion cycles to measure variations in peak pressures, rate of pressure rise, and RPM.*
Pressure-Volume (Compressors, Pumps) P-V	*Evaluate performance of suction and discharge valves, compressor capacity, ring action, volumetric efficiency, and overall compressor, and pump operation.*
Pressure-Volume (Combustion Engines) P-V	*Evaluate engine performance, cause of horsepower variation, measurement of efficiency, compression ratio, capacity, power balancing, and horsepower.*
Pressure-Crankangle P-Θ	*Observe engine events (valve openings and closings, ignition or pre-ignition, etc.), against the crankangle at which they occur. Four-trace oscilloscope displays vibration, pressure, ignition, or any desired combination of curves required to evaluate compressor and engine performance.*
Vibration Analysis	*Detect, locate, and identify defective parts to uncover destructive detonation, improper valve function,s piston slap, improper function of compressor valves, worn valve cams, carbon buildup, blow-by, leaking valves, ring damage, blower bearings, engine cylinder run-in, and other malfunctions.*
Ignition Analysis	*Proper timing of engine, evaluation of breaker point gapping, point arcing, point bounce, low and high resistance in secondary circuits, spark plug condition, shorted primary, coil condition, etc.*

Figure 4-1. Engine Analysis System

Item	Quantity	Type	Description
1	1	7313	Bistable Storage Oscilloscope
2	2	7A18	Dual-channel Amplifier
3	1	7B53A (MOD FB)	Time Base unit with X-Y modification
4	1	TM 504	Mainframe
5	1	AM 502	Differential Amplifier
6	1	AF 501	Bandpass Filter
7	1	DC 504	Counter (RPM)
8	1	PS 501-1 MOD 730F	Rotary Transducer Power Supply
9	1	011-0081-00	Accessory housing
10	3	012-0076-00	18-inch coaxial cable
11	2	103-0030-00	BNC "T" adapters
12	1	015-0126-01	EAS transducer kit, including:
a	1	015-0108-01	Rotational function generator
b	1	015-0117-00	Pressure transducer, piezoelectric
c	1	015-0118-00	Cooling adapter
d	1	015-0116-00	Vibration transducer
e	1	015-0119-00	Reference mark transducer
f	1	012-0139-00	Ignition pickoff cable
g	1	012-0140-01	50-foot RFG cable
h	1	012-0076-00	18-inch coaxial cable
i	3	012-0137-00	50-foot coaxial cable

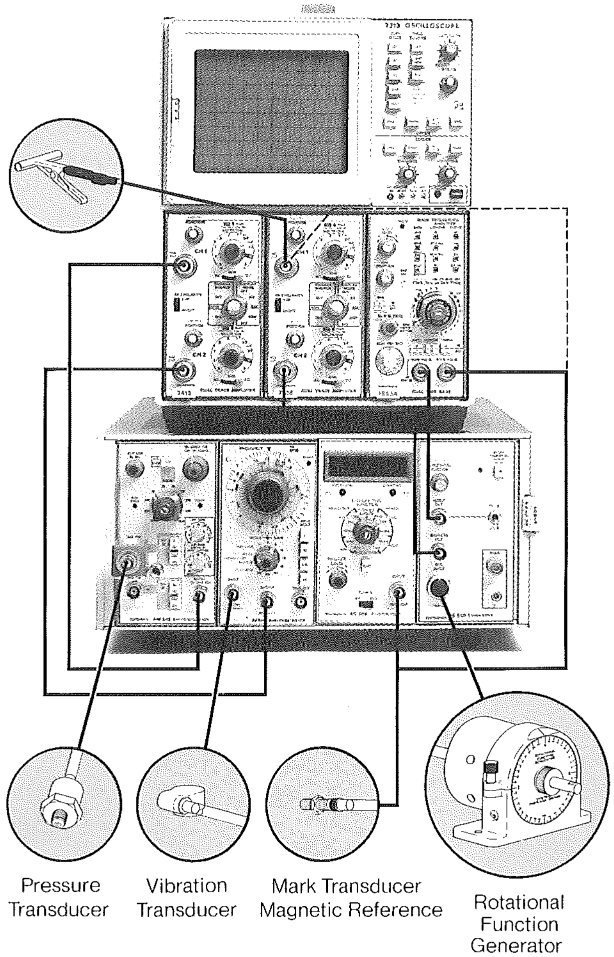


Figure 4-2. 7000-Series Engine Analyzer System

4-3.1. EAS Waveform Photography

This basic system configuration draws on the experience of the 560-Series Systems, which have been in regular use since 1968. The basic system was developed by a refinery customer for his operation and then tailored by some of his associates to meet the needs of the nearby connecting natural gas pipelines. The best source of information on measurement techniques and applications of this equipment is the engineering and field service departments of the machinery manufacturers who supplied the specific pieces of equipment that you must maintain.

Some of these machinery maintenance specialists have developed record keeping techniques using a C-12 P Oscilloscope Camera and special projected graticules. This projected graticule is a premade negative that is projected onto the oscilloscope screen and photographed with the incoming data to make up a complete scaled and labeled picture. Most engine manufacturers supply some form of valve timing diagram, such as shown in Figure 4-3. From this diagram, various types of timing diagrams can be made for the projected graticule. One type marks the zones for each valve operation. When this type is used, a vibration signature should be seen at each edge of the zone.

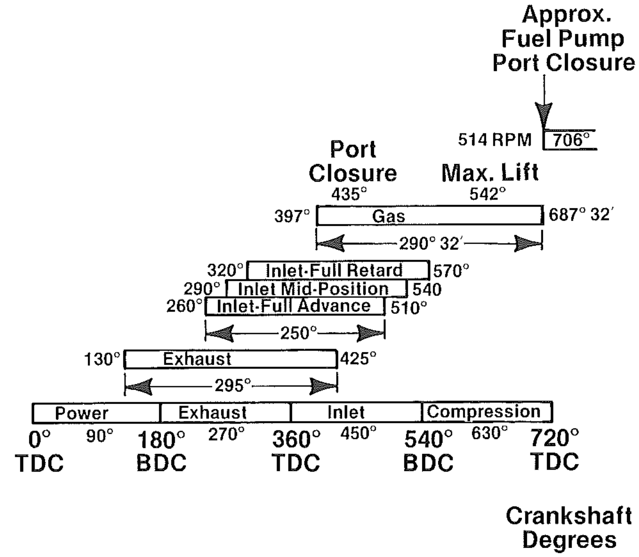


Figure 4-3. Typical Valve Timing Diagram

These are made by taking positive transparency Polaroid pictures of a drawing such as shown in Figure 4-4. This particular drawing is used with a variation of the EAS test setup where three vibration traces and one ignition trace are shown at one time. Figure 4-5 shows a picture of a 4x5 film negative type projected graticule mounted in its carrier frame. This carrier frame is inserted into a slot on the bottom of the C-12 camera and gives the picture shown in Figure 4-6 when combined with the four standard display traces of an EAS. The onscreen readout of amplifier switch positions may be suppressed at the operators' convenience.

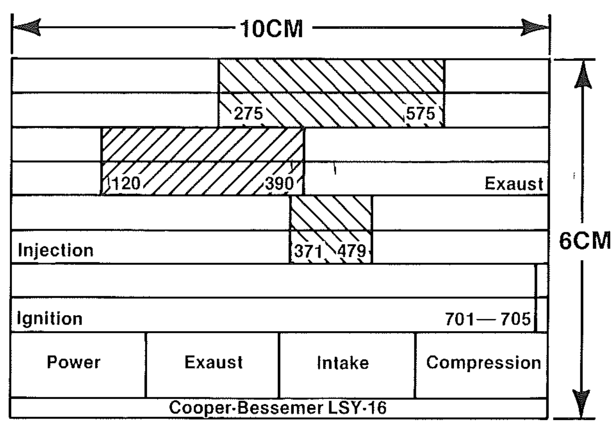


Figure 4-4. Typical Drawing for use as Graticule

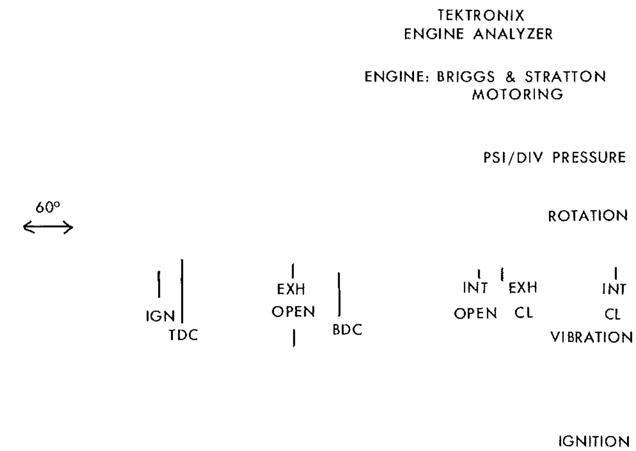


Figure 4-5. Film Negative Type Projected Graticule

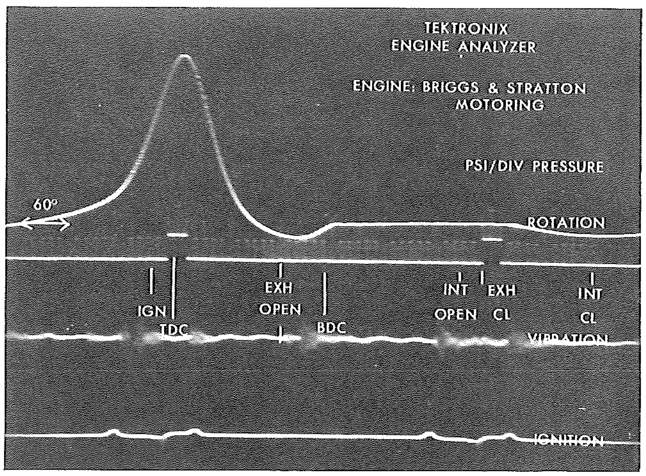


Figure 4-6. Projected Graticule

The equipment list for this operation is as follows:

Quantity	Type	Description
1	C-12P	Camera
1	016-0204-00	Projected graticule adapter
1	016-0263-00	C-12 adapter to 7313 Oscilloscope
1	122-0654-00	Graticule slide assembly

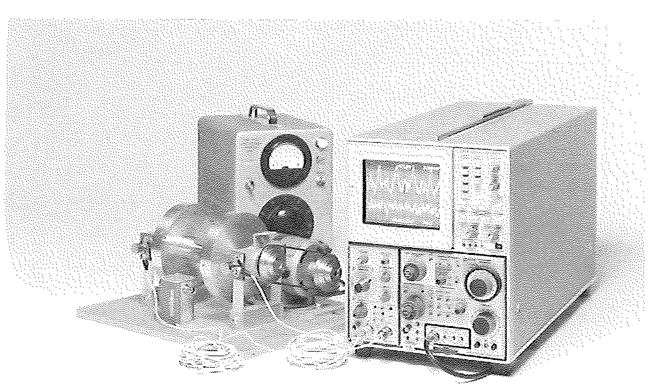


Figure 4-7. Bearing Test Fixture

4-3.2 EAS Ultrasonic Vibration Analysis

The spectrum analyzer is one of the newer tools applied to machinery analysis. The oscilloscope normally displays amplitude on the vertical axis plotted against time on the horizontal axis. But, when the 7L5 Spectrum Analyzer is installed in the 7313 Oscilloscope Mainframe, it converts the oscilloscope display to amplitude on the vertical and frequency on the horizontal axis. While the 7L5/7313 combination was not designed for machinery vibration analysis, it has some very useful features that make it a very valuable tool in ultrasonic analysis of bearing noises, metal-on-metal frictional noise, and other above rotational speed noises. The 7L5/7313 combination as a bearing test fixture is shown in Figure 4-7.

The accelerometer (015-0165-00) is connected to the 7A22 Differential Amplifier, which is installed in the left hand compartment of the 7313. The 7L5 is installed in the center and right hand compartments of the 7313. The 7A22 output signal is switched to the rear panel jack marked VERT SIG OUT by pressing the TRIG SOURCE button marked LEFT. This signal is then connected to the input of the 7L5. The L3 Plug-in Module input impedance switch should be in the 1 MΩ or center position. The low frequency filter switch on the 7A22, marked LF −3 DB POINT, should be set to a frequency that suppresses the X1 RPM noises or to the 10 kHz position initially.

A reference or comparison vibration signature can be stored in the A registers and used to compare with the new unknown signal coming in the B channel. This comparison technique helps the operator who is not a bearing signature expert to identify for further investigation a defective unit or a unit that has some significant signature difference. The resolution of 10 Hz is not sufficient for mathematical analysis of the structural characteristics of a bearing or support structure. But this resolution is sufficient to spot most common problems and to add an extra degree of confidence to the machinery analysis.

