Testing The Behavior of Structures

REPRINTED FROM **TEST**

By Robert W. Lally
PCB Piezotronics, Inc.
Buffalo, N.Y.

BIG THINGS ARE happening today in the field of mechanical technology. Massive inertial dampers atop skyscrapers reduce swaying in the wind by modifying the structural behavior of the buildings. Cars are being tested with hammers similar to the way doctors test reflexes. Oscilloscopes display results in easy-to-interpret, animated, 3-dimensional models. Electrocardiogram-like instruments check vital machine processes. Today it is common practice to test the behavior and monitor the health of mechanical, hydraulic, pneumatic, and acoustic structures—using procedures called modal analysis, signature analysis, and modeling.

Behavior testing and health monitoring technology is proving to be of great value. Knowing more about the behavior of structures is especially important where energy consumption, safety, comfort, expensive materials, or failures are involved. Reducing the structural weight of cars improves fuel economy. Checking the integrity of structures or actual behavior against norms guards against catastrophic failures. Testing and modifying structures can often lower noise and vibration pollution. Behavior testing can also help improve functioning, prolong life, detect faults, diagnose troubles, save material, establish norms, search resonances, reduce troublesome interaction, prevent injuries, and improve comfort.

Knowledge of the function, structure and behavior of things enables engineers to predict what will happen in service and how neighboring objects will interact. Insight into behavior helps diagnose troubles and often suggests ways of modifying a structure to improve its functioning. One way to obtain this knowledge and insight is to construct behavioral models from experimental data. The resulting graphical models make it relatively easy to visualize what is happening in complex mechanical structures. The task of behavior testing requires considerable judgment, skill, and experience. The technology involves the nature and behavior of models, exciters, sensors, and computers.

The Nature of Things

It is the nature of structures to transfer force and motion; to deflect, vibrate, resonate, interact, and conduct sound. This behavior often annoys or destroys. Usually it is beneficial.

It is the nature of things to resonate. Cyclical, oscillatory behavior is related to the properties of matter. Reacting to force, structural characteristics (inertia, elasticity and damping) "impede" or "allow" motion, imparting an inherent "mobility" to structures. Since inertia and elasticity impede motion in different ways and because elastic deflection moves mass, structures resonate at damped natural frequencies. Damping occurs as structural (proportional to displacement), viscous (proportional to velocity), or coulomb friction (non-linear). The geometry associated with a resonant mode of behavior is called a mode shape.

It is the nature of structures to interact. Interaction between structures occurs as energy transferring transactions involving a potential variable (force) and a flow variable (motion). These two inseparable variables always occur together and their product is mechanical energy. The amount of interaction depends upon the transactional (driving-point-impedance) characteristics of the structures.

Testing Behavior

Mechanical structures function to transfer force and motion (or not to). Testing this functional transfer behavior in controlled transactions is called behavior testing. It involves exciting the structure, measuring the stimulus and response and computing the behavior characteristic and patterns. Health monitoring usually involves signature analysis of measured variables (determinates) on operating machines. Actual behavior is compared against baseline (original) or normal behavior. Changes and unusual vibration or noise patterns often signify impending mechanical failure.

Exciters

Behavior testing employs sinusoidal, random, step, or impulse forces to excite the structure. Each method has advantages and limitations. Sinusoidal and random methods using electro-magnetic and hydraulic vibrators are more precise and controllable but require fixturing. The impulse method using hammers is quick and convenient, especially for field, diagnostic, and preliminary testing. Hitting a structure with an instrumented hammer excites it with a nearly constant force over a broad frequency range. Structures assumed to be linear and reciprocal are tested by exciting at one point and measuring the response at all others or by measuring response at one and exciting at the others. Non-linear structures and those with multiple or high density resonant modes may require special random multi-point vibrator excitation or multiple impact hammer techniques.

Health monitoring is generally concerned with the response of the structure to unmeasurable forces generated within or without the machine or structure during normal operation. From response data, it is sometimes possible to determine behavior characteristics of structures or to identify sources of noise and vibration.

