Dynamic Load Simulator: Actuation Strategies and Applications

Swaroop K. Yalla[1] and Ahsan Kareem, M.ASCE[2]

Abstract: The development of a multiple-actuator dynamic load simulator (DLS), for the simulation of correlated dynamic loads on small-scale structural components and substructures, or on bench-scale system assemblage is presented in this paper. Conceptually, the DLS employs actuators to simulate a desired dynamic loading environment due to wind, waves, or earthquakes, which in special cases may serve as a replacement for conventional facilities such as wind tunnels, wave tanks and shaking tables. The actuation strategy of the DLS is based on force-control rather than the customary motion control (displacement/velocity) scheme. The load simulator is ideal for structural components and for systems that can be idealized as lumped mass systems. An actuation strategy for the DLS based on an innovative scheme that utilizes the coupled control system is developed. For implementation of this scheme, the nonlinear control system toolbox in MATLAB is used. In this scheme, the tuning of control parameters in the time domain is carried out by solving a constrained optimization problem. A suite of loading protocols that includes sinusoidal, two-point correlated fluctuations in wind loading, earthquake induced loading and loads characterized by strong non-Gaussian features is simulated by employing the control scheme introduced here. The load simulation examples presented here demonstrate that the loading time histories generated by utilizing the DLS matched the target values with high fidelity.

DOI: 10.1061/(ASCE)0733-9399(2007)133:8(855)

CE Database subject headings: Dynamic loads; Simulation; Feedback control; Structural control.

Introduction

In view of increasing vulnerability of the built environment to devastating forces of nature, the structural engineering community is faced with the major challenge of finding new techniques and devices for testing and validating structural performance under dynamic load effects. Simulation systems that can mimic the natural environment in the laboratory are often very important for gauging the reliability of structural components and systems. Other applications may include the evaluation of motion control devices or the fatigue life of building components.

In the area of wind engineering, efforts to model both the structural resistance and loading have not been successfully accomplished thus far due to the limited capacity of wind tunnels to house a large scale model and to generate winds strong enough to investigate structural capacities (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 generally spatially uniform with desired temporal fluctuations. In certain situations, this uniformity of pressure may not provide data that is representative of the full-scale conditions. Other tests dealing with the mean wind loads on wood frame housing have been conducted using gantry frames around the structure with attached actuators (Reardon 1988; Bartlett 2002). This approach has been either limited to static loading applications or dynamic sinusoidal block loading for cyclical fatigue testing.

The most commonly used method for seismic testing of structures is the use of shaking tables in which ground motion is simulated by the table acceleration. However, the size of the structure is scaled by the capacity of the shaking table. Therefore, the advantage of shaking table experiments may be offset by the associated scaling problem. Large size shaking tables offer an attractive solution to scaling issues and help to minimize the interaction between the test structure and the shaking table. The advent of electromechanically driven shaking tables have ushered the table-top small scale shaking tables era, which are attractive for small scale structural testing, especially for the proof-of-the-concept or structural control problems, but these systems may bear the shortcomings resulting from the structure-table interaction issues.

In earthquake engineering, alternatives to shaking table tests that include effective force method, pseudodynamic method, pseudodynamic hybrid method, or real-time online pseudodynamic methods for testing of large-scale structural components, structural sub or super assemblies, and in some case full or large scale structures, have been evolving over the last few decades. A focus on a number of these concepts is central to the NSF George E. Brown, Jr. Network for Earthquake Engineering Simulation initiative to develop total testing-analysis-visualization-display environments with provisions for tele-experimentation. One of

[1]Morgan Stanley, 1585 Broadway, New York, New York 10036; formerly, Research Assistant, NatHaz Modeling Laboratory, Univ. of Notre Dame, IN 46556.

[2]Robert M. Moran Professor of Engineering, NatHaz Modeling Laboratory, Univ. of Notre Dame, IN 46556. E-mail: kareem@nd.edu

Note. Associate Editor: Henri P. Gavin. Discussion open until January 1, 2008. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on May 24, 2005; approved on May 17, 2006. This paper is part of the ***Journal of Engineering Mechanics***, Vol. 133, No. 8, August 1, 2007. ©ASCE, ISSN 0733-9399/2007/8-855–863/$25.00.