The equipment list for this operation is as follows:

Quantity	Type	Description
1	7L5	Spectrum Analyzer
1	L3	Plug-in Module (1 MΩ)
1	7A22	Differential Amplifier
1	012-0076-00	18-coaxial cable

4-4. Portable Analyzer for Reciprocating Machinery

The need exists for a portable analyzer for the common reciprocating machinery, including the large engines and compressors, used in refineries, processing plants, pipeline pumping stations, sewage treatment plants, power generating stations and as auxiliary equipment in hydroelectric and atomic electric generation facilities. The analyzer should facilitate routine machine inspection and be capable of rudimentary performance analysis. The tests to be performed are: (1) sonic and ultrasonic vibration levels on both time and rotational angle basis with calibrated peak-to-peak visual displays, (2) static pressure levels on both time and rotational angle basis with self electrical calibration, (3) dynamic pressure levels for spark-ignited or pressure-ignited engines on both time and rotational angle basis with compatibility to Keene ports, and (4) ignition voltage measurement on calibrated time and rotational angle displays. Such a portable analyzer is shown in Figure 4-8.

The following listed equipment fulfills these requirements. The performance levels are determined by the transducer's specifications as listed in Section 2 of this handbook.

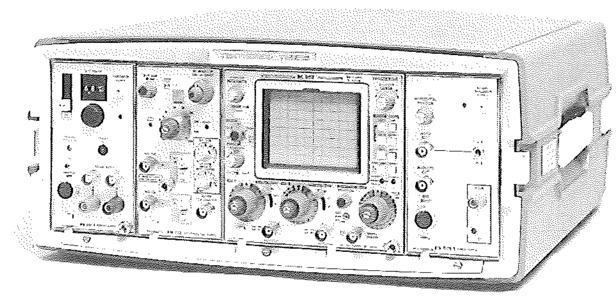


Figure 4-8. TM 515 Rotary Machinery Analyzer

Item	Quantity	Type	Description
1	1	TM 515	Mainframe
2	1	SC 502	Oscilloscope
3	1	AM 502	Differential Amplifier
4	1	PS 501-1 MOD 730E	Transducer Power Supply
5	1	PS 501-1 MOD 730F	RFG Power Supply
6	1	015-0165-00	Accelerometer
7	1	012-0211-00	20-foot Microdot cable
8	1	015-0161-00	Strain gage pressure transducer
9	1	012-0209-00	20-foot cable
10	5	012-0208-00	10-inch BNC cable
11	1	015-0126-01	Transducer kit including:
12	1	015-0108-01	Rotational function generator
13	1	015-0117-00	Pressure transducer, piezoelectric
14	1	015-0118-00	Cooling adapter, pressure transducer
15	1	015-0116-00	Vibration transducer
16	1	015-0119-00	Electromagnetic reference mark transducer
17	1	012-0139-00	Ignition pickoff cable
18	1	012-0140-01	50-foot RFG cable
19	1	012-0076-00	18-inch coaxial cable
20	3	012-0137-00	50-foot coaxial cable

Vibration analysis may be performed using either the PN 015-0116-00 Engine Vibration Transducer or the PN 015-0165-00 Accelerometer. The 0116 is magnetically held and usually applied to engines and compressors operating in the 100 to 6000 RPM range for the purpose of listening to the primary rotation caused vibration signals. The accelerometer is normally used to listen for ultrasonic signals by having the AM 502's LF filter set at 10 kHz to eliminate the lower frequency noises. Metal to metal rubbing, valve hammer, and many other events can create ultrasonic noises, that would be masked by rotational noise if the filter were not used. Figure 4-9 shows two signal examples.

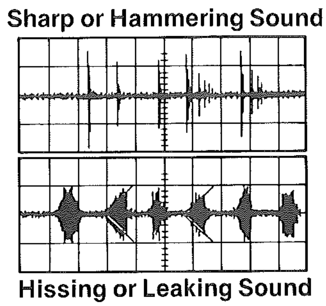


Figure 4-9. Vibration Signals

Timing of the oscilloscope display is achieved by placement of a PN 015-0119-00 Electromagnetic Reference Mark Transducer near the rotating shaft to pick up a once-per-revolution signal from a mechanically known reference angle such as TDC. This signal is used to trigger the sweep circuits of the oscilloscope in the time-per-division mode and to align the outer body and dial of the PN 015-0108-01 Rotary Function Generator (RFG). The RFG supplies the external sweep signal, for the oscilloscope, through circuits in the PS 501-1 MOD 730F RFG power supply. When the HORIZ OUT switch is placed in the lower or "R" position, a linear ramp signal is applied to the SC 502.

This ramp varies linearly in amplitude with rotational angle of the shaft of the RFG, yielding a mechanical phase angle display. When this ramp signal is combined with the effect of the time markers connected to Channel 2, and the test vibration signal connected to Channel 1, it is possible to accurately measure the rotational position of any specific vibration component. The primary use of this feature is in establishing the exact timing of valves or other cam-actuated devices, and often more important, identifying the performance of specific valves or pistons in a multistage or multicylinder compressor. The body of the RFG may be rotated any specific amount, as indicated on a calibrated, dial, to place any observed event at the left edge or at the center of the oscilloscope display. This is the feature that facilitates the analysis of specific cylinders on a multicylinder engine or compressor. A typical display is shown in Figure 4-10.

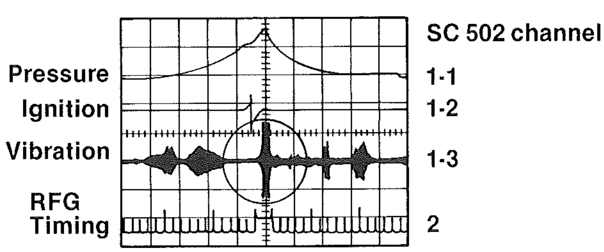


Figure 4-10. Timing Relationships

Ignition analysis of spark-ignited engines is performed using the PN 012-0139-00 Ignition Pickoff Cable as a 1000 to 1 voltage divider and using the RFG setup described above to establish timing relationships. The pedestal of the markers display is usually positioned at the center of the screen and coincident with the firing of cylinder No. 1. A quick look at the ignition parade, as shown in Figure 4-11, can also be performed by connecting the ignition pickoff on the center post lead of the coil or the distributor. The sweep may be timed to any specific cylinder by lightly wrapping one of the coaxial cables around the particular sparkplug cable for a reference (i.e., No. 1) to trigger the oscilloscope sweep.

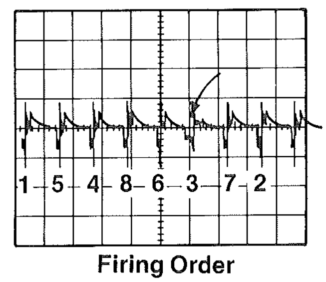


Figure 4-11. Ignition Parade

Compressor cylinder performance analysis can be performed with the PN 015-0161-00 3000 psig (static) strain gage pressure transducer connected through the PS 501-1 MOD 730E Transducer Power Supply. Both pressure versus volume (PV) and pressure versus angle (PΘ) displays may be obtained when this capability is added to the RFG capability. The simulated volume signal is obtained from the RFG by switching the HORIZ OUT switch to the RFG power supply to the up or V position. Pressure versus time (PT) displays using the SC 502 time-per-division switch are available for multi-cycle surge analysis and standing wave detection. A pressure display is shown in Figure 4-12.

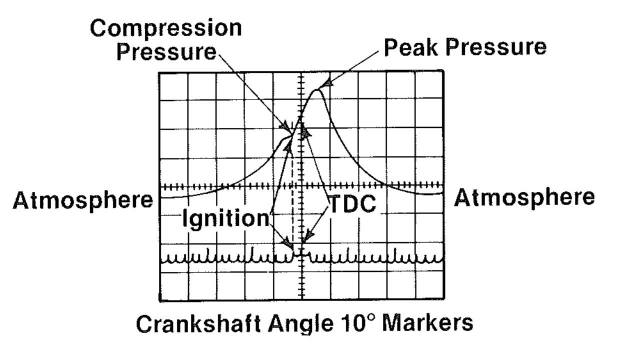


Figure 4-12. Display of Pressure Versus Crank Angle

Power cylinder performance analysis uses the PN 015-0117-00 Piezoelectric Dynamic Pressure Transducer with mechanical connections to the engine through the PN 015-0118-00 Cooling Adapter. The electrical signal connection is made through the AM 502 Differential Amplifier with a shunt capacitor (0.2 μF) from the input to the ground. This shunt capacitor converts the charge-per-psi signal of approximately 200 pC per psi into a voltage signal of approximately 1 mV per psi.

4-5. Incremental Torque Measurement

The force which tends to produce rotation around an axis is called torque. Torque is the product of the force (F) and the perpendicular distance (L) from the axis of rotation to the line of action of the force. This can be shown with Figure 4-13 depicting a shaft, a pulley, and a rope. With a force (F_1) of 25 pounds at a radius of 4 inches (L), the resultant torque is 100 inch-pounds. Incremental torque is associated with a device with changing torque requirements with rotational angle.

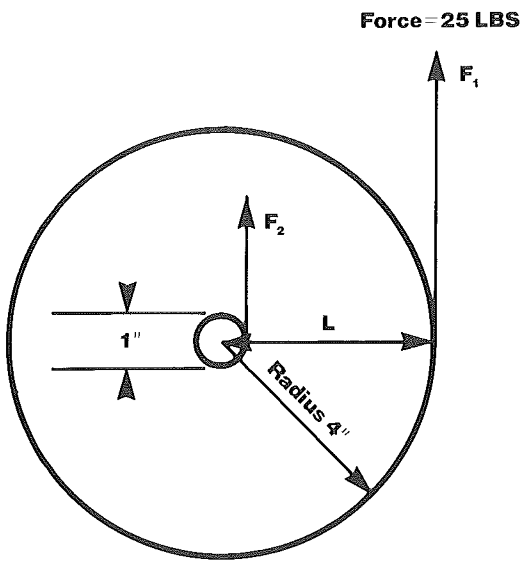


Figure 4-13. Rotational Force—Torque

There are a wide range of torque measuring instruments ranging from torque-watches, torque-wrenches, and torque screwdrivers to some quite elaborate telemetry systems on the rotating shafts of turbines and ship propellers. Often it is not satisfactory to know just the average torque or the peak torque; it is necessary to know how smoothly the torque load varies in steps or increments throughout some cycle of conditions. This incremental torque must be a dynamic measurement rather than the typical static measurement when you need to obtain a true operating picture of mechanical devices. The torsional vibration measurement technique shown in Section 3-11 is an example of a dynamic solution to a repetitive torsional problem. Many mechanical systems use some form of incremental motion which imposes intermittent loads with torsional pulses to the driving shafts. Also, electric motors, and particularly stepper motors, impose torque pulses to thee load as do geneva mechanisms, clock work mechanisms, and many gear driven systems.

Measurement of these dynamic loads is usually accomplished using strain gages mounted on the surface of a shaft as shown in Figure 4-14. When a shaft is twisted, the principal stresses exist 45 degrees to the center line of the shaft. The strain gage (A) which is mounted to sense the 45 degree line leading the direction of rotation will sense tension or elongation of the gage. The gage (B) which is mounted to sense the 45 degree line lagging the direction of rotation will sense compression or shortening of the gage. Figure 4-14 shows the placement of these gages on a shaft.

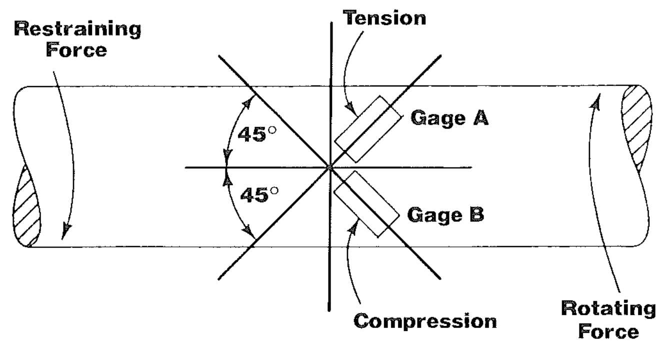


Figure 4-14. Strain Gage Placement on Shaft

Commercial torque transducers often use 4 gages—two in compression and two in tension—to obtain higher sensitivity and bi-directional action. This bi-directional sensitivity is quite necessary for loads with any inertia or with sprint detent actions. These four transducers are connected through slip rings to bridge circuits such as shown in Section 2. The sensitivity of the strain gage is very much a function of the design. Commercial units are available from 10 inch-ounces to 750,000 foot-pounds. The torque sensitivity of a shaft is given by the following equation:

$$T=\Theta \cdot \frac{\pi \cdot C \cdot D^4}{32 \cdot L}$$

where: C=modulus of rigidity
Θ=angular twist of the shaft
D=diameter of shaft
L =length of sensing shaft

In order to increase the sensitivity, often a short section of a shaft is machined down to a smaller diameter. This smaller diameter can present some problems in mounting the strain gages. Accordingly, one engineer worked out a technique of inserting a length of less rigid material and machining two flat surfaces to ease the strain gage mounting problem while increasing the sensitivity. Figure 4-15 is an example of a high sensitivity section for a simple torque transducer.

