Dynamic Load Simulator: Development of a Prototype

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Abstract: This technical note describes prototype development of a next generation of structural testing facility referred to here as a dynamic load simulator (DLS). The DLS simulates dynamic loading environment such as wind, waves, or earthquake effects, utilizing an electric or hydraulic actuator system instead of conventional facilities such as a wind tunnel, wave tank, or shaking table. Similitude requirements or the system capacity often preclude testing of large-scale models utilizing these facilities. In conventional test facilities continuous space-time variations of aerodynamic and hydrodynamic pressure fields and inertial loads are introduced to model the effects of wind, waves, or earthquakes. On the other hand, DLS provides discrete point loads utilizing a single- or multiactuator system to produce global dynamic load characteristics by taking into account the overall spatiotemporal correlation. A suite of typical loading protocols that includes sinusoidal, random correlated Gaussian, and non-Gaussian variations are simulated and verified experimentally utilizing single and dual actuator systems.

INTRODUCTION

Dynamic testing of structures complements and aids the validation of computational methods for studying the behavior of structures under environmental loads. The most commonly used facilities for dynamic testing of structures in the laboratory under wind, wave, and earthquake loads involve wind tunnels, wave tanks, and shaking tables, respectively. Some of the problems with the use of wind tunnels and wave tanks for dynamic testing arise from the inconvenience in modeling structural behavior due to similitude mismatch. Both wind tunnels and wave tanks have served well in ascertaining the wind and wave loads on structures and global response components. However, scale effects hinder the use of currently available shaking tables and wind tunnels in better understanding the performance of large structures under extreme earthquakes and wind environments.

In earthquake engineering, alternatives to shaking tables tests like the pseudodynamic testing or on-line testing have been developed (Takandashi and Nakashima 1987; Mahin et al. 1989). In these systems, actuators at floor levels introduce the inertial dynamic forces. The method involves solving the governing set of equations numerically while the reaction forces used in these equations are measured directly from the structure itself utilizing load cells attached to the actuators. Therefore, although quasi-static loads are applied, the loading is equivalently dynamic in nature since the dynamic effects are implicitly taken into account in the equations of motion. This is an indirect approach and has limitations since a system's exact parameters are essential prerequisites for the operation of this system. In some cases, the rate of loading that influences structural behavior may not be adequately modeled. Moreover, the method is highly sensitive to measurement and control errors. A major advantage of the pseudodynamic test is that it allows substructuring of the system, where a physical model is built of a part of the structure and the rest of the structure is modeled numerically.

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In the area of wind engineering, efforts to model both the structural resistance and loading have not been very successful due to the capacity of wind tunnel needed to house a large-scale model (Cermak et al. 1999). On the other hand, testing devices for structural components (e.g., roofing panels) have been developed using pulsating pressure chambers (Cook et al. 1988). Though successful in testing structural resistance, the aerodynamic loading imparted to the structural components such as roofing elements is uniform spatially with desired temporal fluctuations. In certain situations, this uniformity of pressure may not provide data that is representative of full scale. Other tests dealing with mean wind loads on wood frame housing have been conducted using gantry frames around the structure with attached loading mechanisms (Reardon 1988). This approach has been either limited to static loading applications or dynamic sinusoidal block loading for cyclical fatigue testing.

A dynamic load simulator (DLS) for the simulation of dynamic wind, earthquake, and wave environments has been developed. The proposed DLS system is a multiple-actuator system instead of an aerodynamic system such as a wind tunnel or a large scale, multiple-fan facility. This load simulator can also act as a counterpart to a shaking table because it can simulate loads on a structure through an approach other than base motion. Such a multiactuator system produces global dynamic loads through a set of point loads by taking into account the overall spatial correlation. In this configuration, the aerodynamic loads can be applied with desired spatiotemporal fluctuations but these are limited to applications at discrete locations only, rather than being continuous as in an actual wind environment.

The DLS is based on a force-feedback control system that can directly mimic dynamic loads (Reinhold and Kareem 1996; Kareem et al. 1997). The loads generated by a DLS can be introduced to a structure through a reaction wall or gantry frame (Kareem et al. 1997). This is fundamentally different from the position-feedback servosystems more commonly used in earthquake shaking tables and in some reaction-wall actuator systems. In those systems, the actuator control system matches the desired position of the actuator. However, iterative methods are usually needed in such systems to guarantee matching of the desired and actual accelerations. This problem may be alleviated in force-feedback systems as the inertial force being supplied to the structure is used to control the actuators.