Sensors (Transducers)

Sophisticated stress-gage sensors structured with rigid quartz crystals and microelectronic isolation amplifiers are often employed in behavior testing to measure both the stimulus (force) and response (motion). The exceptional stability, repeatability, and wide dynamic range (10,000 to 1) matching that of most analyzers accounts for the popularity of quartz sensors in behavior testing. Figure one shows typical quartz sensors. Im-

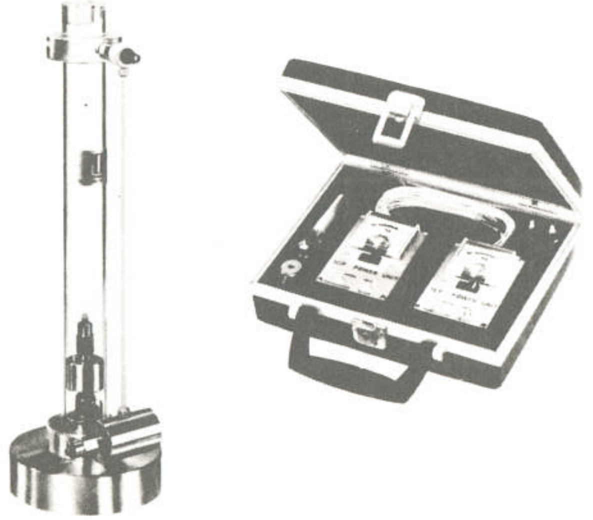

FIG. 1—Instrumented structural model.

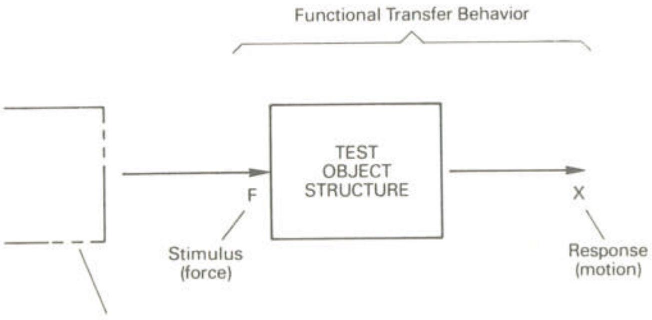

FIG. 2—Behavior testing.

pulse hammers incorporate special rigid force sensors. General purpose force sensors or special high sensitivity force links and flexible wire rods (quills) couple vibrators to test objects. Impedance sensors measure both the force and motion at the driving point. Following Newton's laws, motion-sensing accelerometers measure the force to automatically give their seismic mass the same motion as the point on the structure of the test object where they are attached.

Impulse behavior testing at low frequencies (below 20Hz) usually requires ultra-sensitive force and motion sensors and super-soft hammer tips. In some constrained structures where elasticity dominates the low frequency behavior, it is sometimes possible to extrapolate the dynamic stiffness characteristic to obtain static stiffness. Since sensors (transducers) are mechanical structures, they obey the same physical laws as the test object and behave accordingly.

Computers (FFT Analyzers)

Modern electronic computers, especially FFT analyzers, play a vital role in behavior testing and health monitoring. They function to decompose time-varying signals into their frequency components, to compute the ratio of stimulus and response (transfer function), to extract modal parameters (mass and damping), and to construct graphical models. With these powerful sophisticated tools, it is relatively easy to test, analyze, model, and modify (if necessary) the behavior of complex mechanical structures. In advanced modal analysis, the computer constructs animated 3-dimensional graphical models from experimental test data. Since modeling involves few simplifying assumptions, the resultant model is usually a good approximation of the behavior of the actual test object. Modern computers also employ many different techniques of filtering, windowing, zooming, and averaging (synchronous, time domain, and frequency domain) to enhance the quality of the results. Computers readily calculate velocity and displacement data from acceleration measurements.

Structural Models

Actual test objects and sensors are complex 3-dimensional mechanical structures with multiple resonances and mode shapes. At low frequencies test objects act like rigid or elastic bodies, depending upon their constraints (boundary conditions). At high frequencies these same objects conduct sound (stress-strain waves). In between they behave as lumped-constant finite element structures. A simple structural model (fig. 1) demonstrates these three basic modes of behavior: rigid body, structural, and acoustic. Components of this model assemble into a pendulous mass or free falling rigid body, a finite-element spring-mass seismic structure, and a distributed parameter bar. Figures 3, 4, and 5 present typical test results of these structures. They show both the time-varying signals (oscilloscope results in time domain) and their frequency components (FFT ana-

Test Technology Today

Test technology today plays a vital role in advanced mechanical engineering endeavors such as signature analysis, modal analysis and modeling. Today modern digital computers and analyzers construct realistic behavioral models from test data. Such animated graphical models let you see what is actually happening in complex mechanical structures. Behavioral models of buildings, machine tools and spacecraft structures are widely used. Dynamic behavior models of cars have even made the TV commercials.