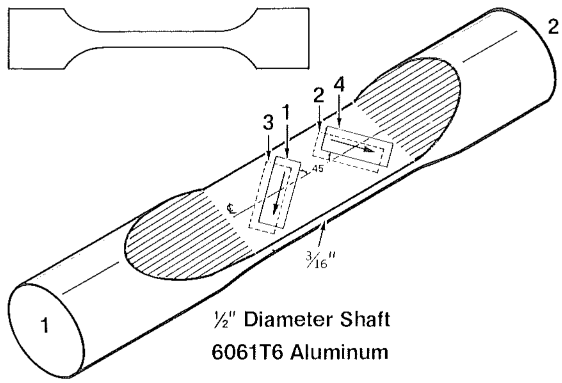


Figure 4-15. Sensor Section of Strain Gage Torque Transducer

Quality control problem solution efforts for electro-mechanical devices have led to the invention of an ingenious array of solutions to various problems. The unit described below was developed to test rotary switches used in electronic equipment. The physical construction of the transducer is shown in Figure 4-16.

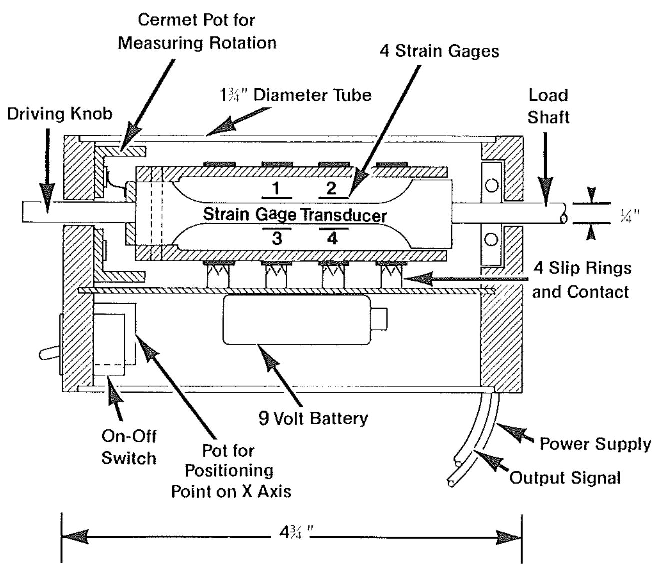


Figure 4-16. Switch Torque Transducer Construction

The strain gages are mounted on a machined-down section as was shown in Figure 4-15. The four strain gages are mounted on the thin section of the machined-down sample of a half-inch diameter aluminum rod. The gages are carefully placed over the center line and angled at 45 degrees to this center line. One gage is placed on top and the second on the bottom below it. A second pair of gages is installed at 90 degrees with respect to the first set. This allows two gages to be in compression while two are in tension for each direction of torque. When the rotational force is clockwise (cw) from end 1, gages 1 and 3 will be expanded and gages 2 and 4 will be shortened. When the rotational force is counterclockwise (ccw) from end 1, just the reverse will occur. These four strain gage units are connected in a bridge configuration and then to four slip rings. The output of the slip rings may be routed through the strain gage adapter (P/N 015-0169-00) shown in Section 2 to the PS 501-1 MOD 730E power supply, or a special cable can be made to connect directly to the PS 501-1 MOD 730E. The electrical connections for this unit are shown in Figure 4-17.

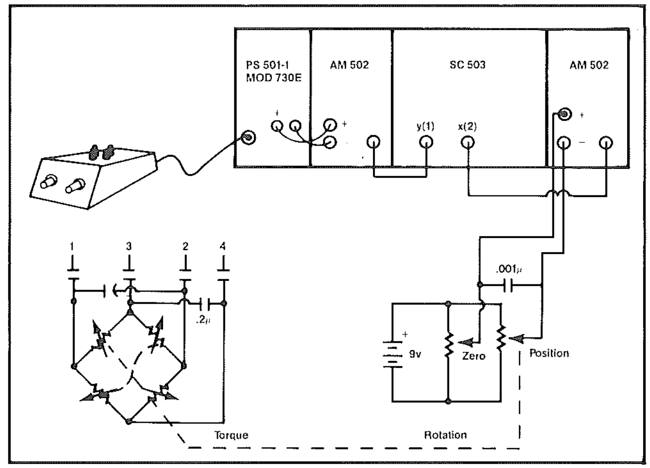


Figure 4-17. Torque Transducer Electrical Circuit

The strain gage bridge excitation voltage (approx. 3.8 to 4.2 volts) is supplied by this power supply. The two strain gage signal leads (+ and −) from the power supply are connected to the (+ and −) inputs to the AM 502 differential amplifier with a gain of 500. This signal is then applied to the Y input or Channel 1 of the SC 503 storage oscilloscope. These two signals are applied to an AM 502 differential amplifier with a gain of 5 and then to the "X" or Channel 2 input of the SC 503 storage oscilloscope.

This system was used to perform the following tests on an "Oak" brand switch. The first photo (Figure 4-18, a, b, c) shows a normal, two-channel oscilloscope display. The upper trace shows the torque signal at a scale factor of 20 ounce-inches per division. The lower trace is the position signal with a scale factor of about 60 degrees per division. The switch positions are 45 degrees apart. The horizontal axis is time. The switch was slowly stepped first clockwise then counter clockwise by hand. While some data is available, careful examination fails to reveal much of the needed dynamic data. A storage oscilloscope was required to obtain even this small bit of data because of the slow sweep speed of the hand and the fast sweep speed of the eye. Storage of the picture allows examination by the operator at his leisure.

The SC 503 has a unique X-Y operating mode which allows plotting one signal versus the other, and storing the results as shown in the second and third photos (Figures 4-18 a & b). The important information was not so much what happened at each position but what happened during the short interval associated with each step. Here the X-Y mode of the SC 503 shows its value. The effect is one of having a very slow speed during the time in position and a fast sweep during step changes. The action starts at the lower right corner of the photo and steps back across the bottom during the clockwise rotation of the switch. The counter clockwise rotation action starts at the left edge and proceeds across to the right displaced up by an amount which is a function of the drive shaft friction. This creates a hysteresis torque which is a function of the direction of previous motion. The torque from the operator's hand force is up in the lower trace and down in the upper trace because of the difference in the direction of rotation.

In both Figures 4-18 a & b, a bounce effect is obvious and the torque value appears high (2.8 × 20 ounce-inches=56 ounce-inches) just to achieve a positive detent action. It was found that this was caused by the detent ball retainer spring being improperly mounted. The third photo (Figure 4-18, c) shows the operation with the spring properly mounted, thereby reducing the torque requirements (1.8 × 20=36 ounce-inches) of the switch. The at rest position of the switch is on the right side of each step. There appeared to be a slight change in location with direction of the lower torque indicating it was not desirable to further lower the torque.

This application shows a class of measurement requirements which can only be met by the TM 500 family and by an oscilloscope with both storage and X-Y display. There are many other low event frequency, not necessarily low data bandwidth, events which require a storage type display with selective time erase.

Torque
20 oz —in/div

Position
60 degrees/div

μs Time
5 sec/div

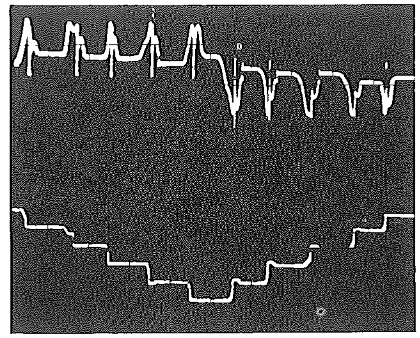


Figure 4-18a.

Torque—Vertical
20 oz —in/div

Position—Hroizontal
30 degrees/div

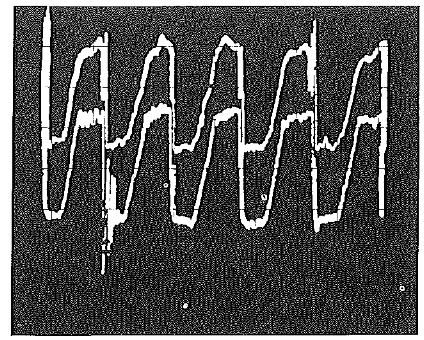


Figure 4-18b.

Torque—Vertical
10 oz —in/div

Position—Horizontal
30 degrees/div

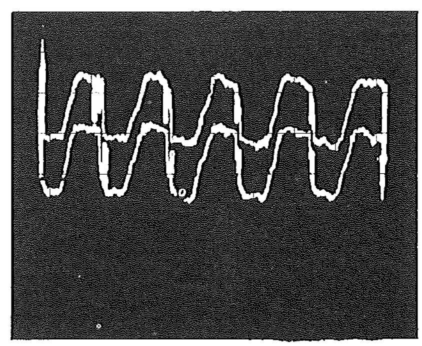


Figure 4-18c.

4-6. Ultrasonic Flaw Detection

A major contribution of electronics to machinery analysis has been in applications of non-destructive testing techniques. New, smaller, highly portable equipment has allowed the move of many laboratory and production testing methods into the field. Ultrasonic flaw detection methods have evolved into a mature testing science with application in many areas of engineering. The TM 500 modular system concept has provided an ideal vehicle for many new ultrasonic applications by a number of vendors. The system shown in Figure 4-19 is made up from both Tektronix modules and outside vendor components and modules.

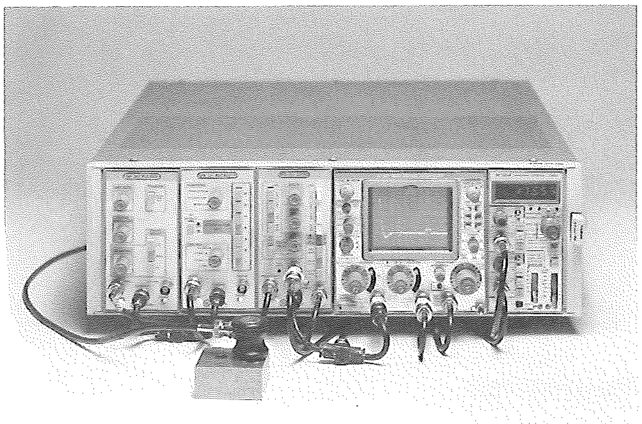


Figure 4-19. TM 506 with Tek Modules and Outside Vendor Components

The ultrasonic signal is generated by the transducer from the high voltage pulse signal, and it also detects that signal for the receiver. Figure 4-20 shows a typical waveform from this test system. The large pulse at the left of the lower trace is the transmitted pulse. The other pulses are return signals from discontinues in the test material. Figure 4-21 shows the signals obtained from a steel reference block which is free of defects. The time interval from the transmitted pulse to the first high amplitude pulse can be measured and averaged directly by the DC 505A Universal Counter/Timer. The SC 503 Storage Oscilloscope allows visual identification of reflections and setting of the DC 505A trigger level for the largest reflection pulse. One or more gating units may be added to select out any pair of reflections (i.e., first surface, second surface, etc.) for measurement by the DC 505A. The storage mode allows retention of the signal for analysis. This is quite important in difficult measurement circumstances where total operator attention is required for transducer placement and is not available for instantaneous analysis and measurement. The SC 503's two-trace capability allows a view of the total signal and some gate-selected portion of the signal, either in single sweep or external trigger operation.

Similar test sets can be made up for any ultrasonic testing application by some of the 14 "offshore" TM 500 module manufacturers listed at the rear of this manual, or you can make up your own.

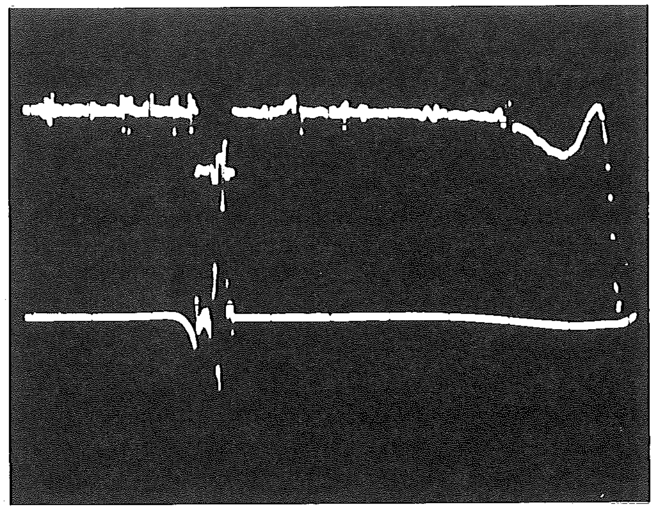


Figure 4-20.