SIMULATOR SYSTEM DESCRIPTION

The system is described schematically in Fig. 1. A target time history of the desired force is introduced in the computer as an input which is converted to an analog signal using a

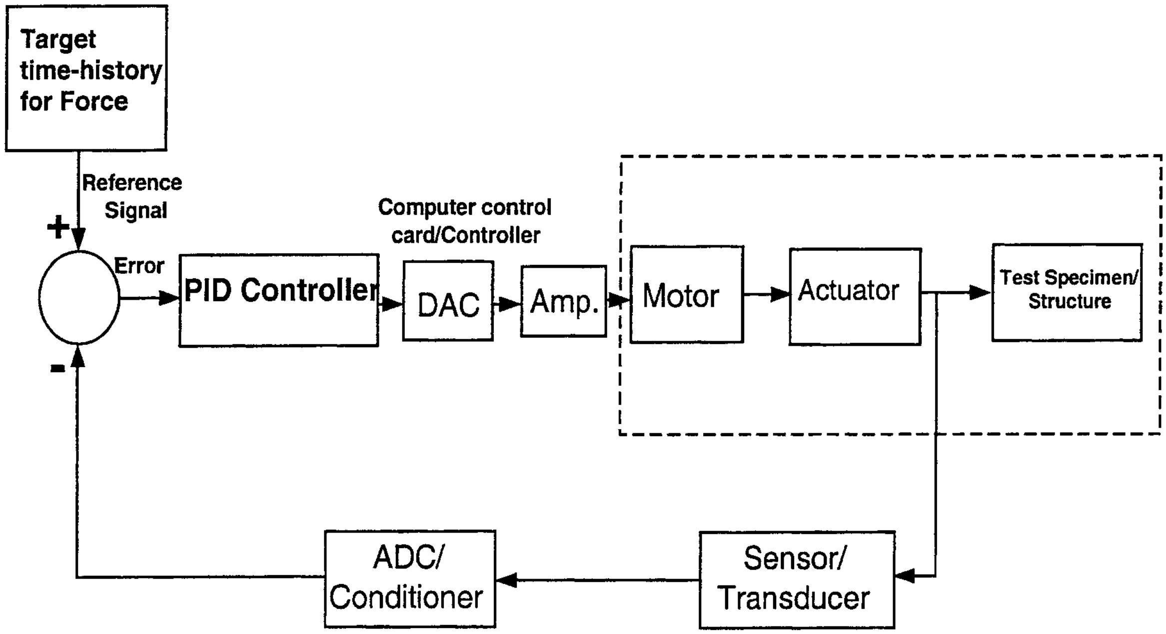

FIG. 1. Schematic of DLS Concept

DAC (digital-to-analog) converter. This signal is then amplified and fed into the servomotor which drives the actuator. The stroke of the actuator creates a force on the test specimen/structure while a force transducer (load cell), placed in between the actuator and the specimen, measures the actual force imparted to the structure and sends the signal back to the computer using an ADC (analog-to-digital) converter. The error between the measured force and the applied force is corrected using a conventional proportional integral derivative (PID) controller. A general PID controller can be described by the following transfer function:

$$G_c(s) = K_P + \frac{K_I}{s} + K_D s \tag{1}$$

PID controllers have robust performance under a wide range of operating conditions and are relatively simple in design and implementation for reducing the steady-state error and improving the transient response (Dorf and Bishop 1998). The gains of the PID controller (i.e., proportional gain K_P, integral gain K_I, and derivative gain K_D) are chosen so that the measured output force tracks the input voltage command signal.

The prototype system for this study consists of a ball screw-type actuator, DC servomotor, force transducer/load cell, test specimen which is an aluminum beam whose end supports can be shifted to change the stiffness of the system, PC with ADC and DAC boards, amplifiers, power supply, and software for real-time control. Two types of prototypes were built: one with a single actuator acting on a one-span beam and a multiple-actuator system (in this case two actuators) acting on a two-span beam.

The ball screw-type actuator is central to the DLS hardware. The ball screw drive is located at the center and two linear motion guide raceways on each side of the actuator provide an extremely rigid and highly accurate actuator function. Proximity sensors are mounted on the actuator which restrict actuator stroke motion to preclude the transfer of damaging loads to the system. The actuator is driven by a DC servomotor which is attached to the motor mounting flanges. The experimental setup is shown schematically in Fig. 2 for a dual actuator system.