Once a structure has been designed and built, behavioral models created from test data present more realistic behavior patterns than analytical or mathematical (finite-element) models. However, finite-element models still remain a powerful design tool and give valuable insight into behavior modification possibilities.

Although many people have been involved, special credit for developing and promoting mechanical behavioral technology goes to Dr. Dave Brown, Professor Ivan Morse and associates at the University of Cincinnati. A number of computer and analyzer companies have also been intimately involved.*

At a recent SESA (Society for Experimental Stress Analysis) meeting in Wichita, Kansas, the winner of the prestigious Murray award, Dr. Robert Mueller, presented a technical paper on the value of constructing behavioral models from test data. Dr. Mueller manages the Institute for Structural Modal Analysis at the University of Stutgart, West Germany. At the same meeting, Peter K. Stein, president of Stein Engineering Services, Tempe, Arizona, astutely observed that only the actual test object structure knows all of the differential equations, all of the boundary conditions and all of the solutions.

Good models depend upon valid test data and good measurement engineering practice. Since behavior testing technology applies to the sensor structure as well as to the test object structure, it offers the opportunity for a common approach and terminology, understood by both test and design engineers. When testing any object, it makes sense to talk about its function, structure, and behavior (functional transfer or transactional). Test technology is destined to play an increasingly important role in mechanical engineering projects.

** Such companies would include EMR, GenRad, Hewlett-Packard Nicolet Scientific, Norland, Princeton Applied Res., Rockland, Spectral Dynamics, Structural Dynamics, Zonic, et al.*

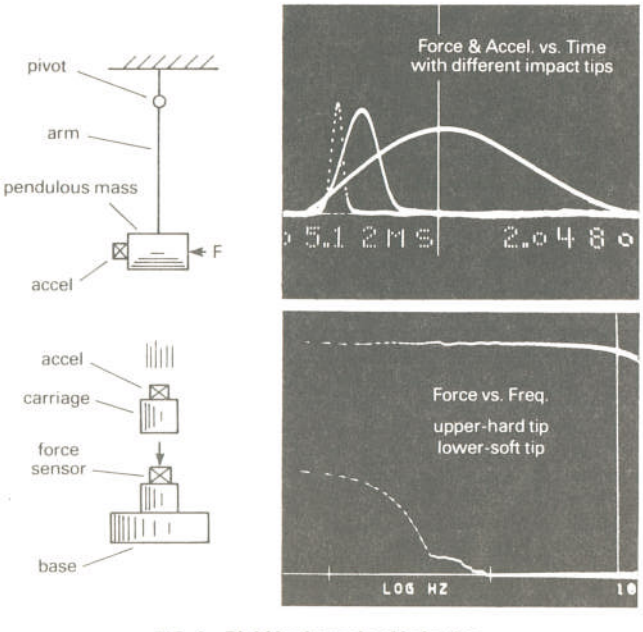

FIG. 3—Rigid body mode of behavior.

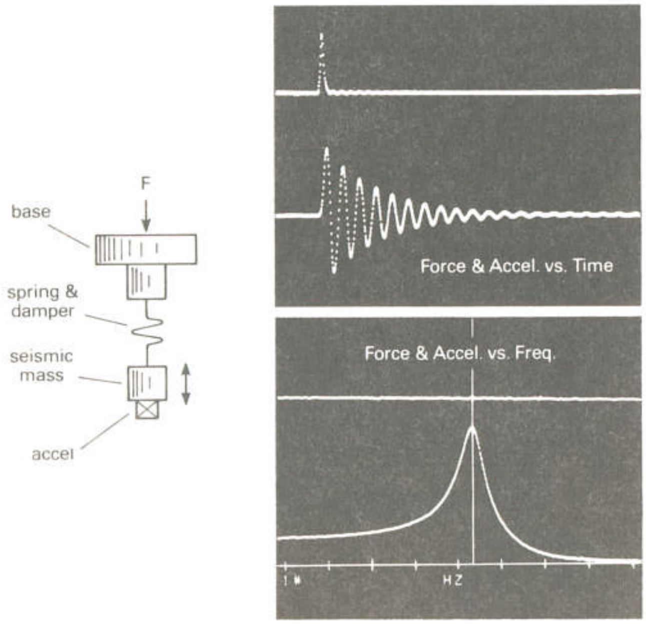

FIG. 4—Structural mode of behavior.