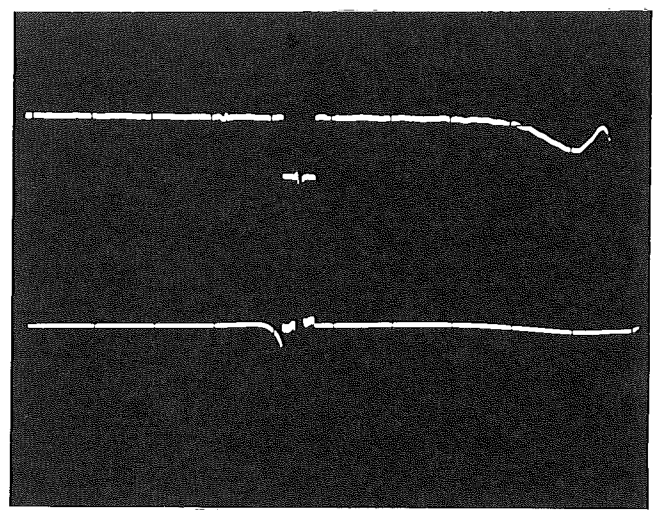


Figure 4-21.

4-7. Materials Testing by Acoustics

The higher reliabilities now required of more complex machinery of higher efficiency, lighter weight, and manufactured from new materials has created a need for extensive testing. Many of the new testing techniques are simply qualification of classical quality judgments. The new computer-based analytical methods of design often leave nagging questions as to the quality of the final product. These questions can only be answered by more extensive design testing, prototype testing, and production testing. The loss of highly-trained craftsmen with years of experience has created a need to develop new, rediscover old, and apply all possible testing methods. The testing methods utilizing the velocity of sound in materials have seen a sharp resurgence. Ultrasound methods of flaw detection have been expanded towards the use of traditional components and digital components to very accurately determine the composition of a material. A good example is the Tektronix WP 1100 AC Ultrasonic Velocity Test System shown in Figure 4-22 following. This system determines the thickness of ductile iron parts to ±0.001" with a repeatability of ±0.003." The installed equipment combines the talents of three companies to solve a serious quality control problem. One ingenious customer has applied this system to testing of critical nodular iron parts by the method shown in Figure 4-23.

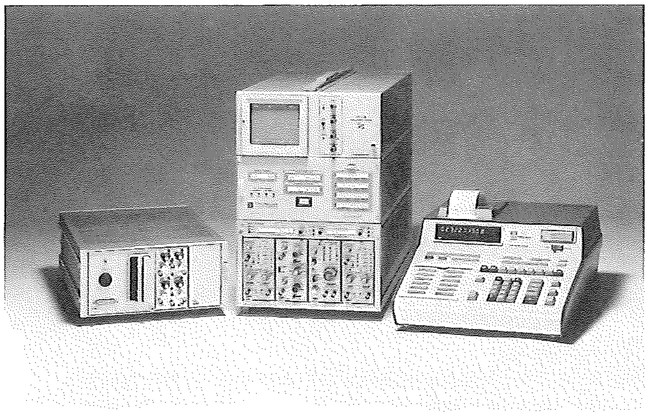


Figure 4-22. Tektronix WP 1100 AC Ultrasonic Velocity Test System

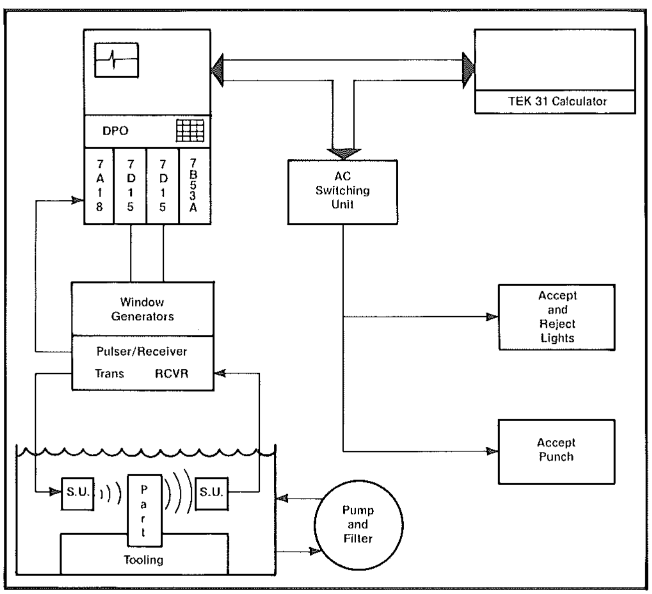


Figure 4-23. Nodularity System Block Diagram

Mechanical impedance testing is one of the engineering design techniques coming out of the laboratory and onto the production floor. In engineering terms, mechanical impedance is identified as the ratio of force applied to the velocity resultant. In mathematical terms, it is quite similar to the equations for the complex electrical impedance networks. A great deal of effort has been expended over the years to solve these electrical problems, and now they can be used to solve the mechanical problems. When the Digital Processing Oscilloscope (DPO) used in the velocity test system is combined with some new forms of old transducer, you have an automated mechanical impedance measuring device. The excitation force can be applied with a hammer upon which is mounted a force transducer to measure this force, and an accelerometer can be mounted to the test object as shown in Figure 4-24. The DPO captures and digitizes the transient signal, analyzes the signal for frequency and phase content, computes the velocity from the acceleration data, computes the impedance and transfer characteristics, and displays the results on the visual readout or to a hard copy unit. All of this action may be automated to the point of pushing a button and swinging a hammer.

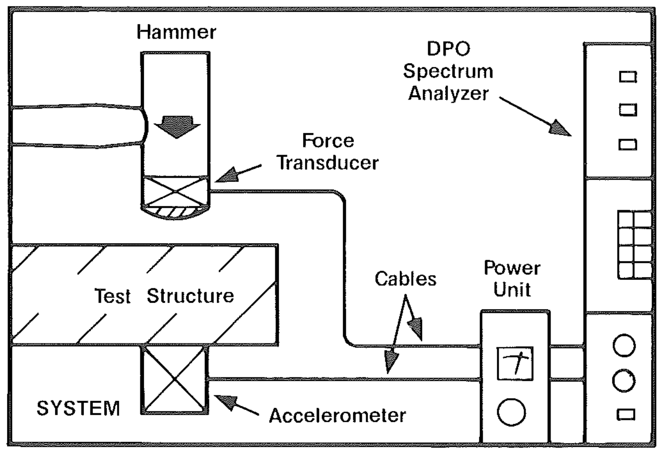


Figure 4-24. Digital Processing Oscilloscope

A much simpler form of material testing using this "electronic hammer" combined with the SC 503 Storage Oscilloscope is used to grade materials and teach the physics of materials. Figure 4-25 depicts the operation of this simple system. The hammer blow creates the force impulse and its resultant compression wave traveling along the bar.

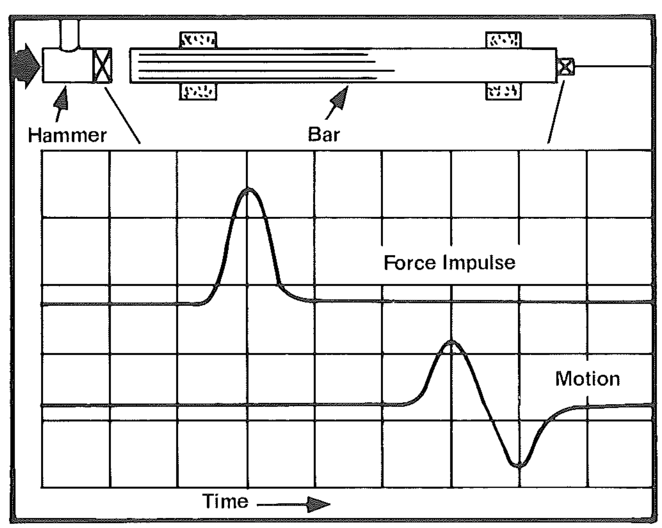


Figure 4-25.

The velocity of this wave is a function of the density of the bar and the modulus of elasticity. After examination of the equations, a set of seven 20-centimeter long bars were made of different materials available in the Model Shop. These were tested by the impulse method to obtain the velocity of sound in each material as listed in Figure 4-26. Most values were within experimental error, but better values would be obtained with bars 40 to 50 cm long or with samples where the transient time is longer than 50 microseconds.

MATERIAL	TIME (μsec)	($X10^{-5}$ cm/sec)	TABLE VALUE
Lead	106	1.8	2.16
Plastic	48	4.2	
Brass	42	4.76	4.4
Aluminum	20	10	6.32
Steel	20	10	5.9
Hardwood	80	2.5	4.1
Softwood	100	2.0	1.1

Figure 4-26. Velocity of Sound in Materials

4-8. Reference Materials

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NBS Special Publication 423.
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Milwaukee, Wisconsin 53213
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80 Lincoln Ave.
Stamford, Connecticut 06904

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Diesel and Gas Turbine Progress Magazine, June 1972.

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Sound and Vibration Magazine, November 1977.
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ASTM Specification E 114-75 *Testing by Refection*

ASTM Specification E 214-68 Immersed Ultrasonic Test

ASTM Specification E 165-74 *Ultrasonic Contact Inspection of Weldments*

Section 5.

Section 5. Instrumentation Calibration Test Sets

5-1. Introduction
5-2. MICS (F5230H1), (F515BM1)
5-3. Transducer Electronics Calibration System
5-4. Communications Test Set (F5150R1)
5-5. Oscilloscope Calibration Test Set (F5040R3)
5-6. General Electronics Service Set (F5040R2)

5-1. Introduction

The explosion of new industrial applications of electronic instruments, transducers, computerized displays, data acquisition systems, etc. has created major maintenance and calibration problems. Because these instruments have a wide variety of characteristics, a wide variety of specialized single-purpose test equipment has resulted. A considerable engineering design effort has been directed toward development of these special purpose test sets. Also the variety of test sets required, just to maintain and calibrate permanently installed instrumentation, often costs more than the instrumentation. A simpler solution to the special, expensive, single usage test sets is required. The test sets described herein are inexpensive multipurpose collections of standard TM 500 Test Modules. These allow a capable technician or engineer to perform many tasks at a fraction of the cost of special purpose equipment. Probably the most outstanding of these TM 500 based test sets is the series originally configured to maintain the electronics equipment in hospitals. The commonality of frequency ranges, signal leads, reliability and other specifications indicates that these hospital equipment maintenance test sets can be applied to the mechanical world without additional development time or costs. While MICS stands for Medical Instrumentation Calibration System, it could just as well stand for Mechanical Instrumentation Calibration System because the performance ranges are very similar even if the names of the devices being tested are not.

5-2. MICS

The basic configuration of the TEKTRONIX Medical Instrumentation Calibration System is a special mobile cart, carrying an oscilloscope and two TEKTRONIX TM 503 Mainframe Power Units, as shown in Figure 5-1.

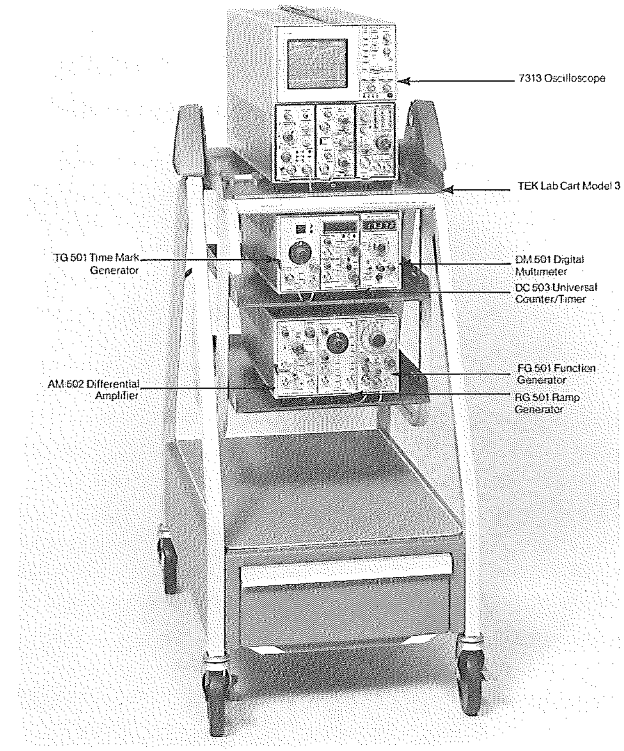

Figure 5-1. Medical Instrumentation Calibration System

The major primary power supply components are located in the mainframe units and shared by the plug-in instruments. Signal interconnections between plug-ins can be made through the mainframe, which keeps the front panels uncluttered and easy to use. It also cuts down on the number of cables and adapters that must be taken to the job. An important benefit of the system concept for portable instrument calibration and repair is that all of the units on the cart share a common ground, which insures that the cases are at equal potential for safe use. This is especially important when tests or emergency repairs must be done in facilities that cannot be closed down. The compactness and mobility of the MICS are other significant advantages.

For repair or calibration of permanently installed equipment, a full selection of instruments can easily be brought to the job site, and the convenient mounting eliminates the need to find accessible surfaces on which to put everything. Even when testing and repairs have to be performed at adjoining workbenches, it is difficult to constantly move large, heavy, separate instruments. While the specific requirements and the TM 500 instruments selected vary at different locations, typical examples of the test sets used on fairly sophisticated systems are described in the following paragraphs. More detailed descriptions of these selected TM 500 units follow this discussion.