The digital PID control system was implemented using a dSPACE rapid controller real-time system (*dSPACE* 1997). This system uses a Texas Instruments TMS320C31 (Texas

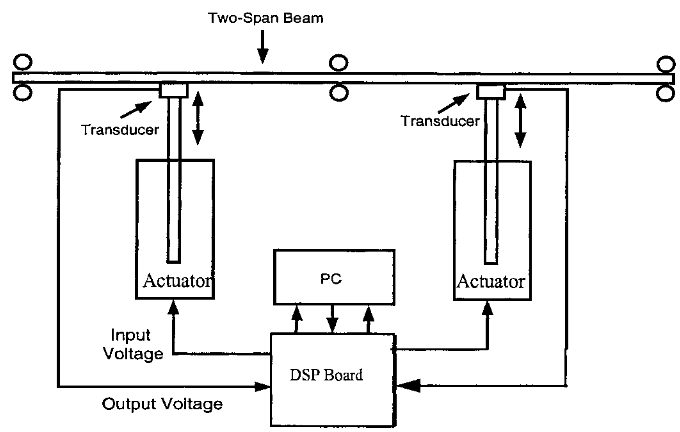

FIG. 2. Dual-Actuator DLS Prototype

Instruments Inc., Austin, Tex.) DSP (digital signal processing) chip for fast computing speeds required for accurate control. The control system prototyping was performed using the MATLAB/SIMULINK programming environment. The C-code generation and its subsequent download on the DSP chip was performed using Real-time Workshop and Real-time Interface.

DLS PERFORMANCE

The initial testing of the DLS was done using sinusoidal loads. A single and a combination of sinusoidal load variations were introduced. The target and the output signals showed a good match. As a next step, a random loading based on Gaussian white noise with a cutoff frequency of 8 Hz was simulated. The comparison of the signals in the time domain is shown in Fig. 3(a). The resulting spectral density plots of both the input and output loadings are shown in Fig. 3(b). The excellent match between the input and output spectral density functions shows great promise for applications involving loads comprised of a host of spectral descriptions based on filtered white noise.

The next step involved verification of the loading cases for a multiactuator system. Input dynamic loads for the two actuators can be either uncorrelated or correlated. These loads are generated by a multivariate simulation based on a pre-