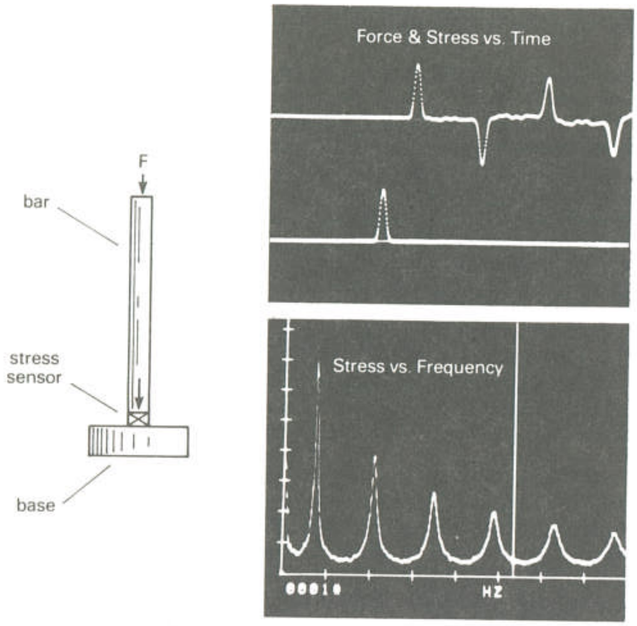

FIG. 5—Acoustic mode of behavior.

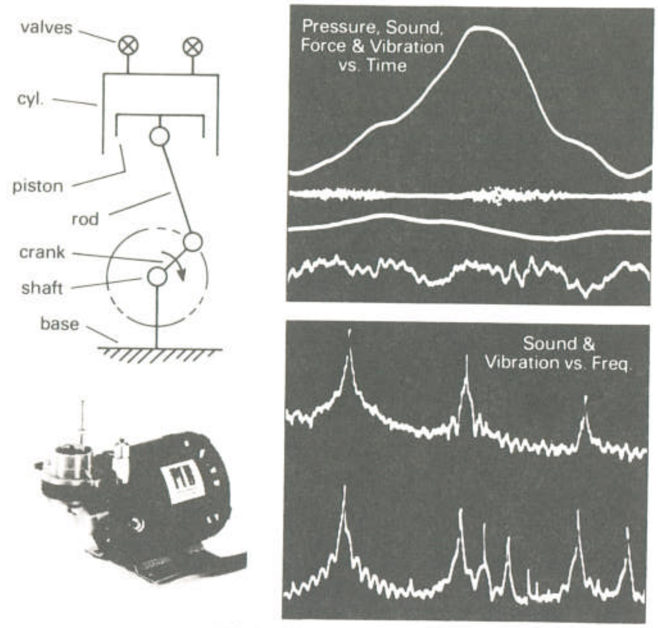

FIG. 6—Signature analysis.

lyzer results in frequency domain).

Rigid Body Modes

At low frequencies, a solid steel cylinder (mass) hit with a hammer or impacting a base behaves like a rigid body, obeying Newton's laws of motion. Superimposed force and motion signals in Figure 3 show that at any instant in time, force/mass is numerically equal to acceleration, verifying Newton's law. Figure 3 results also show that different impact tips vary the pulse width and frequency content of the impact force. In more complex, lightly sprung structures the resonant pendulum-like behavior is called a rigid body mode.

Structural Modes

A mass on the end of a threaded nylon rod (spring and damper) forms a simple lumped-constant, spring-mass structure (Fig. 4). When disturbed by an impulse forcing function (hammer tap), the seismic mass resonates at its damped natural frequency while its sinusoidal motion exponentially decays to zero. In the frequency domain, this behavior is that of a classical single-degree-of-freedom, second-order mathematical model. Finite element analysis and modal modeling assume that complex mechanical structures are made up of a multiplicity of these basic systems. The behavior illustrated approximates that of many sensors (transducers) and is called a structural mode. It could be either a general or local structural mode.

Acoustic Modes

At high frequencies mechanical structures function to transfer force and motion as stress-strain waves (sound). A simple long round bar is a distributed spring-mass model. The particular vertical bar in Figure 5 has one end fixed and the other free to demonstrate sound propagation in solids and other acoustical phenomena. Tapping the free end with a mini-hammer sends a compression stress-strain wave form traveling down the bar at the speed of sound in the material. The original compression wave reflects upright as a compression wave from the fixed end and then as a tension wave (inverted) from the free end, causing it to pull on the stress sensor on the second pass. This process continues until the energy is dissipated by friction. Such "Hopkinson" bars are used for impulse testing, calibrating sensors, measuring properties of materials, and researching fast strain effects.