5-2.1 Display Unit and Chart Recorder Maintenance

Linearity of the drive or sweep and amplifier fidelity are the critical factors for chart recorders and display units. A time mark generator (TG 501 Time Mark Generator) or a function generator (FG 501 Function Generator) provides a signal for the linearity check.

The TG 501 Time Mark Generator will also display the existing time error if desired. For repair of the amplifiers in chart and display units, a wide selection of general test equipment is usually required. This includes a multimeter (DM 501 Digital Multimeter), function generator (FG 501 Function Generator), and dual trace oscilloscope (434, 5111, or 7313). A known working amplifier (AM 502 Differential Amplifier) is often necessary for making comparisons with suspect sections of defective equipment.

5-2.2 RF and Direct Telemetry Maintenance

Many monitoring or sensor systems are either directly connected to central data stations or are used with radio links to a receiving system. Measurements commonly made during maintenance include frequency, amplitude, modulation and timing. The list of equipment includes a multimeter (DM 501 Digital Multimeter), dual trace storage oscilloscope (434, 5111, 7313, or similar unit), counter/timer (DC 503 Universal Counter), and function generator (FG 501 Function Generator). A differential amplifier (AM 502 Differential Amplifier) and a decibel reading multimeter (DM 502 Digital Multimeter) might also be called for.

5-2.3 TM 500 Plug-ins for the MICS

For general portable calibration and repair use, the following instruments have been selected as best suited to the needs of most mechanical and instrumentation MICS users.

DM 501 Digital Multimeter. As a wide range, easy-to-use digital multimeter, this unit can be used to make many of the common voltage, current, and resistance measurements required in repair and calibration of electronic equipment.

DC 503 Universal Counter. From very slow changing central loop signals to high frequency servo and digital data equipment, this counter can measure the signal frequency for quick, clear display. It can also count the number of times an event occurs, provided that the event generates a signal of at least 300 mV; and can be used for checks on pulse counters, control equipment, and equipment or process monitor alarm systems. Other measurements possible include: period and frequency of an ultrasonic system output pulse, as well as the interval before the echo; carrier frequencies; the frequency of tones in modulated systems; and events counts for digital systems. The DC 503 can also measure pulse widths and pulse intervals for both remote and direct data collection systems. With suitable sensors, the counter can also measure the speed of rotating machinery such as pumps, centrifuges, and motors.

FG 501 Function Generator. The FG 501 provides a variety of signals over a wide range of frequencies for triggering, simulating inputs, isolating defective stages, providing known input wave shapes or pulsing circuits. The FG 501 Function Generator can provide the information required to determine bandwidth, frequency fidelity, and modulation characteristics of a wide range of equipment either by checking set frequencies or using the sweep mode with an input to the VCF control.

AM 502 Differential Amplifier. The AM 502 is used to provide high gain for low level signals, either as a substitution check for the front ends of equipment under test, or to extend the measuring capabilities of other test instruments. It can also be used to condition signals by limiting the passband to frequencies of interest. A differential high gain amplifier is required to measure the output of many transducers. The AM 502 can be used as a filter, isolator, signal conditioner, or high gain amplifier—all functions that are often necessary in equipment repair.

TG 501 Time Mark Generator. Oscilloscope or monitor sweep timing tests are the prime function of the TG 501. The pulses from the TG 501 are used to calibrate the horizontal time section of the device. Error in existing settings can also be determined. The accuracy and linearity of chart and strip recorders can be checked or set with extreme accuracy using the TG 501. The traces of the regular pulses from the TG 501 are measured for equal distance and current position. Accurate calibration of ultrasonic equipment requires an accurate time reference such as the TG 501. The TG 501 can also be used as a precise clock for substitution in computerized systems or for general timing and stepping functions in any device under test.

RG 501 Ramp Generator. The RG 501 provides an accurate ramp signal for the repair of time bases. The ramp signal is the basic waveform for the horizontal sections of monitors, oscilloscopes, oscillographs, and plotters. Also, the RG 501 can be used to supply the synchronizing signal to slave several display units to a common signal.

Oscilloscope. Low frequency phenomena, most common to the physical world, are best displayed and examined on storage oscilloscopes of the bistable, multitrace type. The four most accepted units are the SC 503, the 5111, the 7313, and the 434. Different activities though may require other oscilloscopes. It may be advisable to have a local Tektronix Field Engineer match the oscilloscope to your specific application.

5-2.4 Instrument Maintenance System F5203H1

A basic laboratory quality instrument maintenance system using the Type 7313 Oscilloscope was developed for a group of customers and was given the designation F5203H1. This number covers all of the items listed below. In addition to the 7313, the six standard MICS TM 500 Modules are included. This system is shown in Figure 5-1. The intent of this system was that it could be moved to the equipment to be maintained; and on the cart is the complete equipment to analyze anything from a digital computer to a chart recorder.

Quantity	Type	Description
1	7313	Oscilloscope, 25 MHz, bistable storage
1	*7A22	Differential Amplifier
1	*7A18	Dual Trace Amplifier
1	*7B53A	Dual Time Base
1	TG 501	Time Mark Generator
1	DC 503	Universal Counter
1	DM 501	Digital Multimeter
1	AM 502	Differential Amplifier
1	RG 501	Ramp Generator
1	FG 501	Function Generator
2	TM 503	Mainframe
1	Model 3	Lab cart
1	346-0136-01	Safety belt
1	436-0132-01	Second shelf for lab cart

*plug-ins for the 7313 Oscilloscope

5-2.5. Portable Maintenance System F515BM1

A number of activities required a portable instrument maintenance and calibration system that was more portable than the Model 3 Lab Cart allowed. Additionally, these requirements often were in support of an existing oscilloscope or in some activities where an oscilloscope was not required. The F515BM1 system shown in Figure 5-2 uses the TM 515 Traveler Mainframe to house five modules most applicable to control system instrumentation, calibration and maintenance. Four of these modules, the DM 501, DC 503, FG 501, and AM 502, are common to the other systems in the MICS Series. The PS 503A Dual Power Supply is an addition for control instrumentation maintenance. This unit has two 0 to 20 V supplies that may be operated independently or in a tracking mode. In the tracking mode, the two may operate as plus and minus supplies, symmetrical from zero, or as a 0 to 40 V supply. The addition of the power supply allows a checkout of both P/I transducers and I/P control valves on site rather than in the shop. Components of this system include the following items:

Quantity	Type	Description
1	PS 503A	Dual Power Supply
1	DM 501	Digital Multimeter
1	FG 501	Function Generator
1	DC 503	Universal Counter
1	AM 502	Differential Amplifier
1	TM 515	Mainframe

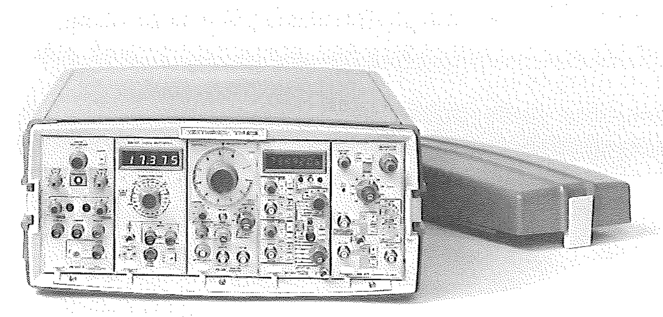

Figure 5-2. F515BM1 Portable Maintenance System

5-3. Benchtop Electronics Transducer Calibration Systems

Activities that use a number of transducers require both electrical and physical parameter test equipment to verify performance. A complete range of electrical and physical comparison tests may be performed using, in part, the transducer calibration system as listed below and shown in Figure 5-3.

Quantity	Type	Description
1	DM 501 MOD 718D	Digital Multimeter, high sensitivity
1	PS 501-1 MOD 730E	Transducer Power Supply
1	AM 502	Differential Amplifier
1	SC 503	Oscilloscope
1	DC 503	Universal Counter/Timer
1	TM 506	Mainframe
3	012-0118-00	8-inch coaxial cable
1	012-0209-00	TEKTRONIX Transducer Cable
1	012-0210-00	Customer-adapted Transducer Cable

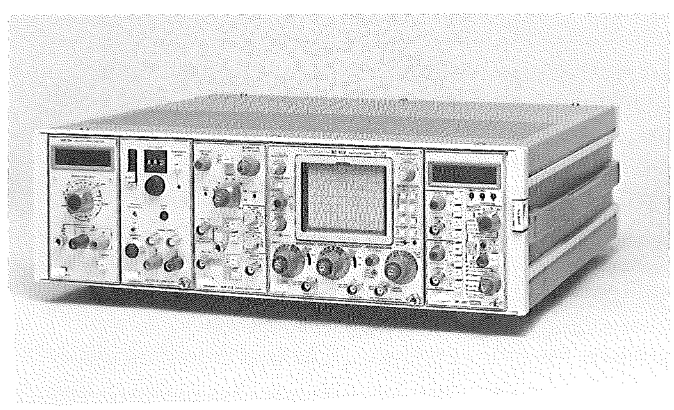

Figure 5-3. Benchtop Transducer Calibration System

The PS 501-1 MOD 730E Transducer Power Supply may be used to power either transducers of the Tektronix Family through the PN 012-0209-00 Cable or other brands through the PN 012-0210-00 Cable, which has a connector on the power supply end only. The units of the TEKTRONIX Transducer Family for pressure, force, or displacement may be used as comparison standards to questionable units when both are installed in mechanical test fixtures.

The DM 501 MOD 718D Digital Multimeter has a particularly high sensitivity of 10 μV per div which allows it to resolve very small changes in the electrical characteristics of transducers. It can be directly connected to the PS 501-1 MOD 730E Transducer Power Supply as a digital readout for strain gage pressure, displacement, or force transducers.

The AM 502 Differential Amplifier may be used as a signal conditioner for transducers using the PS 501-1 MOD 730E for excitation, or directly on self-excited units such as accelerometers and vibration transducers.

The SC 503 Storage Oscilloscope is the basic instrumentation tool. It allows visual examination of transient and dynamic electrical output signals. Many characteristics of transducers as well as the defects, intermittents, etc., can only be viewed by an oscilloscope. And transient, one-shot, or very low speed functions can only be analyzed by the use of a storage oscilloscope. The SC 503 has an auto-erase feature which allows good views of frequencies below 600 rpm down to fractional rpms. The X-Y capability allows visual transfer function evaluation of operational amplifiers, analog computing modules, power amplifiers, and controllers as well as the traditional orbital (Lissajous pattern) balancing technique.

5-4. F5150R1 Communications Test Set

One of the newer pieces of equipment that creates major unknowns during troubleshooting a large system is the information communication subsystem. These subsystems include direct signaling loops, receivers or transmitters, tone signaling, telephone pulse or tone control, digital data transmission, modems, and others. Such units are among the more reliable elements, but the heavy use and vital nature create some very annoying problems, such as erratic data, noise, etc. The communications test set shown in Figure 5-4 is one of several that can be made up of standard TM 500 Modules. This specific set addresses the more common industrial signaling systems, their associated problems, and consists of the following components:

Quantity	Type	Description
1	TM 515	Mainframe
1	DC 508/01	Digital Counter
1	DM 502	Digital Multimeter
1	FG 502	Function Generator
1	SC 502	Oscilloscope
2	010-6108-01	Oscilloscope
1	010-6430-00	Temperature Probe (DM 502)
1	012-0426-00	Red Test Lead (DM 502)
1	012-0426-01	Black Test Lead (DM 502)

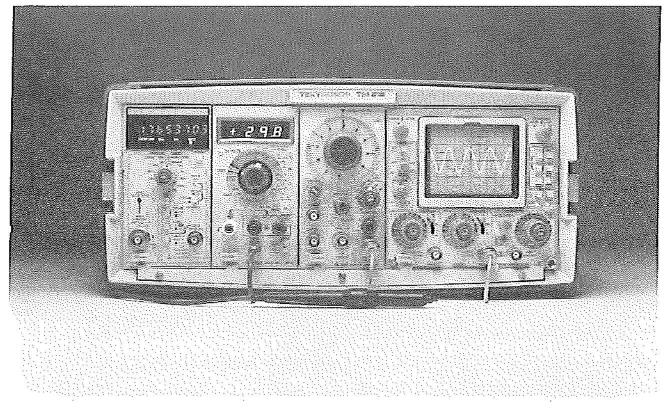

Figure 5-4. F5150R1 Communications Test Set

The DC 508 Option 01 Frequency Counter covers the frequency ranges from below the audio (10 Hz) to over 1,000 Megahertz (1 GHz) including all of the major telemetry and communication bands. It has a resolution multiplier (×100) for the very important tone signaling channel frequencies up to 25 kHz. The very high 20 mV rms sensitivity for 75 to 1000 MHz prescaler input and 15 mV sensitivity for the 10 Hz to 100 MHz direct input simplify the communications front end testing. The option 01 time base utilizes a temperature-controlled crystal oven to obtain an accuracy of 0.2 parts per million after a ten-minute warmup.

