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Closed-loop random vibration control of a shaker table with a microcomputer

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Electromagnetically actuated vibrating platforms designed for fatigue testing of assemblies have been available for some time. These platforms are primarily designed for extended duration, constant-amplitude sinusoidal excitation for stress testing of aerospace and military products, and are frequently available at considerably reduced prices. In the original design, operation was neither closed-loop nor capable of swept-frequency output. One of the objectives for this study is to design and renovate a used shaker table into a state-of-the-art vibration testing station. The methods by which such an electromagnetic force generator is converted for utilization as a closed-loop materials testing station is described. This paper also discusses using a microcomputer as a viable, cost-effective alternative for short duration tests as opposed to more sophisticated and costly equipment. For certain applications, a microcomputer can be configured into a dynamic vibration system to control the desired random vibration imposed on a structure. In this case, the control signal (a digital signal from the microcomputer) can be generated for a given spectral density function.

Key words: shaker table, random signal, data acquisition, control.

INTRODUCTION

An electromagnetic shaker is identical to a loud-speaker in a music system. An AC-carrying coil in a magnetic field generates the excitation. Force is transmitted through an armature assembly to the fixture, which supports the structure to be tested. An electromagnetic shaker creates clean sinusoidal vibrations as well as tightly controlled random vibrations with a prescribed spectral density function. The cost of an electromagnetic shaker system is usually expensive and increases with the shaker force rating.

Used shakers are frequently available through the military or aerospace industry at greatly reduced prices. Although these shakers are being replaced because of their age, in most cases they are in excellent condition except for their original power supply and control system. In this study, the original power supply or control system of the exciter was abandoned; only the exciter was retained. The result is an up-to-date and inexpensive closed-loop vibration material testing system. This system is used to study the effects of earthquakes and vibration on buildings, critical equipment qualifications, and auto and aerospace environmental simulation experiments.

RENOVATION OF A SHAKER TABLE

The electromagnetic force exciters were an excited-field design, originally supplied with variable-speed alternators, or high-power transformer-coupled amplifiers to power the driver coil, and with rotating DC sources for the field. The residual driver reactance was turned at each frequency by means of switched capacitors to match the output of the driver amplifiers. Very low frequency or DC operation was unavailable, and the operation was open-loop. In this study, the original power supply and control system of the exciter were abandoned, and only the exciter was retained. Power supply, field power supply, and a function generator were purchased to replace the old units. Custom-designed electronic control packages were designed and constructed. Detailed descriptions of these units are given in the following sections.

Original unit

The unit has a force output of 3336 N (750 lb) continuous duty and its total travel is 2·5 cm (1 in) peak-to-peak amplitude. The original design frequency range is 2–500 Hz in sinusoidal operation only.

The unit was originally driven by means of a rotating motor generator set as the DC field source and a variable-frequency motor alternator to excite the driver coil. These power sources do not adapt easily to solid-state control and are no longer easy to maintain. The exciter's original power supplies and control system components were excluded from this study, and only the exciter was retained.

Power supply

The driver coil is easily driven by a programmable DC power supply, if the supply can reach both source and sink currents. It is desirable to have bi-polar output voltage available, but it is not required if a second supply and bridge operation of the driver can be implemented. The programming speed, of course, must be appropriate for the desired frequencies of operation. The power supply was selected based on four-quadrant units (i.e. capable of operation with any combination of current and voltage polarities), which feature high programming speed and are easily interfaced. A unit that is in a voltage-programming mode operates the exciter very well. It produces 36 VDC for 10 VDC excitation, and the maximum current is 12 A.

Field power supply

The field windings are highly reactive, precluding any high frequency modulation of the field. A variable-output voltage DC power supply producing 0–300 VDC at 0–6 A was utilized for the field supply, but testing after installation indicated that a fixed-output unit would have sufficed. The field current originally specified by the manufacturer is quite near the magnetic saturation point, and there are no advantages in under-exciting the field. Full excitation of the unit requires 140 VDC from the field power supply at about 3·5 A.

Function generator

The function generator selected was a function/sweep generator, which allows swept excitation and external gating control. One experimental procedure utilized with this apparatus computes progressive sample deterioration by resonance; sweep capability facilitates those measurements. External gating permits sample stressing for predefinable numbers of cycles.