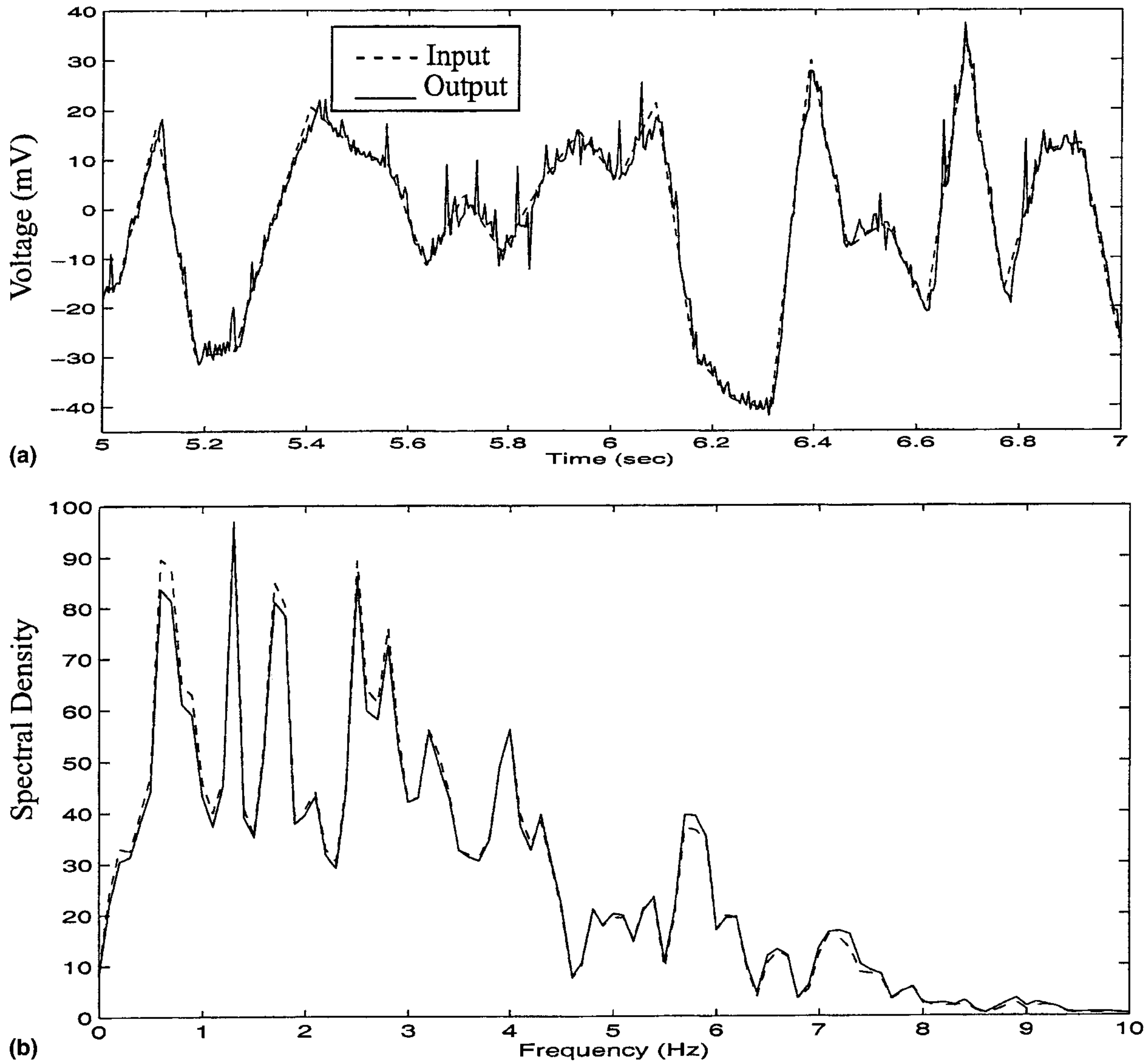

FIG. 3. Single Actuator Simulation of Random Loading Signal: (a) Comparison of Actuator Output Signal to Reference Signal; (b) Comparison of Spectral Density of Actuator Output and Reference Signal

scribed cross-power spectral density matrix. The loading case involved simulated time histories of wind fluctuations with natural correlation structure. In a typical wind-excited structure, the correlation between the wind loads at two points decreases as the distance between the two points increases. The low correlation signals were selected from two well-separated locations whereas the higher correlation case involved two closely spaced locations. Figs. 4 and 5 show that the actuators reproduced, with high fidelity, two signals representing time histories of wind pressure fluctuations with low and high correlation. As in the previous cases, the output signals match the target input signals quite well.

The preceding correlated and uncorrelated target signals had a Gaussian distribution. However, for component testing under wind-generated localized loads, the load fluctuations are highly non-Gaussian with skewness resulting in very high negative pressures (Gurley and Kareem 1998). Experiments were conducted using simulated correlated non-Gaussian time histories. Fig. 6 shows the comparison between the target input and output signals. The generated signals clearly exhibit the negative skewness of the original target pressure signals. Though not shown here for the sake of brevity, the probability descriptions were also faithfully reproduced by the simulated loads.

The DLS concept can be extended to simulate earthquake loading on the test structure. In relative motion coordinates, the effect of ground motion is equivalent to applying a force equal to lumped mass multiplied by the ground acceleration. This approach is applicable to both lumped mass-type multiple-degree of freedom structures and for substructure testing commonly used to study large-scale systems. One of the concerns in seismic applications is the fidelity of the DLS in the inelastic range. The DLS performed satisfactorily in initial testing of the beam in the elastic range with large displacements. Additional validations are needed in this context. The DLS is ideally suited for testing structures with damping devices, such as viscoelastic dampers, under seismic and wind loads in which the structure remains elastic. Similar testing of offshore platforms under dynamic wave loads including the effect of wind can also be conveniently performed. The development of a full-scale real-time DLS that utilizes high-capacity electromechanical actuators with existing support structure in structural testing laboratories will be a valuable tool for testing structures under realistic wind, wave, and earthquake loads.