these techniques with established success is the pseudodynamic test method in which the test is performed quasistatically, yet provides a realistic simulation of the response of structures under dynamic loading provided the material is not very sensitive to the rate of loading (Takanashi and Nakashima 1987; Mahin et al. 1989). In these systems, actuators at floor levels introduce inertial dynamic forces. The equations of structural motion are numerically evaluated on line and the floor displacements are calculated. These displacements are then applied to the structures by actuators and the load cells on the actuators measure the forces necessary to impose the required deformations. These are then used in the next time step of the numerical calculation and the process is continued. This is an indirect approach and has limitations as a system's exact parameters are an essential prerequisite 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 as a part of the structure and the rest of the structure is modeled numerically. More recently, real-time substructure tests have been developed involving a hybrid experimental modeling of actuator-excitation and computer simulation proceeding on a common time scale (Horiuchi et al. 1996; Darby et al. 1999; Williams and Blakeborough 2001; Nakashima 2001). In a study by Dimig et al. (1999), an effective force technique (EFT) similar to the dynamic load simulator (DLS) was introduced for applying seismic forces at the lumped masses of a multidegree of freedom (MDOF) system. However, that study was verified only on single degree of freedom systems. The EFT is being extended to nonlinear systems (Zhao et al. 2004). A real-time dynamic hybrid testing system has been developed by implementing combined physical testing and computational simulation to enable dynamic testing of substructures including the rate and inertial effects while taking into consideration the overall system (Reinhorn et al. 2004). This testing system relies on a new force control scheme with predictive compensation procedure that facilitates the implementation of the real-time feature.

The hardware in the loop (HIL) is another development, which refers to a simulation technique in which some of the system components are numerically simulated while others are physically modeled with appropriate interface conditions. This is similar to real-time substructuring where a physical test and a numerical model interact in real time. HIL developed out of a hybrid between control prototyping and software-in-the-loop simulations (Isermann 1999). It is routinely used in aerospace and automotive control in embedded systems as an inexpensive and reliable rapid-prototyping technique for product development. It is ideally suited for testing structures with dampers (Yalla 2001). One can build a virtual structure in a computer model and the nonlinear elements such as dampers, base-isolators, etc., can be included in the physical model (Yalla and Kareem 2001). Some of the advantages of HIL simulation over conventional testing methods are the cost and time savings in repeated simulations as it offers on-the-fly tuning of parameters.

The experimental testing schemes described in the preceding paragraphs are still evolving and are primarily limited to a single actuator with the potential to expand to multiple actuators. For example, in a real-time substructuring scheme most of the structural system is numerically modeled and the complex part of the system, e.g., a base isolation device, is physically modeled utilizing a single actuator (e.g., Nakashima 2001). Extension to a MDOF system is theoretically straightforward as the effective force at each floor level depends on the ground acceleration and the structural masses only. Nonetheless, structural masses in this scheme have to be accurately included and the actuators at higher floors may require specialized large-flow servovalves along with high quality controllers. Although fully correlated loads at different levels of the structure may be used in the case of earthquakes, for other loads like wind and waves, the actuator control strategy must incorporate correlation among load levels. Therefore, decoupling of interacting control loops is extremely important for the effective simulation of correlated loads at multiple locations for application to MDOF systems.

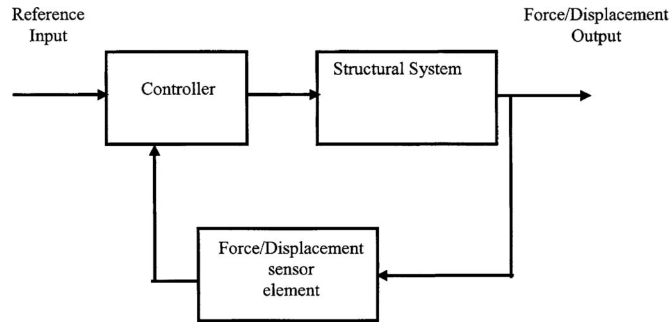

Fig. 1. Force-feedback system

To address some of these challenges, a pilot DLS was developed by the writers for simulating wind, wave, or earthquake loads on structures. The pilot DLS was based on a *force-feedback* control system that could 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 system was envisioned as a low-cost test simulator, which could be readily assembled using existing infrastructure of a typical structural dynamics laboratory. In this paper, first a brief introduction of the force-feedback based control methodology is presented, which is followed by an introduction of various control strategies used for controlling multiple actuator systems. For efficient and robust simulations, a new type of coupled control system (CCS), using the Nonlinear Control System toolbox in MATLAB (The MathWorks, Inc., Natick, Mass), is developed. This control scheme is used for the simulation of a suite of loading protocols utilizing the DLS, which is validated through comparisons with target load signatures.