Electronics and control unit

The custom-designed electronics packages were constructed in a pair of rack-mounted enclosures with integral power supplies.

Connection of the two power sources to the actuator was performed in the power control unit, which contains the switching relays, interlocking, and over-voltage protection devices. The power control unit has both 'low power' and 'high power' settings. In 'OFF' conditions, both power sources were disengaged, and the actuator was disabled completely. In 'low power' mode, only the programmable power supply was connected to the actuator, without field excitation. In 'high power' mode, the field supply was also applied, and the full output force was available from the actuator. Some residual magnetic fields existed in the actuator without the field supply connected in 'low power' settings.

Controls and inputs for the power control unit

Functions as designed for the power control unit are given in the following:

EM off: de-energizes everything; puts unit in plugged state.
Start: energizes the driver coil, but not the field coil. The unit will move from the residual magnetic field, but no real force is available. The 'low power' indicator also illuminates.
High power: energizes the field coil allowing the full range of output power. The 'high power' indicator also illuminates.
Low power: de-energizes the field coil but does not drop out the driver.
Clear: resets the count on the cycle counter to zero. This does not reset the latch, which is set by the limit counter.
Reset: resets the 'limit reached' latch and reloads the limit datum.
Control chassis: the specimen under test is monitored with various transducers such as load cells, extensometers, LVDTs, and accelerometers. The transducers are conditioned by appropriate preamplifiers, the outputs of which are cabled to the control chassis.

The following functions are included in the control chassis:

(1) Preset gain range selection and zeroing of all of the preamplifier output signals.
(2) Adjustable limit detection for each of these signals and interlocking on disallowed levels of those limits, error signal amplitude, or power control unit error.
(3) Feedback selection allowing selection of control transducer.
(4) A three-mode (proportional/integral/differential) amplifier receiving electronic signals from the function generator and the feedback selector to provide the error signal to drive the power amplifier operating the sample actuator.

Additionally, the control chassis was designed to provide the analog instrumentation required for plastic strain computation, but this feature has not yet been required in the present work.

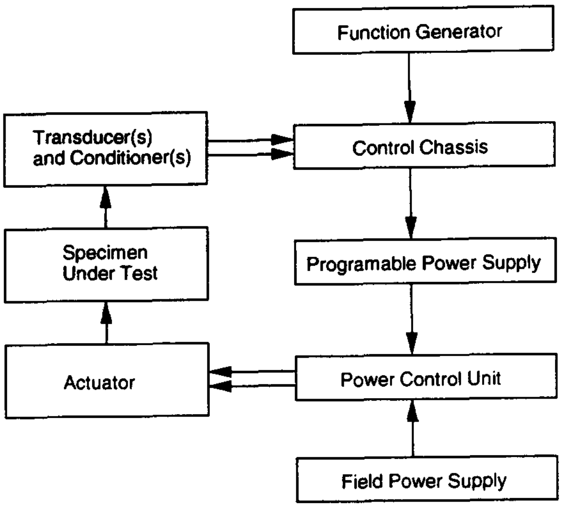

Fig. 1. Simplified block diagram of testing apparatus.

Altogether the operator was presented with 35 controls and indicators on the control chassis, but many of these needed no routine adjustment.

A simplified block diagram of testing equipment is shown in Fig. 1. The exciter can produce a force of about 340·5 kg (750 lb) which is shared between specimen stressing and acceleration of the combined mass of the specimen and the specimen actuator. The electromagnetic force generator will operate from DC to 500 Hz, and the programmable power supply (which drives the electromagnetic force generator) has a bandwidth of 1·8 kHz, which means that the upper frequency limitation of the exciter in a small signal operation is dictated by the electromagnetic force generator design itself. The unit will operate with a bandwidth in closed-loop fashion with typical transducers and conditioners, depending on their frequency response. A further limitation is the large reactive component of the driver input impedance (measured to be 5·8 mH_{Y_x}) at higher frequencies, lowering the energy-producing traction of the applied voltage. The unit can be operated as a closed-loop specimen exciter from DC to about 200 Hz at full travel and can be utilized as a low amplitude sweep generator over a somewhat wider bandwidth. The complete set-up is shown in Fig. 2.