The DM 502 Digital Multimeter, in addition to the normal six functions, has the dBm or dBV function, over a range of −60 dB to +56 dB, for communications circuits.

The FG 502 Function Generator is a basic signal source to check out the response of all forms of communications circuits.

The SC 502 Oscilloscope is the heart of the instrument in that its display allows the technicians' skills to be brought into the solution of the communications problem. Visual displays on an oscilloscope are the best ways to detect and identify noise, interference, cross talk, and intermittents in circuits. The SC 502 has two traces, for comparison techniques, and external synchronization to allow freezing a specific event. A local Tektronix Field Engineer can show you the operation of any oscilloscope in circuit problem isolation.

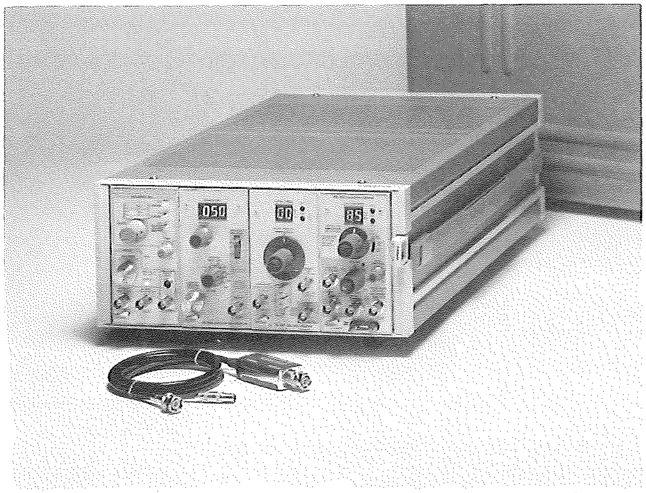

Figure 5-5. F5040R3 High Performance Oscilloscope Calibration Package

5-5. F5040R3 High Performance Oscilloscope Calibration Package

The High Performance Oscilloscope Calibration Package contains a set of precision test and measurement instruments essential to the calibration of most high performance scopes. These four instruments are all packaged in a TM 504 mainframe for easy portability and lightweight handling.

The TG 501 Time Mark Generator creates accurately spaced vertical time marker pulses for horizontal time base adjustments. The PG 506 Calibration Generator has three different square wave modes for vertical or amplitude deflection factor calibration, input attenuator compensation and rise-fall time adjustments and measurements. The SC 503 and SG 504 are both constant amplitude sine wave generators used in verifying the oscilloscopes upper −3 dB frequency bandpass limits and trigger bandwidth and sensitivity. The SG 503 covers the 250 kHz to 250 MHz frequency range and the SG 504 extends the frequency range up to 1054 MHz. All the preceding instruments are designed to minimize operator calculations so the quality control engineer can concentrate more on the oscilloscope and less on the calculations.

Since the F5040R3 system is contained in one lightweight package, it allows the user to conduct on-site performance verification and calibration, reducing the time each scope would be out of service if removed from the site for calibration.

The F5040R3 Package also includes a durable carrying case to further protect the instruments during transportation to the test site.

Quantity	Type	Description
1	TM 504	Mainframe
1	TG 501	Time Mark Generator
1	PG 506	Calibration Generator
1	SG 503	Signal Generator
1	SG 504	Signal Generator
1	012-0482-00	Precision 50 ohm cable
1	016-0608-00	Carrying Case

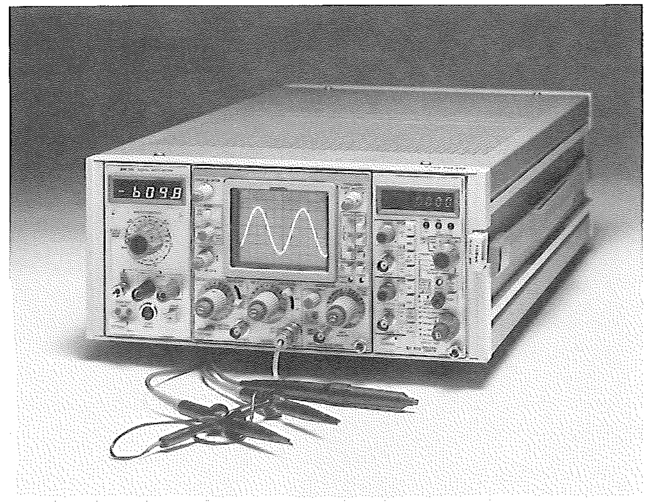

Figure 5-6. F5040R2 General Electronics Service Set

5-6. F5040R2 General Electronics Service Set

The three most versatile items in test and measurement equipment today are the oscilloscope, the multimeter, and the digital counter. The F5040R2 combines these three units into one economical, portable and easy-to-use package. Its compact, single unit design also helps reduce unnecessary clutter on a benchtop. and still supply the basic tools for electronic equipment service.

The F5040R2 system starts with a DM 501 Digital Multimeter, to measure volts, current, resistance and temperature, and a DC 503 Universal Counter/Timer which has six measurement functions along with period and ratio averaging. Completing this system is the SC 502 Dual Trace Oscilloscope. The SC 502 is a compact, general purpose scope which offers a wide range of sweep rates, versatile triggering and a high writing rate.

Because of this versatility, the F5040R2 system can be used to service a wide range of electronic equipment including computer terminals, electronic office machines, production control equipment and electronic display terminals.

Quantity	Type	Description
1	DM 501	Digital Multimeter
1	SC 502	Oscilloscope
1	DC 503	Universal Counter
1	TM 504	Mainframe
2	010-6108-01	Probes

Section 6.

Section 6. Special Purpose Modules

6-1. Introduction

Despite the wide variety of standard TEKTRONIX TM 500 Modules, a requirement arises occasionally for some new additional special purpose modules. This requirement has been met by one of three methods: (1) modification of standard products, (2) user-built modules, and (3) modules built by other vendors.

The modification of standard modules requires an individual quotation on price and delivery for each order because such modules are not parts of regularly scheduled production. Any new modification will necessitate an engineering and documentation charge in addition to the modification charge. The modified modules listed in this section are some that have received a number of orders from mechanical measurements customers.

In order to facilitate customer fabrication of their own modules, Tektronix has made available hardware kits, construction notes, and systems interface handbooks. For large quantity buys, the raw metal parts are also available to other vendors. General fabrication details are presented in this section.

A number of Tektronix customers now offer application oriented test sets and modules that are TM 500 compatible. The test sets shown here cover both industrial, medical ultrasonic as well as logic testing and analysis areas. These units are available only from the vendors mentioned. A list of addresses and phone numbers has been added for your convenience. There is a large number of additional TM 500 test systems customized for special applications that are not listed here because of the lack of information, or because the systems are not for sale. Also listed here are some of the many customer-built TM 500 compatible modules that are for sale only from the listed vendor.

6-2. Modified Products

The following modifications are detailed in this section:

DM 501 MOD 718D
PS 501-1 MOD 730E
PS 501-1 MOD 730F
RG 501 MOD 198F
SG 503 MOD 719X
7B53A MOD FB
5111 MOD 710R
5B10 MOD 711C
SPS 015-0274-00 AC Switching Unit

DM 501 MOD 718D Digital Multimeter, High Sensitivity. This modification deletes the temperature measurement circuitry and probe, and substitutes a "200 mV dc" range. This 199.99 mV full scale range has a resolution of 10 μV. To achieve this added sensitivity, a gain of 10 amplifier was added in front of the 2 V range position. The normal DM 501 specifications apply with the following additions for the 200 mV dc range:

Accuracy: 0.3% of reading ±2 counts over the +15° to +40°C temperature range.

Input resistance: 100 KΩ ±5% in the 200 mV dc range only.

Maximum input voltage between HI and LO Inputs: 12 V in the 200 mV range only.

Maximum input voltage common mode HI-LO to ground: 1.5 kV without damage.

The basic application of this instrument (see Figure 6-1) is for very low level bridge circuit nulling and thermocouple readout with an electronic ice point reference circuit module.

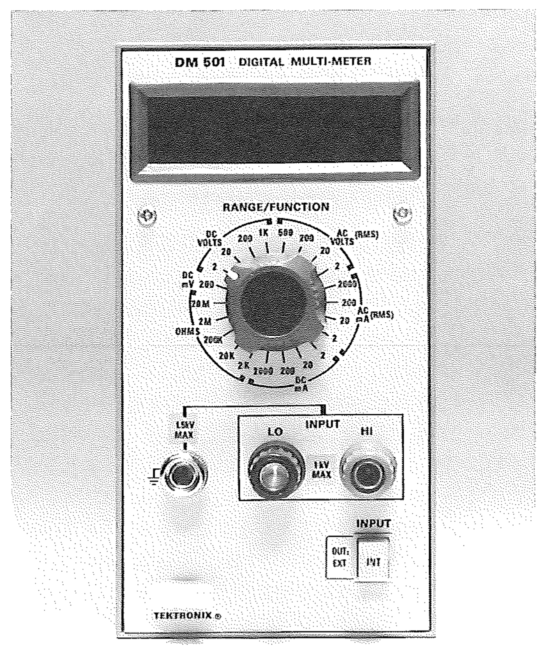

Figure 6-1. DM 501 MOD 718D High Sensitivity Digital Multimeter

PS 501-1 MOD 730E Transducer Power Supply. This modification to the power supply supplies the interface connector and components for the TEKTRONIX Transducer Family. It was specifically made for the following units, but may be used with other units with discretion.

015-0161-00 Pressure transducer
015-0162-00 Pressure transducer
015-0164-00 Force transducer
015-0168-00 Displacement transducer
015-0169-00 Strain gage bridge adapter

This modification replaces the standard power supply front panel with a new panel on which are located some new items (see Figure 6-2). The following is a list and description of the function of each item on the panel.

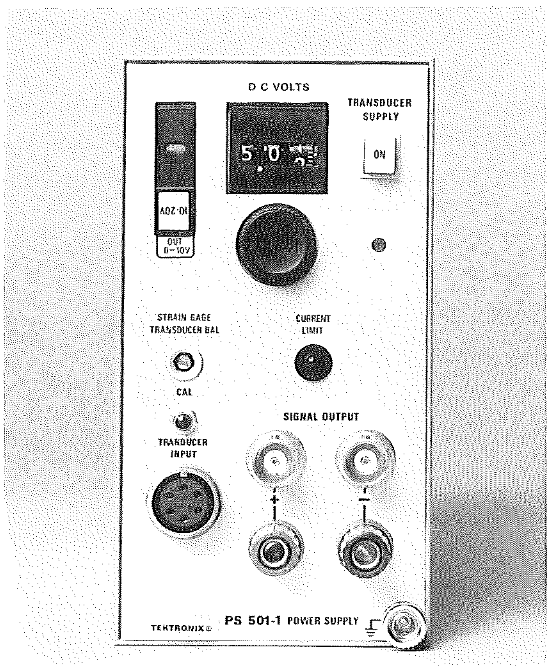

Figure 6-2. **PS501-1 MOD 730E Transducer Power Supply**

The upper ⅓ of the panel contains the standard PS 501-1 adjustment controls and power on indicator. The ON button switches the ac power to the power supply dc regulators, but does not switch on any of the transducer circuitry. The DC VOLTS adjustment functions just as a standard PS 501-1, but a caution should be noted about the range button. The full PS 501-1 range is 20 V and has been retained for those who will be working with semiconductor and other very high impedance strain gages. The internal current limit adjustment pot (R65) is adjusted to 75 mA at shipment to prevent damage to 350 Ω gages if the voltage range button is pushed to the 10 to 20 position. If you do not require voltage levels over 10 V, one precaution, to prevent accidental damage, is to remove the plastic rod that connects the front panel button to the switch. The internal current limit circuit can be adjusted to 400 mA without damage to the power supply.

The lower ⅔ of the front panel contains the transducer interface components. The STRAIN GAGE TRANSDUCER BAL screwdriver adjustment is included to provide a vernier balance for the transducer. The values of 100 kΩ for the pot and 40 kΩ for the series resistor were chosen as optimum for 350Ω gages and acceptable for the Tektronix-furnished 121Ω gages. The small red button marked "CAL" shorts pins E and F of the transducer connector. Several of the higher quality transducers have internal shunt calibration resistors. This switch shunts these resistors across one leg of the bridge circuit, thereby creating a known electrical imbalance. In the case of the PN 015-0169-00 Strain Gage Bridge Adapter, this shunt calibration value is equivalent to 1000 microstrains across leg 4. (Complete details are included in the transducer section.) This feature allows the operator to adjust the DC VOLTS level to obtain an even number of divisions of deflection on the oscilloscope screen, or an even number on the digital multimeter display.