CONCLUDING REMARKS

The dynamic load simulator concept has been developed based on computer simulations and the subsequent implemen-

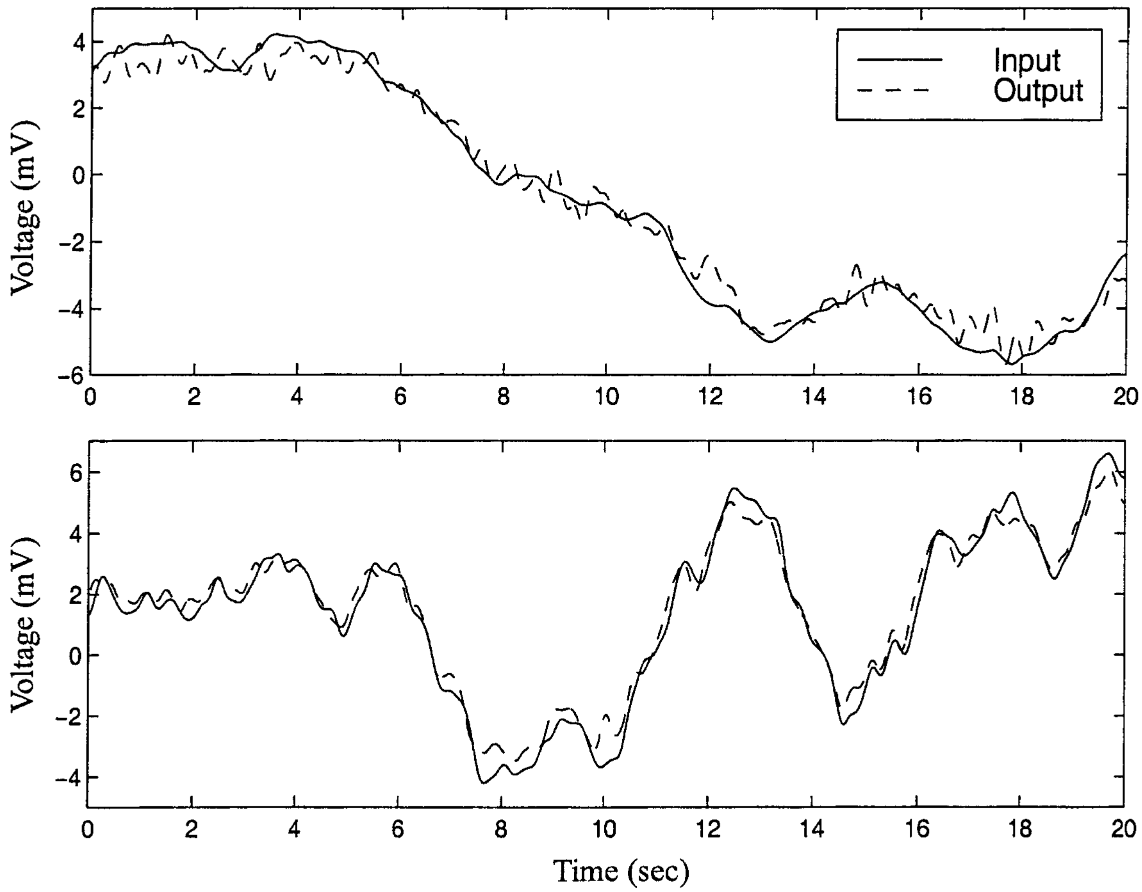

FIG. 4. Dual-Actuator Simulation of Loading with Low Correlation

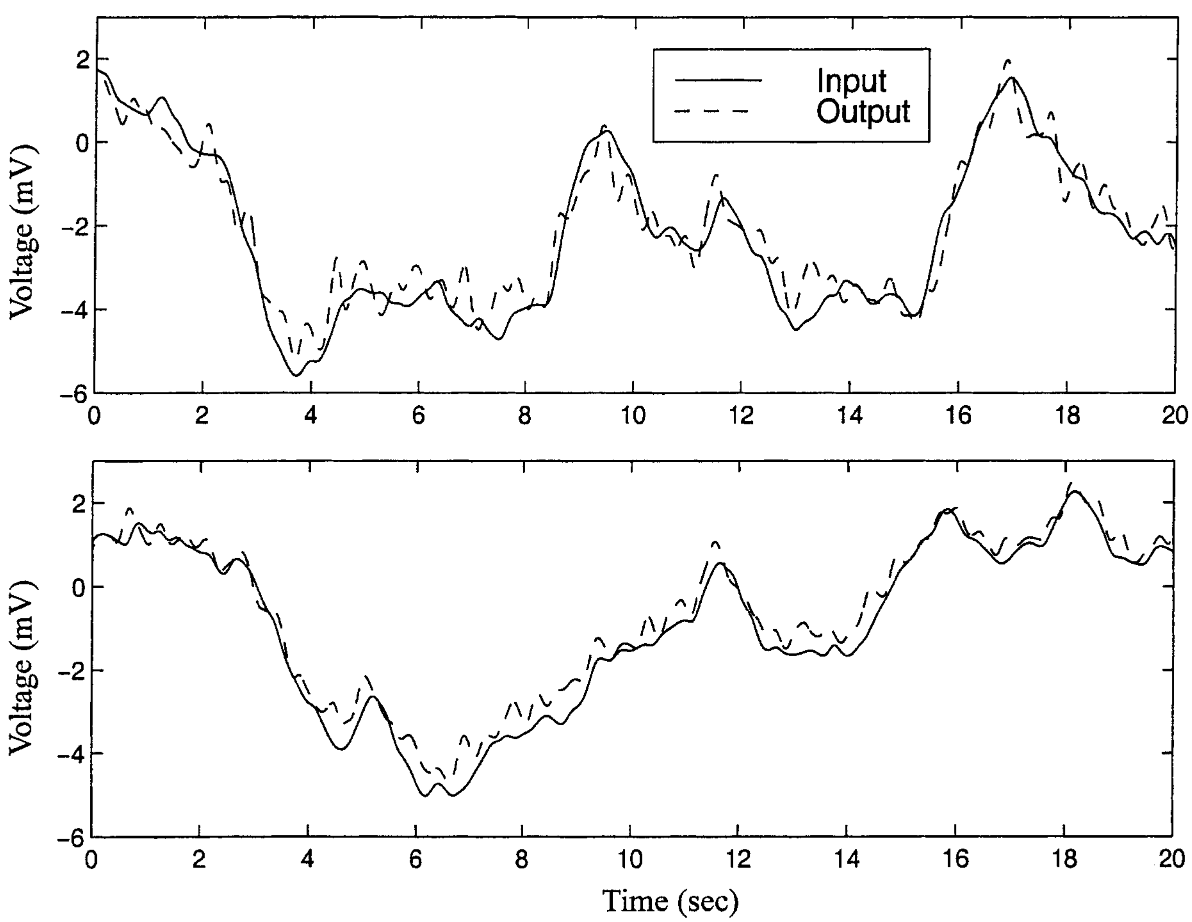

FIG. 5. Dual-Actuator Simulation of Loading with High Correlation

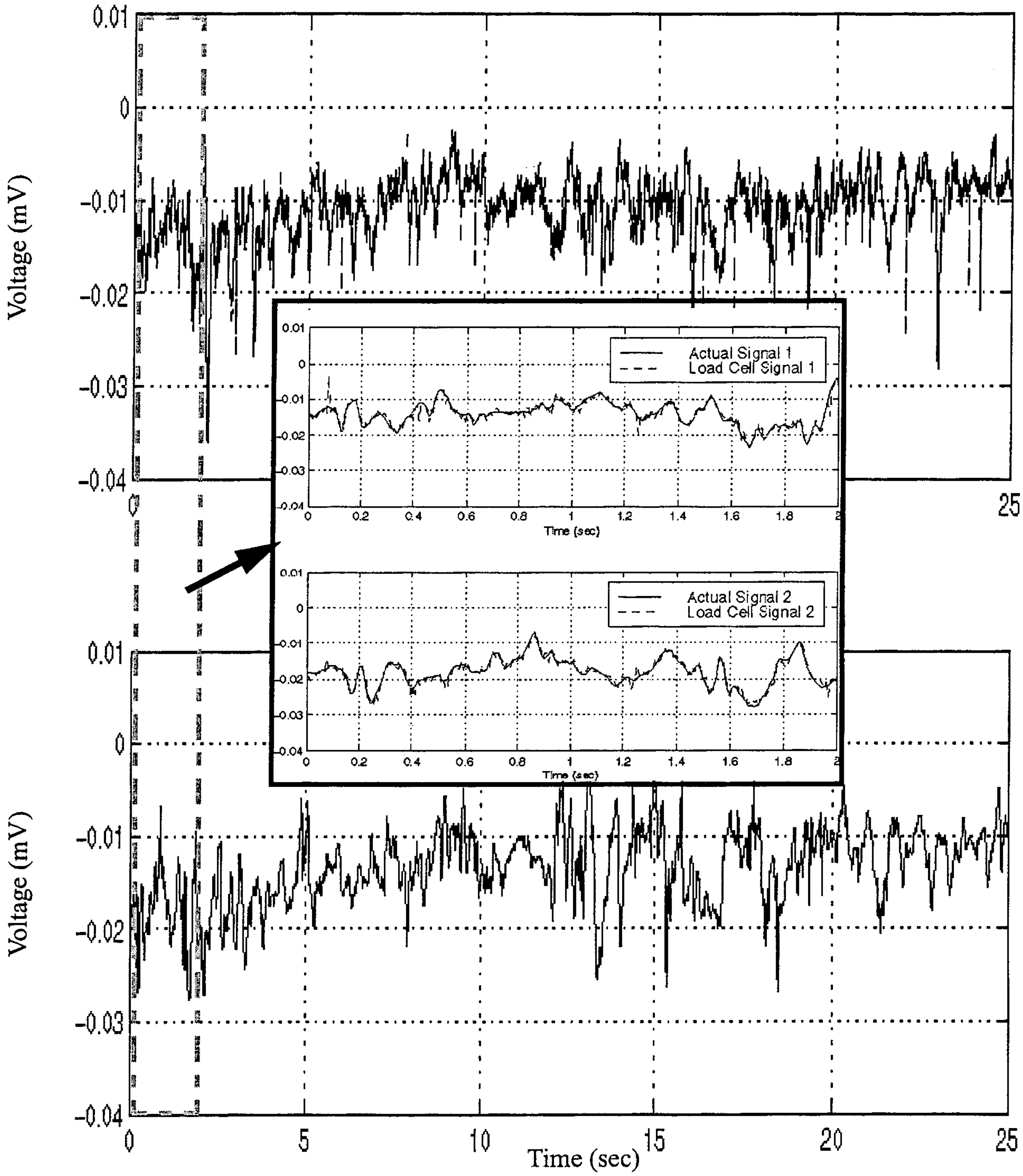

FIG. 6. Dual-Actuator Simulation of Non-Gaussian Loading

tation on a prototype system. A single actuator and multiactuator system was developed to load a single and two-span aluminum beam for demonstrating the effectiveness of the system. Different loading cases ranging from sinusoidal, random, correlated, and non-Gaussian signals were used as test cases to showcase the robustness of the controller in matching the prescribed loads. The results show good agreement between the simulated and desired values. The demonstrated