RANDOM VIBRATION CONTROL

The incorporation of the microcomputer as the controlling component essentially developed a new, alternative cost-effective vibration system as shown in Fig. 3. In this system, Digital's modular instrument computer (MINC) was used as the input signal to the vibration system and also recorded the response. The computer's processing unit was a PDP-11/23^{TM} which contained a 64 K main memory with 256 K extended memory. For the vibration system, three modules were connected: a digital-to-analog (D–A) converter; an analog-to-digital (A–D) converter, and a clock. The converters used a 12-bit binary number. The desired digitized vibration signal was stored in the computer's memory and then output through the D–A converter. During the same scan, the response was recorded through the A–D converter. The clock provided the

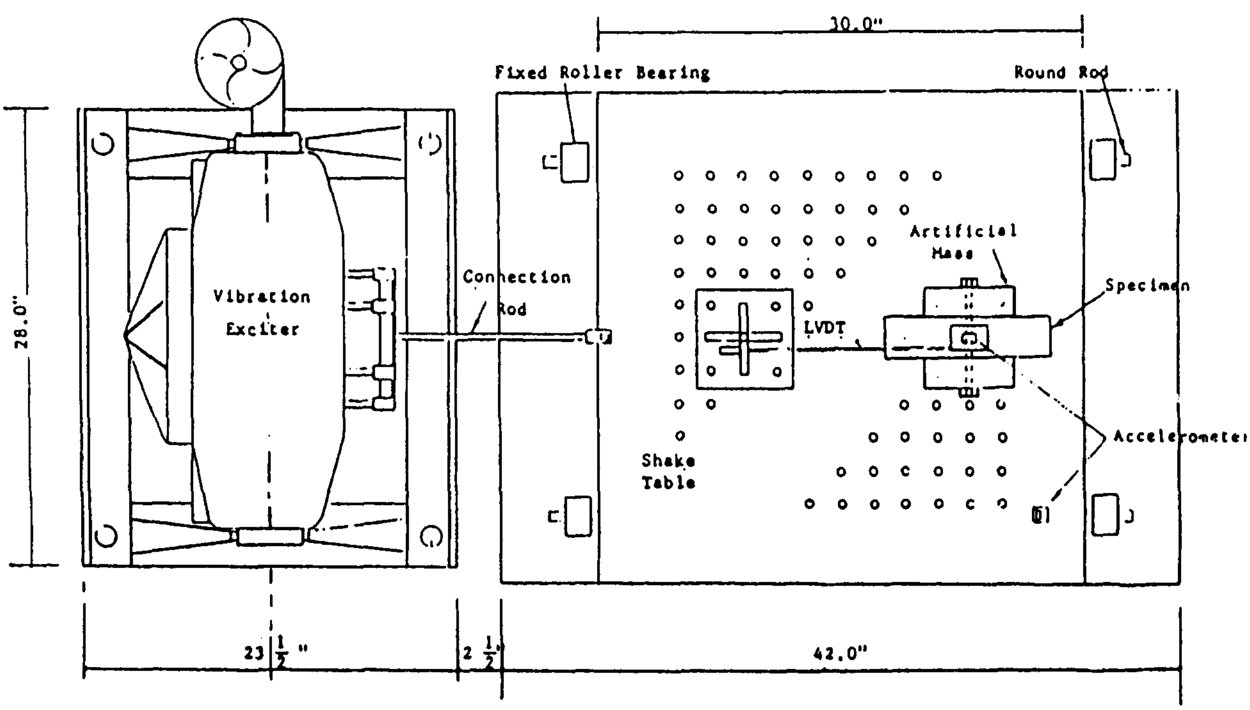

Fig. 2. Plan view of the vibration shaker table.

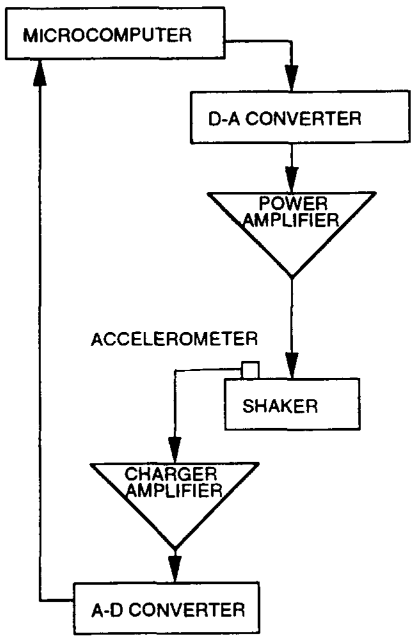

Fig. 3. Vibration system with microcomputer.