Signature Analysis

Time domain and frequency domain signatures from a small compressor are shown in Figure 6. The time-varying signals include measurements of cylinder pressure, sound (noise), force, and vibration. The FFT record shows the frequency content of the vibration signal. The frequency components of this signal relate to rotational speed (orders), power line frequency, and

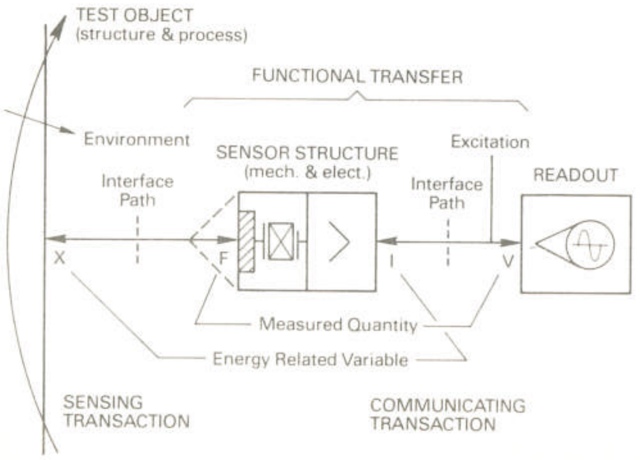

FIG. 7—Transduction process.

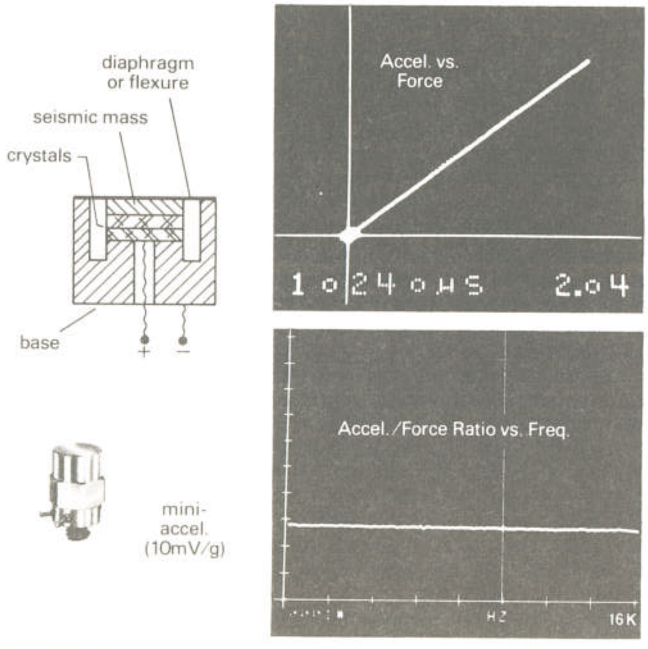

FIG. 8—Sensor behavior.

structural resonances (mechanical and acoustic). Behavior testing (modal analysis) of operating machines is difficult because of the multiple sources of force and noise. Also, modulation by interacting structures can complicate the interpretation of signatures by suppressing fundamentals and leaving only the side bands. Because of the direct relationship between unbalance forces and acceleration, recent tests with FFT analyzers indicate that acceleration measurements are superior to displacement sensing for balancing.

Transduction

Good modeling results depend upon good measurements. Good measurements require some knowledge and understanding of the structure and behavior of the measuring instruments. Measuring systems (Fig. 7) are composed of elements arranged in an organized structure and physically separated into component blocks: a sensor (transducer), a modifier (for signal and power), and a readout instrument. To complete the feedback process, the measured result is compared with the test objective and corrective controlling or adaptive action is taken according to the difference.

Transduction employs an energy transfer process to sense and communicate information. In the system modeled in Figure 7, double-ended arrows depict these energy-transferring transactions. Between neighboring components, a communicating transaction to one is a sensing transaction to the other.

One basic principle of transduction is the conservation of energy. Since a measuring transaction extracts energy from the source, it will always in some small way change the process being tested and the quantity being measured. For valid measurements when measuring a flow or motion variable, select a sensor that readily allows motion. When measuring a potential or forcing variable, choose a sensor that greatly impedes motion. In terms of transactional behavior, use a measuring instrument with low or high input impedance relative to the output impedance of the source. For example, in the electrical transaction in Figure 7, a unity-gain isolation amplifier transfers the ultrahigh impedance voltage signal from the crystals to the relatively low input impedance of the readout. The purpose of the measurement, research, test, control, or calibration imposes different tolerances on this interaction effect.