success in generating a wide range of signals with high repeatability and robustness suggests that the DLS concept will be ideal for fatigue testing of structural components under multiple-correlated loads. Current work on the simulator includes testing more complicated signals such as nonstationary loading cases (e.g., sudden wind gusts or near-source earthquakes) and consideration of inelastic behavior.

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REFERENCES

Cermak, J. E., et al. (1999). *Review of the need for a large-scale test facility for research on the effects of extreme winds on structures*, National Academy Press, Washington, D.C.

Cook, N. J., Keevil, A. P., and Stobart, R. K. (1988). ''BRERWULF—The big bad wolf.'' *J. Wind Engrg. and Ind. Aerodynamics*, 29, 99–107.

Dorf, R. C., and Bishop, R. H. (1988). *Modern control systems*, Addison-Wesley, Reading, Mass.
dSPACE floating-point controller board user's guide. (1997). Paderborn, Germany.
Gurley, K., and Kareem, A. (1998). ''Simulation of correlated non-Gaussian pressure fields.'' *Meccanica*, 33(3), 309–317.
Kareem, A., Kabat, S., and Haan, F. L., Jr. (1997). ''Dynamic wind load simulator.'' *Proc., 8th U.S. Nat. Conf. on Wind Engrg.*
Mahin, S. A., Shing, P. B., Thewalt, C. R., and Hanson, R. D. (1989). ''Pseudodynamic test method—Current status and future directions.'' *J. Struct. Engrg.*, ASCE, 115(8), 2113–2128.
Reardon, G. F. (1988). ''Simulated wind loading on houses.'' *Proc., Int. Conf. Housing and Constr. in Age of Technol*.
Reinhold, T. A., and Kareem, A. (1996). ''Next generation of wind test facilities: A feasibility study.'' *Proc., 2nd Int. Workshop of Struct. Control, Next Generation of Intelligent Struct.*
Takandashi, K., and Nakashima, M. (1987). ''Japanese activities on on-line testing.'' *J. Engrg. Mech.*, ASCE, 113(7), 1014–1032.