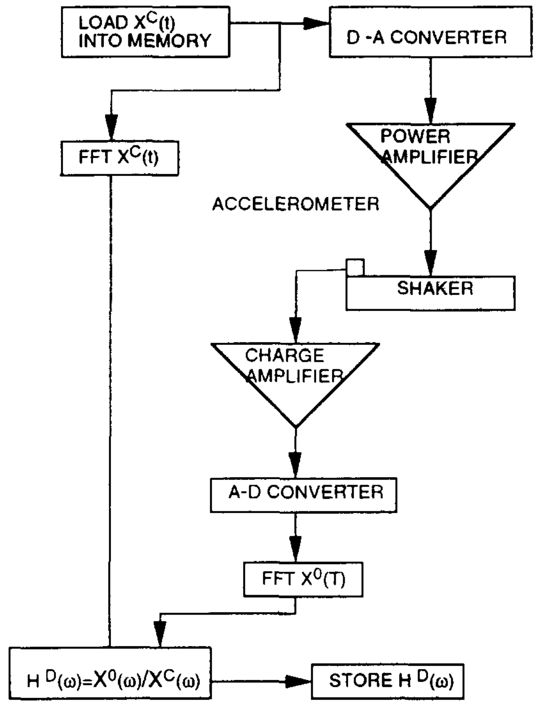

Fig. 4. Step 1: Determination of $H(\omega)$.

scanning rate. This configuration can digitally convert up to 10 000 points per second; however, only 2000 points per second were used.

Finally, some microcomputer converter card scanning rates decreased below acceptable levels when simultaneously outputting an analog signal and recording another analog signal. To increase the scanning rate, another data acquisition system was added to the vibration system to allow only the D–A converter to be used on the microcomputer. This type of configuration was set up using an ISACC 2000 data acquisition system by Cyborg. The ISACC 2000 contained a C-100 and an I-100 A–D converter card, which replaced the function of the A–D.

METHODOLOGY AND TESTING PROCEDURES

For a linear single-degree-of-freedom structure, the response can be determined in the frequency domain as:

$$Y(\omega) = H(\omega)X(\omega) \tag{1}$$

where $Y(\omega)$ is the response; $X(\omega)$ is the input; and $H(\omega)$ is the response function. If $H(\omega)$ is known, then an input can be determined for a desired response; that is:

$$X^{\mathrm{I}}(\omega) = [H(\omega)]^{-1}X^{\mathrm{D}}(\omega) \tag{2}$$

where $X^{\mathrm{I}}(\omega)$ is the input and $X^{\mathrm{D}}(\omega)$ is the desired response. Equation (2) provides the basis for controlling the shaker table by using the micro-computer.

For a driving signal to be calculated for a specific desired response, the response function must be determined in at least the frequency range of the desired response. The determination of $H(\omega)$ falls into two categories: first where the test specimen assumes no damage and second where the test specimen is damaged as the testing progresses.

The estimation of the response function takes advantage of the improved method proposed by Mitchell.[1] This estimation takes an average of the common estimator of $H(\omega)$, shown in Bendat,[2] along with a second estimator. Following the nomenclature

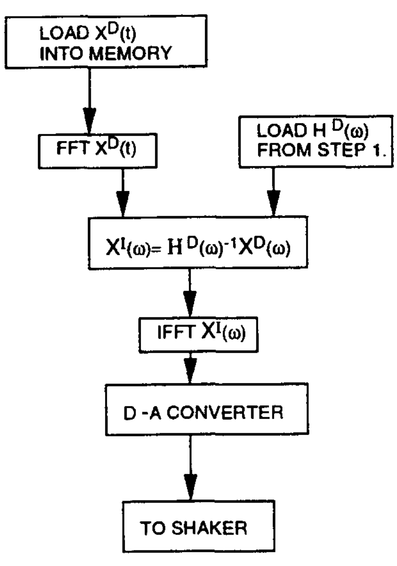

Fig. 5. Step 2: Determination of input signal for a desired response.