The structure of the interface path between components also affects the behavior of the system and modifies the information being communicated. For example, the behavior of an accelerometer mounting structure, especially if it is wax, putty, or adhesive, ought to be checked to insure that it is not adversely affecting the measurements. Flat, precision interface surfaces clamped together with an elastic stud transmit force and motion at high frequencies.

Like humans, measuring instruments are sensitive to all environmental factors, as well as to the quantity being measured. Environmental changes generate spurious output signals and affect the functional transfer behavior. Insulating, isolating, and compensating reduce environmental effects.

In performing their function, instruments and computers, obeying the laws of nature, also tend to delay, distort, and degrade the information being transferred. Processing adds noise. This is another reason why it is important to start with good measurements.

Sensor Behavior

Sensors are mechanical structures subject to behavior testing and modal analysis. They are elastic structures that function to transfer deflection caused by force (stress) into an electrical signal more convenient for communicating, displaying, or processing. Within specified ranges, ideal sensors treat all amplitudes and frequencies the same. Behavior objectives for sensors are simple straight lines: a straight line relating output and input and their ratio (sensitivity) with frequency. Test results presented in Figure 8 show that rigid quartz stress-gage sensors with built-in isolation amplifiers approach this ideal behavior over very wide amplitude and frequency ranges. Computers can correct for deviations from ideal when the behavior is repeatable. The useable frequency range of sensors is generally well below the first resonant mode. Also, sensor behavior should not appreciably delay the signal, alter the structure of the test object, or change the quantity being measured.

Many sensors can be represented by a simple seismic model—the familiar basic finite-element spring-mass structure. In this structure, the crystals perform a dual function: they act as a precision spring and they also generate the electrical signal. The basic structure illustrated in Figure 8 is sensitive to pressure, force, and motion. Practical designs, however, emphasize sensitivity to only one of these variables. Sensor elements experience both force and displacement (stress and strain) during the measuring transaction. They are classified as stress or strain gage types, depending upon which parameter the elements experience the most. Phonograph cartridges are examples of piezoelectric strain gages. Stress gage types generally excell in behavior testing and shock or vibration applications. To transducer manufacturers, sensors are test objects subject to modal analysis.

Sensor Calibration

In behavioral terminology, cailbration is testing the functional transfer behavior of a sensor in controlled transactions and environments. Behavior objectives are straight lines. The impactor model illustrated in Figure 1, combined with a dual-channel digital oscilloscope or analyzer, calibrates sensors and hammers. Impulse vibration cailbration of an accelerometer involves lightly impacting a known mass on a stationary force sensor. Shock calibration involves dropping a known mass from greater heights. Hammer calibration involves hitting an instrumented stationary or pendulous mass with the specific hammer structure to be used. Because of inertial effects, the force sensor in the hammer structure experiences a different force from the one occurring at the hammer and test object interface.

Ideal Structures

Behavior goals and objectives for structures vary with their function. However, the human bone serves as an ideal model for many structures. Because of the light weight and composite structure of the human bone, moving it requires little energy. It is strong and rigid enough to perform its function, yet flexible enough to absorb high impacts. Furthermore, it signals trouble and is self healing. Healthy joints also absorb considerable impact energy, yet transmit force adequately. An ideal structure often balances weight, strength, rigidity, flexibility, and energy absorption.

History

While some of the terminology, procedures, techniques, and instruments are new, behavior testing is not. In the distant past this technology appeared and evolved in a rather fragmented way under such terms as mechanical impedance, mobility, compliance, and measurement engineering. Behavior testing adapts the transfer function and impedance concepts of electrical and control engineering to mechanical structures. Since the advent of the digital FFT analyzer a few years ago, the technology has advanced rapidly. It has now advanced to a level where production line behavior testing is practical. NASA recently allocated $20,000,000 for modal analysis of the space shuttle. While many people have been involved, special credit goes to Dr. Dave Brown, Professor Ivan Morse, and associates in the mechanical engineering department of the University of Cincinnati. Years ago these people envisioned the value and potential of this technology and developed many of the practical procedures and instruments.

REPRINTED FROM **TEST**