In the case of the two pressure transducers, this shunt resistor simulates a half scale value. In the case of the 3000 psi transducer (PN 015-0161-00), the value is approximately 1500 psi (the exact value is given on the calibration sheet), which allows setting up the display for 1.5 div at 10 mV per div. The power supply can now be set to somewhat less than 10 V and the oscilloscope will be calibrated for: 100 psi per div at 1 mV per div, 200 psi per div at 2 mV per div, 500 psi per div at 5 mV per div, and 1000 psi per div at 10 mV per div. The calibration for the 300 psi transducer is the same, but the values of the scale factors resulting are 10 psi per div at 1 mV per div, 20 psi per div at 2 mV per div, etc. When the 7A22 or 5A22 Differential Amplifier is used, the scale factors for the 10 mV per div would be 1 psi per div for the 3000 psi transducer, and 0.1 psi per div for the 300 psi transducer. In most practical cases, noise pickup and thermal factors limit operations to above 50 μV per div. This produces a calibrated scale factor of 5 psi per div and 0.5 psi per div.

An 11 kΩ resistor is installed in the connector on the PN 015-0164-00 Universal Cell to simulate calibration points on the 50 gr force and 50 lb force ranges. To calibrate the 50 gr scale, set the power supply voltage to approximately 4.5 V, adjust the zero point with the balance adjustment, and then hold down the red "CAL" button while adjusting the power supply voltage for a 25 mV output from the unit. This is the approximate calibration point. The exact voltage or weight value is given by the following equation from the calibration sheet.

$$Eoc = 0.02\ Ec_{50} \times Wcc$$

i.e.: 0.02 x 62.17 x 25 grams = 31.08 mV

$$Wcc = \frac{50}{Ec_{50}} \times Eoc$$

i.e.: $\frac{50}{62.17}$ x 31.19 mV = 24.86 grams

where: E_{oc} = Output voltage at shunt calibration point
W_{cc} = Simulated calibration weight or force from calibration sheet data in grams
E_{C50} = 50 gr calibration sheet output voltage.

CAUTION: Never apply more than 7.0 V to the universal cell.

Readjust the excitation voltage to obtain the exact value after the unit has thermally stabilized. A similar half scale point calibration value for the 50 lb load button is also listed on the calibration sheet.

The "transducer input" connector is part number MS3101A-10-6S and mates with Bendix part number PC06A-10-6P (SR) on the transducer cable (PN 012-0209-00). The pin assignments are as follows:
A Power Supply +
B Transducer Output +(and BAL)
C Transducer Output −
D Power Supply −
E CAL Switch 1
F CAL Switch 2

The transducer should be connected with the special six-connector, triple-shielded pair cable. If you don't have this cable, use three twisted pair shielded leads. Pins A and D connect to one pair, pins B and C to one pair, and pins E and F to the last pair. This arrangement minimizes the noise pickup effects on the circuitry and the oscilloscope trace width. The connector shell is used as the shield ground for all cables because it connects to chassis ground at the front panel.

The signal output connectors are connected in parallel. The two marked + are positive with respect to the two marked − when the resistance of the sensor lines between pins A and B decreases. The two BNC connectors connect to their matching counterparts on the front of the AM 502, 5A13N, 5A19N, 5A20N, 5A21N, 5A22N, 5A26, 7A13, or 7A22 Differential Amplifiers. The shortest practical coaxial cables, twisted to reduce noise pickup, should be used. The two binding posts are used to connect to the DM 501 MOD 718D high sensitivity digital multimeter.

PS 501-1 MOD 730F Rotary Transducer Power Supply. This modification to the power supply installs the signal conditioning and interface components to support applications of the Rotary Function Generator (RFG), PN 015-0108-01. The combination of these two units facilitates the horizontal (X) axis display of rotary motion. Typical applications are described in the earlier sections on the Rotary Machinery Analyzer and the Engine Analyzer System. The nomenclature on the new front panel (see Figure 6-3) reflects these applications.

The ON button switches the ac voltage to the −12 V and +5 V regulator circuits, but does not interrupt the front panel connections. The GAIN knob is concentric with the HORIZONTAL POSITION knob. These two controls have very wide ranges and do interact.

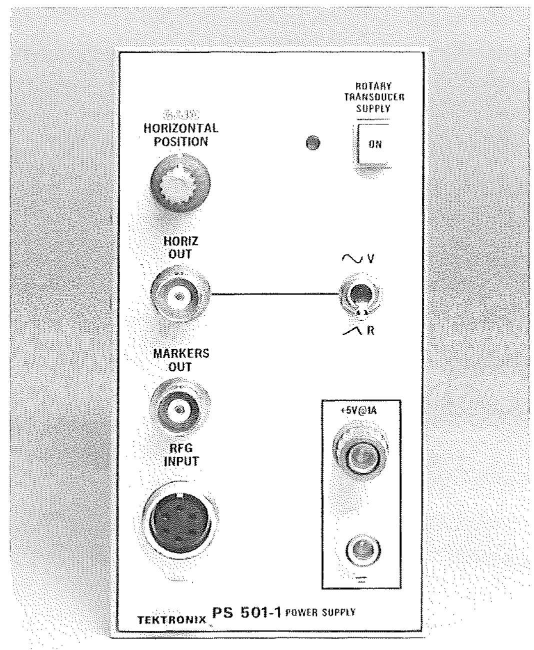

Figure 6-3. PS501-1 MOD 730F Rotary Transducer Power Supply

For normal operation, first center the display and then adjust the sweep width on the oscilloscope display to exactly 10 div in width. One of the two horizontal display forms V the simulated volume, or R the ramp signal, is selected by the toggle switch. The selected signal is routed through a set of integrated circuit amplifiers to increase the signal level and remove the internal offset voltages imposed by the RFG circuitry. The HORIZ OUT signal is normally connected to the external amplifier input to the sweep circuit of the oscilloscope. Following is a list of oscilloscopes, with some of the connection information.

Model	Connector Marking	Time/Div Switch Setting
SC 502	EXT TRIG or AMPL 50 mV/DIV	AMP
434	EXT HORIZ (on rear) 50 kΩ 0.5 V DIV	EXT HORIZ
7B53A	MAIN TRIG IN OR AMP IN	AMPL
5B10N	EXT INPUT	50 mV

The MARKERS OUT signal is approximately 30 mV p-p and is normally applied to a vertical channel with a sensitivity of 50 mV per div. Markers are ac coupled by a 100 μF capacitor and should be direct coupled to the oscilloscope or excessive distortion will result. The RFG input connector is part number MS3101A-10-6S and mates with Bendix part number PC06A-10-6P (SR) on the RFG cable, PN 012-0140-00. The PN 012-014-00 RFG cable has identical end connectors; but the PN 012-0209-00 cable for the transducer has different end connectors. The output connector pin assignments are as follows:

Pin	Function
A	RFG volume signal
B	RFG ramp signal
C	−12 volt power supply to RFG
D	Power common
E	RFG marker signal
F	−12 volt power interlock
Shell	Shield ground

The internal power supply is adjusted for −12 V output and the current limit is set for 300 mA.

CAUTION: This power supply should not be used with other transducers as damage to the transducer may result. The independent +5 V at 1 A is retained to allow use with machine tool optical shaft encoders for torsional vibration testing, or similar applications.

RG 501 MOD 198F Ramp Generator. This modification changes the ramp duration ranges to ten times that of the standard unit. The catalog unit ranges are 10 μs to 10 s, and the modified unit is 100 μs to 100 s. With the DURATION MULTIPLIER dial set to 10 and the 10 SEC button pressed, the ramp duration is 100. This longer time function is often used as the control signal for slow frequency sweeps on shake tables, hydraulic test fixtures, and in mechanical resonance testing. A common setup would use the FG 501 as the frequency source and the RG 501 MOD 198F as the sweep source. This same function can be performed by the FG 504 alone.

SG 503 MOD 719X FM Sinewave Generator. This modification adds the capability of generating a narrow band FM signal for checking telemetry circuitry. A +5 V signal from 10 to 100 kHz will produce approximately the frequency deviation values shown in the table below.

7B53A MOD FB Dual Time Base Plug-in Unit. This modification adds a gated X-Y mode of operation. This feature enhances the low frequency X-Y operation of 7000-Series Storage Oscilloscopes and, in particular, operation with the PS 501-1 MOD 730F and the Rotary Function Generator for rotary machinery analysis. This feature is activated by pushing a latching pushbutton that is concentric with the POSITION control. This pushbutton allows normal time base operation in the IN position and gated X-Y operation in the OUT position. The AMPL (main trigger signal) is applied to the deflection amplifiers instead of the sweep sawtooth signal of the time base. The unblanking signal for the crt is obtained from the TIME/DIV circuits and is front panel controllable. It can be timed to start from auxiliary trigger sources such as the vertical preamplifiers, or external signals (i.e., the magnetic marker at TDC). It can also be delayed by the DELAY TIME MULT CONTROL.

This modification is necessary for X-Y one shot, timed storage, single revolution storage, and other X-Y photographic modes, and reduces the danger of screen burning on slow sweep X-Y operation.

5111 MOD 710R X-Y Storage Oscilloscope (L vs R X-Y mode), 5B10 MOD 711C—Time Base Plug-in Unit (L vs R mode). These modifications, when combined with any two identical vertical amplifiers (i.e., 5A15, 5A18, 5A22), allow horizontal (X) deflection from the center plug-in compartment or time base deflection from the righthand compartment. In a typical application, 5A15's are installed in the left and center compartments and the modified 5B10 in the righthand compartment. In L vs R mode, the left 5A15 drives the vertical deflection and the center compartment 5A15 drives the horizontal deflection. In normal mode, the 5B10 drives the horizontal deflection and either or both 5A15s drives the vertical deflection for single or two trace operation. Installation of two 5A14's allows four simultaneous X-Y patterns at once. This modification is used with multiplane balancing systems and in visual perception research.

SPS 015-0274-00 AC Switching Unit. This two-wide TM 500 Module (see Figure 6-4) is the output signal controller for the TEKTRONIX Model WP1100AC Ultrasonic Velocity Test System used for foundry quality control. It has many uses as an output device for TEK 31 Calculator-Based Systems used to control ac line powered equipment in cyclic testing, life testing, quality control testing, and any activity where some action must be taken as the result of the data obtained. The Ac Switching Unit is a device that can be used to randomly switch on (close) and switch off (open) up to 10 discrete, 115 V ac circuits under the remote control of a TEK 31 Calculator. Components included in the unit are 10 solid state relay switches,

Range	Dial Setting	Δ f for 5 Volts	% Deviation	Δ f per Volt
100-250 MHz	250	600 kHz	0.24	120 kHz
	100	45 kHz	0.045	9
50-100 MHz	100	250 kHz	0.25	50
	50	30 kHz	0.06	6
25-50 MHz	50	90 kHz	0.18	18
	25	10 kHz	0.04	2
10-25 MHz	25	125 kHz	0.2	25
	10	3 kHz	0.03	0.6
5-10 MHz	10	20 kHz	0.2	4
	5	2.5 kHz	0.05	0.5

TTL logic drivers, and the input logic decoding circuitry to operate those components from the calculator data and control bus. Each of these normally open switches makes contact at zero V ac and break contact at zero to minimize the switching transients associated with most relays.

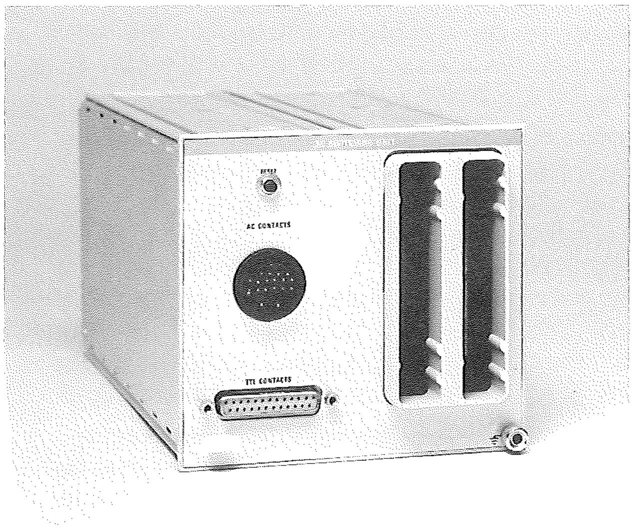

Figure 6-4. AC Switching Unit

Board construction includes two adjacent calculator I/O connectors that are accessed through the unit front panel by the TEK 31 I/O cable (PN 012-0498-01). The ac switches are connected through a front panel 28 pin connector and mating 15 foot cable (PN 012-0706-00). The TTL signals are available at a DB25S front panel connector.

The following electrical characteristics apply when the Ac Switching Unit is normally installed in a TM 500 Series Mainframe.

Output Characteristics
(each solid state relay switch)

Current (rms):	0.05 A min to 2.0 max
Voltage (rms):	12 V min to 130 V max
Frequency range:	50 Hz min to 70 Hz max
Contact voltage drop:	1.5 V max
Turn on time (60 Hz):	16 ms
Turn off time (60 Hz):	16 ms
Voltage across load at turn on (115 V ac):	0 ±6 V
Off state leakage (−30°C to 100°C):	10 mA (rms)
Voltage switch contact separation (turn off):	00.0 ± 12.0 V ac[1]

TTL Contacts

Turn on voltage:	3.0 V min to 3.8 V max
Turn off voltage:	0.8 V min to 1.0 V max
Loading:	1.6 mA min/max

[1] Load voltages less than 90 V ac (rms) will slightly degrade the zero voltage switching performance.