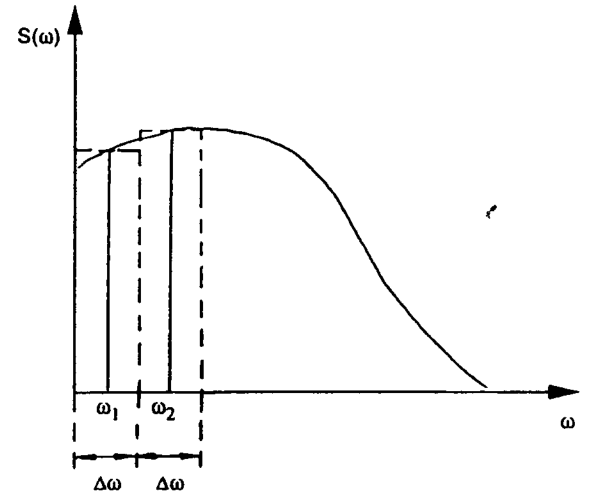

Fig. 6. Spectral density notation used in eqn (13).

of Mitchell, Bendat showed that the first estimator (common estimator),

$$H_1(\omega) = \frac{G_{xy}}{G_{xx}} \tag{3}$$

is less than or equal to the true transfer function. G is the auto- or cross-spectrum of one or two signals, respectively.

The second nomenclature,

$$H_2(\omega) = \frac{G_{yy}}{G_{yx}} \tag{4}$$

was shown to be greater than or equal to the true transfer function.

The transfer function used in deriving the driving signal is the average of $H_1(\omega)$ and $H_2(\omega)$:

$$H(\omega) = \frac{H_1(\omega) + H_2(\omega)}{2} \tag{5}$$

For the first category, the test specimen is assumed to be unchanged and the transfer function remains constant. The driving signal is calculated from:

$$D^n(\omega) = [H(\omega)]^{-1} X^n(\omega) \tag{6}$$

where $D^n(\omega)$ is the driving signal to produce the desired excitation, $X^n(\omega)$. The estimation of $H(\omega)$ was upgraded after each test with a new average. Using these assumptions, the following procedures were used for this category of test specimens (see Fig. 4):

(1) A reference signal, $x^n(t)$, was generated and loaded in the computer memory.
(2) The FFT of $x^n(t)$ was computed and the driving signal, $D^n(w)$, was computed using eqn (6).
(3) The driving signal was transformed to the time domain and fed to the shaker system through the D–A converter.
(4) The response was measured and used to compute $H_1^n(\omega)$ and $H_2^n(\omega)$.
(5) An average of $H^n(\omega)$ was computed after each test run and stored for future test runs.
(6) Steps (1)–(5) were repeated for each test run.

The second category of testing is for damageable specimens. Initially, a low input $x^1(t)$ was applied to estimate the first $H(\omega)$. This application prevented damage to the specimen. Secondly, as the specimen was damaged the $H(\omega)$ changed; therefore, a weighted average of $H(\omega)$ was implemented as the test runs were performed. The procedures were similar to the first category (see Fig. 5). Similar procedures have been used in the investigation of the concrete nonlinear response under earthquake excitation.[3–5]

SIMULATION OF DIGITAL RANDOM SIGNAL

A computer-generated waveform simulates a random process. The waveform is stored as a digital signal that is transformed into an analog signal by a digital-to-analog converter. The waveform is created for a specific stationary random process by correlating with its spectral density function, which allows applications for physical phenomena of stationary and special cases of nonstationary random processes.

A random process is classified by probability properties as stationary or nonstationary.[2,6] The mean value and the autocorrelation function were two properties necessary to classify the random processes in this report.

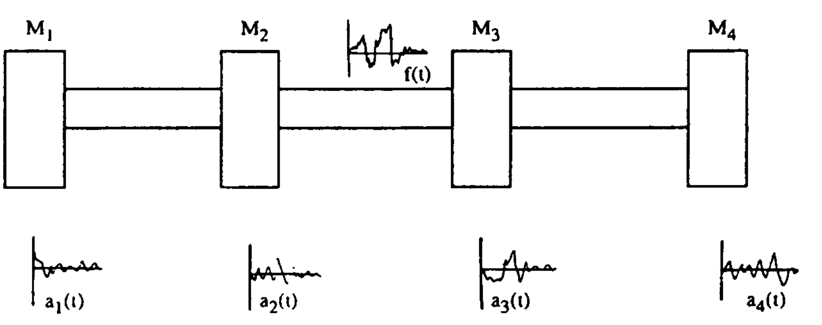

Fig. 7. Force identification specimen.

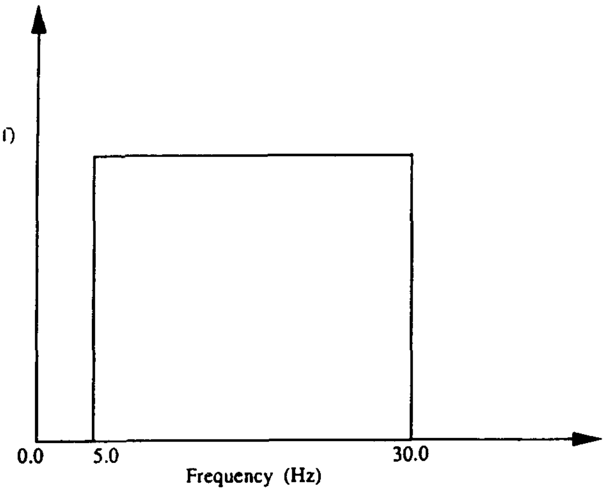

Fig. 8. Spectral density curve with bandwidth of 5–30 Hz.

For an ensemble of a sample function, $x_j(t)$, the mean value, $\mu_x(t_n)$, is computed by taking the value of each $x_j(t)$ at time t_n, summing the values, and dividing by the number of sample functions, N. The autocorrelation function, $R_{xx}(t_n, t_n + \tau)$, can be computed by taking the ensemble average of the product of values at two times, t_n and $t_n + \tau$. In equation form, these two properties are:

$$\mu_x(t_n) = \lim_{N \to \infty} \sum_{k=1}^{N} x_k(t_n) \tag{7}$$

and:

$$R_{xx}(t_n t_n + \tau) = \lim_{N \to \infty} \frac{1}{N} \sum_{k=1}^{N} x_k(t_n) x_k(t_n + \tau) \tag{8}$$

where x_k corresponds to a sample function; and N is the number of sample functions.

If either the mean square or the autocorrelation function varies as t_n varies, the random process is said to be nonstationary. If these two properties do not vary with time, the process is called stationary or weakly stationary. Stationary random processes are further divided into ergodic and nonergodic categories. The process is ergodic if the mean value and autocorrelation function along any one sample function are equal to the ensemble average. If the random process is not ergodic, it is called nonergodic.

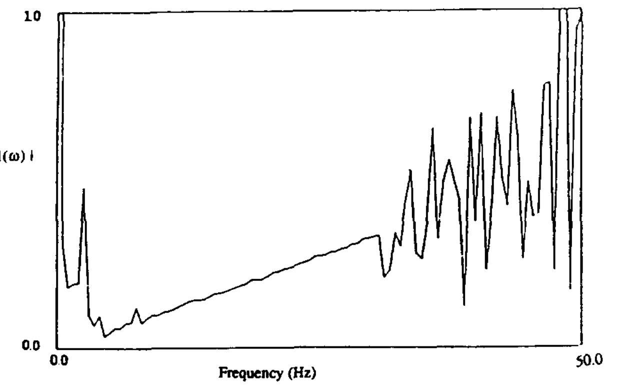

Fig. 10. Modulus of $H_1(\omega)$ for force identification set-up.

Pseudo or periodic random data simulate ergodic random processes by correlating to their spectral density functions. The spectral density function, $S(\omega)$, is the Fourier transform of the autocorrelation function. Assuming only stationary random processes, $S(\omega)$ is always positive and symmetrical around the y-axis.