6-3. Custom Module Construction

The wide variety of modules and mainframes make the TM 500 family a natural for the fabrication of test sets tailored to specific applications. Often, these applications require just one additional custom module for a specific requirement. These modules seldom are required in large quantities and often are simple clean up modifications or convenient cable terminations, or adjustment potentiometer-switch combinations. Accordingly, blank plug-in construction kits are available. A typical kit is shown in Figure 6-5. These kits are available in three forms:

1. PN 040-0652-03 Blank Plug-in Kit (one wide)
2. PN 040-0754-04 Blank Plug-in Kit (two wide)
3. PN 040-0803-04 Blank Plug-in Kit with power supply (one wide)

These kits contain the complete hardware and sheet metal parts, the printed circuit board, and assembly instructions. Some notes on power supply designs and circuit precautions are included. The exploded view drawing shows the assembly of the one-wide unit.

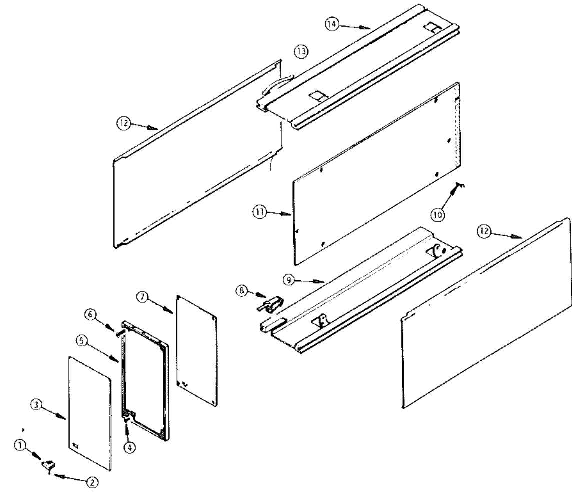

Figure 6-5. Blank Plug-in Kit 040-0652-03

Components making up the PN 040-0652-03 Blank Plug-in Kit (one wide):

Item	Quantity	Description	Tek Part Number
1	1	Knob, latch	366-1690-00
2	1	Panel, front	333-1483-00
3	1	Screw, 2 x 32 x 0.250 FH	213-0254-00
4	1	Subpanel, front	386-2402-00
5	4	Screw, thread forming No. 6 X 0.375 FH	213-0229-00
6	1	Subpanel, back	200-1273-00
7	1	Release bar	105-0718-00
8	1	Retaining latch	105-0719-00
9	1	Frame section, bottom	426-0724-00
10	4	Screw, thread forming No. 6x0.31 PH	213-0146-00
11	1	Circuit board	388-3490-01
12	2	Shield, electrical (side covers)	377-1399-00
13	1	Spring, electrical ground	214-1061-00
14	1	Frame section, top	426-0725-00

The two-wide kit, PN 040-0754-00, contains two circuit boards and uses a somewhat different fabrication procedure, as shown in the instructions included with the kit. Another variation on the one-wide kit is PN 040-0803-00, which includes the components to fabricate a simple set of three power supplies on the back of the special circuit board. This added convenience should greatly shorten the time to fabricate simple bread board circuits.

The 5000-Series Oscilloscope also has a blank plug-in kit, PN 040-0818-00, which is quite similar but uses a different printed circuit board and grounding fingers. Note that the 5000-Series Mainframes were designed as oscilloscopes, not instrument power supplies as was the TM 500 Mainframe, so the current available is smaller and varies with the 5100 or 5400-Series Mainframes. Also, the internal pin assignments for the 5000-Series are much different from the TM 500 and care should be exercised to avoid damage by interchanging fabricated modules. The quickest way to fabricate a special display module is to use the 5A24N module. This module contains basic circuits, and one half of the circuit card is blank. Also, the 7A17 is available for 7000-Series Oscilloscope applications in which a special module is required.

NOTE: No engineering services are available at Tektronix for fabrication of custom modules.

6-4. Blank Plug-in Construction Notes

To further facilitate the fabrication of custom modules by customers, Tektronix publishes a series of construction notes and other materials. The following is a short description of some of the construction notes available from local field offices.

Telephone Relay Power Supply 48 V 1 Amp (AX-3342). This single sheet application note gives the schematic, parts list, and component layout for a very useful relay power supply.

Suggested Power Supply Circuits for the TM 500 Blank Plug-in Kit (A3303-1). Complete guide to power supply circuits including those using discrete components, operational amplifiers, and integrated circuit regulators. A total of 37 different regulator circuits are shown using standard commercially available components to achieve a wide variety of voltage forms in the standard blank plug-in. This is a basic design tool for your own custom module designs.

60-Hz Notch Filter (AX-3415). This is about the simplest circuit design you can ask for. It uses the technique of prepackaged functional modules to solve common instrumentation problems. The most persistent and annoying problem is the effects of 60Hz power line pickup. It is possible to buy an extremely sharp notch filter from several different vendors and install it in this module. The part number 783RQ10-60 for 60 Hz and part number 783RQ10-50 for 50 Hz from the FDI Company (Haverhill, Mass. 01830) will provide a 70 dB notch at 60 Hz to eliminate this hum from the signal. It has wide application in instrumentation and the total cost, when you fabricate the unit with this kit, is far below any manufacturers' cost.

Analog Multiplier (AX-3416). Some special instrumentation and data reduction requirements dictate the multiplication of two analog signals to obtain a useful display. This construction note uses a high quality, prepackaged analog multiplier module and standard components in a TM 500 Blank Plug-in to make an exceptional analog multiplier module useful in instrumentation systems.

Thermal True RMS Converter (AX-3418). There are many applications in which custom dictates an rms amplitude display, and there are applications that demand an accurate rms converter. The design shown in this construction note is one of the most accurate units available today. It is far superior to the simple operational amplifier computing units, which are limited by crest factors. Complete performance data are included.

Medical Isolation Amplifier (AX-3417). This construction note addresses the very sensitive issue of isolating people from electrical shock while obtaining useful data. A secondary problem of obtaining very low level signals in the presence of high common-mode signals, such as 60-Hz pickup, is also addressed in this application note. Two companies (Burr-Brown and Analog Devices) have developed isolation amplifier modules of medical quality. This construction note shows how to package those units in the TM 500 Mainframes.

Digital Enhancement for Oscilloscope Measurements (AX-3475). This construction note addresses the problem of adding digital time and amplitude readout to any oscilloscope. It uses a technique of cascaded sample and hold integrated circuits to capture a fast oscilloscope trace signal to the relatively slow digital voltmeter. The note includes layouts for both printed circuit and hand wiring, and application information for a range of oscilloscopes.

If your custom module application will use the rear interface feature to interconnect your modules, there is a complete book available to assist you. The TM 500-Series Rear Interface Data Book, PN 070-2088-03, contains data on all standard TM 500 module interface characteristics. This feature greatly enhances the value of the resultant test set to the user because of the elimination of front panel cables.

6-5. Non-Tektronix Commercial TM 500 Modules.
There are a number of other manufacturers of TM 500-compatible modules for sale. This paragraph lists these manufacturers and some of their products. These companies offer both TM 500-compatible modules, and TM 500-based test sets that are specifically tailored to given industry conditions. The specialized expertise of the companies in these applications adds further value to the TM 500 concept. These companies represent areas of ultrasonics (both medical and industrial), digital logic, data acquisition, and data display. The list of ultrasonic modules and test sets is very complete and very impressive in the advance detection and display techniques used by these vendors. This total list is not as complete, but includes only those who are distributing data sheets widely. A number of transducer and systems manufacturers fabricate TM 500 modules for their own use. Also, a number of companies make interface modules for digital data acquisition systems and specialized cabling interfaces.

Description	Model	Mfgr.
Ultrasonic Modules:		
Pulser	MP203	MetroTek
Pulser, High Energy	MP 215	MetroTek
Pulser-Receiver	XP/R-1	Xenotec
Pulser-Receiver	XP/R-2A	Xenotec
Pulser-Receiver	NDT-142RF	Nortec
Receiver	MR101	MetroTek
Gate	NDT-144	Nortec
Delayed Linear Gate	XLG-1A	Xenotec
Delayed Linear Gate	XLG-2	Xenotec
Stepless RF Signal	MG 701	MetroTek
Gate	NDT-144	Nortec
Delayed Linear Gate	XLG-1A	Xenotec
Delayed Linear Gate	XLG-2	Xenotec
Stepless RF Signal Gate	MG 701	MetroTek
Dual Window Generator	AE 106	Automation Engineer
Variable Gain Amplifier	XVG-1	Xenotec
Intervalometer, Echo	XEI-1	Xenotec
Scale Factor Velocity	NDT-145D	Nortec
Peak Detector	XPD-1	Xenotec
Marker/Video	XM/V-1	Xenotec
Pulse Converter (Peak)	XPD-1	Xenotec
Analog Quantizer	XAQ-1	Xenotec
Sector Display	XDC-1	Xenotec
Display	NDT-141	Nortec
Isometric Projection/ Trace Rotator	M3D-802	MetroTek
RF to Video Converter	XVC-1	Xenotec
Other Modules:		
Description	Model	Mfgr.
Custom Plug-In Kit	M100	MetroTek
Clock Generator, 4 Channel, 50-MHz	PI-100A	Pulse Instrument Company
Dual-Channel Clock Generator	PI-110	Pulse Instrument Company
Word Generator, 4 Channel, 50-MHz	PI-10	Pulse Instrument Company
Interface Driver, 4 Channel, 5 V	PI-400	Pulse Instrument Company
Breadboard Plug-in	PI-910	Pulse Instrument Company
Data Acquisition System—	DT-2007	Data Translations
Dual Channel −31	(TM 500)	
DAC-Point Plotter, Dual	DT-212 (TM 500)	Data Translations
Magnetometer, Electronic	A101	Superconducting Technology, Inc.
Logic Analyzer	Logi-corder 8	Scanoptic

Real Time Clock	—	P. K. Enterprises
NBS Frequency Standard Receiver	8162	Spectracom
NBS Frequency Standard Receiver	8163	Spectracom
Phase Comparator	8150	Spectracom
MOS/CCD Driver	PI-451	Pulse Instrument Company
Time Interval Gate	MG 703	MetroTek
Quad Gate Multiplexer	MG 704	MetroTek
Isolation Amplifier	TMN-3A-ECG	Otrona
Isolation Amplifier	TMN-5A-EEG	Otrona

Ultrasonic Test Sets:

Nortec
NDT-140-3 Ultrasonic Test System (Laboratory)
NDT-140-6 RM Ultrasonic Test System (Rackmount)
NDT-140-5 Ultrasonic Test System. (Portable)

Holosonics
System 200 Pre-select 3D Display Ultrasonic System
System 200 Real-Time 3D Display Ultrasonic System
System 400 Hol-Scan Ultrasonic System

MetroTek
M-Series 101/203/502/515 Ultrasonic System
M-Series 101/203/502/505/515 Ultrasonic System
Iso-Scan 802/504/701/101/203/506 Ultrasonic System
Iso-Scan 802/801/701/101/203/515 Ultrasonic System

Xenotec
Model UR-1 Ultrasonic Radiometer System
Real Time Ophthalmic Scanner System
Automatic Ultrasonic Attenuation Measurement System
Differential Echography System

Logic Test Sets:

Scanoptik-Logic Analyzer System 515
Pulse Instruments—4 channel Logic Test Source TM 503

Manufacturers Address and Telephone Number List:

1. Pulse Instruments Co.
   P.O. Box 1655
   San Pedro, CA 90732
   (213) 541-3204
2. Data Translations, Inc.
   109 Concord St.
   Farmington, MA 01701
   (617) 879-3598
3. Xenotec, Ltd.
   244 West Patrick St.,
   P.O. Box 247
   Frederick, MD 21701
   (301) 694-9494
4. Holosonics, Inc.
   2400 Stevens Drive
   Richland, WA 99352
   (509) 946-7641
5. Spectracom Corp.
   1667 Penfield Road
   Rochester, NY 14625
   (716) 381-4827
6. MetroTek, Inc.
   80 Wellsian Way
   Richland, WA 99352
   (509) 946-4778
7. P.K. Enterprises
   910 Robertson Road
   Sharon, PA 16146
   (412) 346-3772
8. Scanoptik, Inc.
   P.O. Box 1745
   Rockville, MD 20850
   (301) 977-9660
9. Nortec, Inc.
   3001 George Washington Way
   Richland, WA 99352
   (509) 943-9141
10. Central Echo Labs
    Seattle, WA
    (206) 622-1331
11. California Cedar Products Co.
    P.O. Box 8449
    Stockton, CA 95208
    (209) 931-2448
12. Superconducting Technology, Inc.
    1400 Stierlin Road
    Mountain View, CA 94043
    (415) 964-4104
13. Automation Engineering
    3621 Marine Road
    Toledo, OH 43609
14. Otrona Corp.
    Box 3189
    Boulder, CO 80307
    (303) 449-8592