The spectral density of a sine wave has a value at only one point. Using the spectral density function as the reference for a random process, a combination of sine or cosine waveforms will simulate the random process for experimental purposes. In particular, one group of cosine waveforms is:

$$x(t) = \sum_{j=1}^{n} C_j \cos(\omega_j t + \varphi_j) \tag{9}$$

where ω_j, $j = 1, \ldots, n$ are the band of frequencies; φ_j, $j = 1, \ldots, n$ are chosen to be uniformly distributed random variables in the interval $(0, 2\pi)$; and C_j, $j = 1, \ldots, n$ are equal to $2\sqrt{S(\omega_j)\Delta\omega}$.

The values of C_j, $j = 1, \ldots, n$ are derived by taking the $R_{xx}(\tau)$ of eqn (9) (the notation $R_{xx}(\tau)$ replaces $R_{xx}(t_n, t_n + \tau)$ for ergodic random processes). The substitution of time variables t_0 and

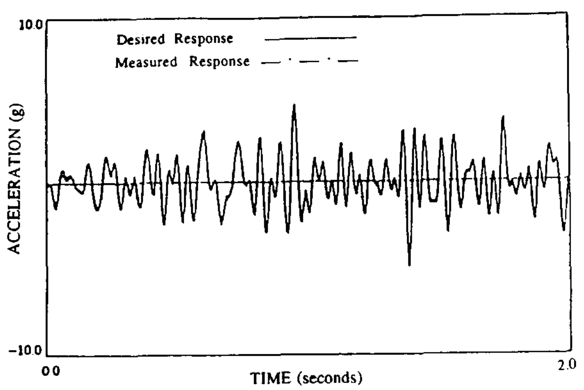

Fig. 9. Desired and measured response.

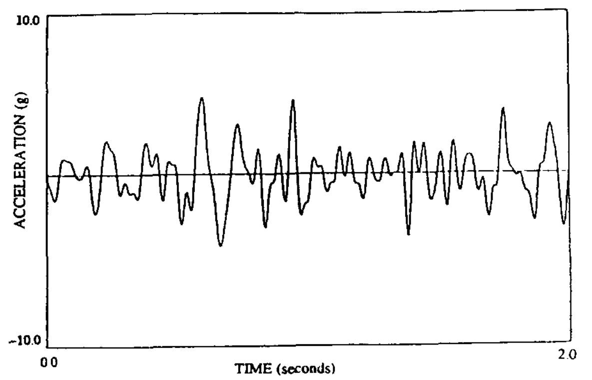

Fig. 11. Input signal for desired signal of Fig. 8.

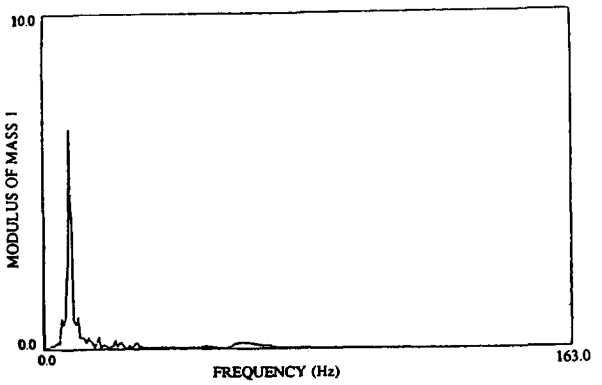

Fig. 12. Modulus of acceleration for mass 2.

t_1 yields:

$$R_{xx}(\tau) = \sum_{i=1}^{n} \frac{C_i^2}{2} \cos(\omega_i(t_0 - t_1)) = \sum_{i=1}^{n} \frac{C_i^2}{2} \cos(\omega_i(\tau)) \tag{10}$$

As stated before, $S(\omega)$ is defined to be the Fourier transform of the autocorrelation function:

$$S(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} R_{xx}(\tau) e^{-i\omega t}\, d\tau \tag{11}$$

Substituting eqn (10) with limits of T into eqn (11) yields:

$$S(\omega) = \frac{1}{4} \sum_{i=1}^{n} C_i^2 [\delta(\omega_i + \omega) + \delta(\omega_i - \omega)] \tag{12}$$

From eqn (12), C_i, $i = 1, \ldots, n$ are determined to be $C_i = 2\sqrt{S(\omega_i)\Delta\omega}$. Then eqn (9) becomes:

$$x(t) = \sum_{i=1}^{n} 2\sqrt{S(\omega_i)\Delta\omega} \cos(\omega_j t + \varphi_j) \tag{13}$$

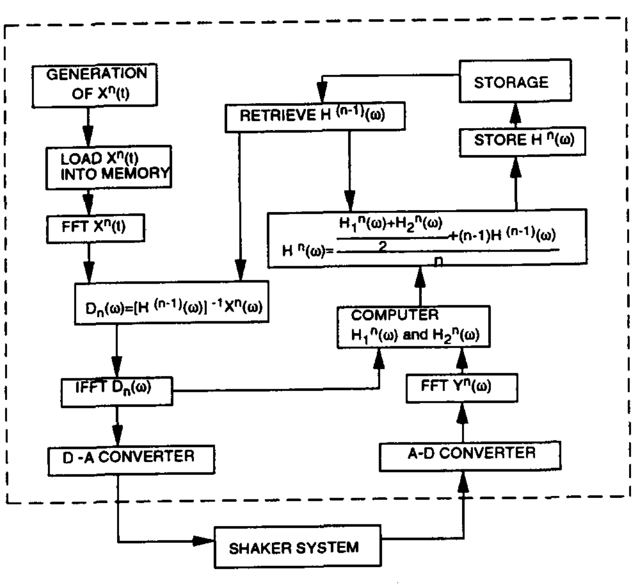

Fig. 13. Schematic of random vibration control method.

where φ_j, $j = 1, \ldots, n$ is randomly distributed on the interval $(0,2\pi)$; $S(\omega)$ is the value at ω_j; and $\Delta\omega$ is the bandwidth of the dividing interval for the specific spectral density function (see Fig. 6). Equation (13) was used to generate a random signal with a specified spectral density function, $S(\omega)$.

EXPERIMENTAL VERIFICATION

In the specimen shown in Fig. 7, the first and second modes of vibration were 8 and 58 Hz, respectively. This specimen was tested for force identification.[7] The objective was to excite predominantly the first mode of vibration. A spectral density function (see Fig. 8) with a bandwidth of 5–30 Hz was proposed for generating an excitation signal. Some standard spectral density functions for vibration environments other than Fig. 8 are provided for reference.[8,9]

Using eqn (13), a random signal was produced in the microcomputer. This signal became the desired response $x_D(t)$ (see Fig. 9). In this test, the first run was done at normal levels because the specimen was assumed to be undamaged after each run. Figure 10 shows the modulus of $H_1(\omega)$. In the region of concern, the curve was smooth, but the outside region was rough; however, the values of the outside region are not important in determining the input signal to obtain the desired response.

Figure 11 shows the calculated signal to produce the desired response. The desired and measured responses are compared in Fig. 9. The modulus for the acceleration at mass 2 (see Fig. 12) shows that the first mode of vibrations was excited, thus achieving the goal for this test run. Finally, a schematic block diagram of the system for random vibration control is shown in Fig. 13.

SUMMARY AND CONCLUSION

A material vibration testing station to simulate sinusoidal, swept-sinusoidal, and random signals was developed using an aged shaker system. The original power supply and control unit were replaced with a custom-designed, closed-loop control unit. The result was an up-to-date and inexpensive vibration station at one-quarter the price of the commercially available model for the same capability.

Using the microcomputer in controlling random vibration can be a cost-effective asset to a structural dynamic laboratory; however, when using the microcomputer, certain limitations should be considered. First, the duration of the signal is limited by the amount of memory in the computer that can be used with the D–A converter and by the time increment between points. For a longer duration, the processing of the digital signal increases, thus the set-up time increases. Another consideration is the voltage range from one component to another in the vibration system. The output from the microcomputer should be the full range for the power amplifier. Also, the gain on the power amplifier needs to be adjusted to match the desired output.

In the selection of a D–A converter and an A–D converter, it is convenient to be able to output, record, and still obtain a fast enough rate. These functions were possible with the present system, but another data acquisition system can be used to record the response if the D–A converter is not available or if the above conditions cannot be met.

In equipment connection, interfacing is crucial in making an effective system. The microcomputer is not limited to just one application; many manual tasks and trigger set-ups, such as universal testing machines, can also be applied. Rooney's information presented for data acquisition systems provides the background language necessary for other A–D and D–A converter connections for equipment.[10] The many uses of the microcomputer in testing laboratories are limited only by the mind of the engineer.

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