Force-Feedback System

In the control of dynamic systems, an appropriate feedback is customarily introduced to effectively achieve the necessary control objectives (Fig. 1). Typically, there are two types of control schemes, i.e., the motion (displacement/velocity) control or force (and torque) control. In most structural engineering applications, e.g., shaking tables and other large testing equipment, motion control is commonly employed. This choice may have resulted from the relative ease with which the position/velocity of the system can be controlled in comparison with the force. This has led to some obvious shortcomings concerning the control of shaking tables as noted in its inability to match accurately the prescribed accelerations (Spencer and Yang 1998). This problem may be ameliorated in force-feedback systems as in this case where the inertial force is supplied to control the actuators. Moreover, in many applications, force control is critical for maintaining precise application of force, e.g., in robotics and in precision machining

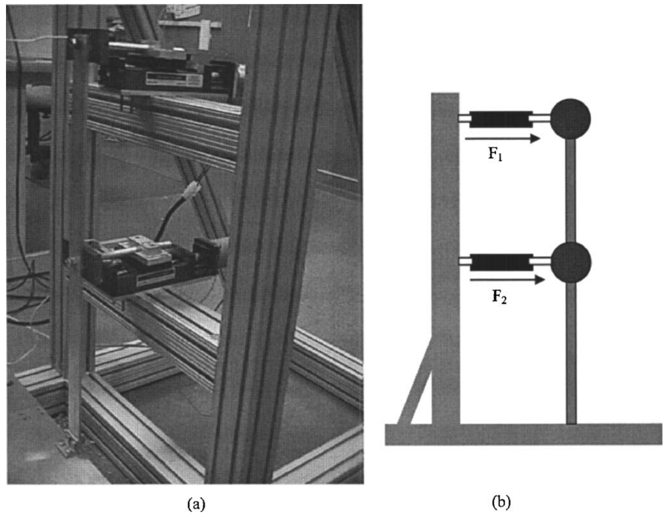

Fig. 2. (a) DLS facility; (b) schematic of the DLS experimental setup

equipment where a large force may be exerted due to a slight error in motion, resulting in either damage to the tool or unacceptable product quality.

DLS System Configuration

The development of a first generation of dynamic load simulator prototype was presented in Yalla et al. (2001). The prototype was tested using an aluminum beam with end supports that permitted convenient changes in the beam span. This system has been extended to study a multiinput multioutput (MIMO) system as shown in Fig. 2. A cantilever type structure with two lumped masses is attached to actuators. The actuator assembly is in turn mounted on a rigid reaction frame [Fig. 2(a)].

The system employs electromechanical type actuators comprised of a ball screw couched in two linear motion guide raceways on each side, which provide an extremely rigid and highly accurate actuator transfer function. The actuators are driven by dc servomotors, which are attached to the motor mounting flanges. The computer-controlled system was implemented using WinCon real-time system, which uses MATLAB/SIMULINK for control system prototyping. The C-code was generated and subsequently downloaded to the digital signal processing chip by utilizing the Real-time Workshop and Real-time interface from Mathworks, Inc. Data acquisition was accomplished using a WinCon, Quanser, Inc., Markham, Ontario, compatible MultiQ-3 board equipped with 8 single ended analog inputs, 8 analog outputs, 16 bit digital input/output, as well as 8 encoder inputs. A SigLab, Spectral Dynamics, San Jose, CA, 20–22 spectrum analyzer was used for obtaining the frequency response functions of the various components of the system. Target time histories of the desired forces are inputted to the computer, which are converted to analog signals using a digital-to-analog converter. These signals are then amplified and fed into the servomotors, which drive the actuators. The stroke of actuators creates forces on the test specimen/structure while an axial load cell placed in between the actuator and the structure, measures the actual force imparted to the structure and sends the signal back to the computer using an analog-to-digital converter. The error between the measured force and the applied force is corrected using a feedback control system.

Actuator Control Strategies

This section discusses briefly some of the control strategies that can be used to control multiple actuator loading systems. These systems can be categorized as multiple actuator single-axes (MASA) or multiple actuators multiple-axis (MAMA) systems. Although MAMA systems represent general loading conditions, e.g., loads on automobiles, the DLS configuration in this study by design is uni-axial. Therefore the focus in the ensuing sections will be on MASA type systems. The DLS concept presented here can be extended to MAMA configuration. Two main types of actuators used to drive these systems can be categorized as electromechanical or servohydraulic actuators. In this study, electromechanical actuators, each consisting of a servomotor and a ball screw, are employed. Mechanical systems other than ball screws are possible, e.g., rack and pinion, belts and pulleys, etc. Alternatively, for some applications linear motors can be used as they offer high accuracy and a linear transfer function (Cruz 1997).

There are a number of issues, particular with MASA/MAMA systems, which pose serious challenges in their control. In order to optimally control these systems, some prior information of the loading and the test structure itself (system identification) is needed. This is usually obtained before the actual test commences or during testing (for on-line adaptive nonlinear type control). Furthermore, in a single-actuator single-axes system, the control system can be designed based on judgment or using well-defined rules such as the Ziegler-Nichols scheme for Proportional Integral Derivative (PID) controllers (Dorf and Bishop 1998). However, for MASA/MAMA systems this becomes an arduous task since the number of control gains to be manipulated becomes large. This aspect is further complicated as multiple exciters result in introducing interactions (cross-coupling) among various components of the MIMO system. This implies that for an accurate control, the system should have the capability of suppressing undesired force contributions induced by other actuators (*cross-coupling compensation*). Various types of control systems used for multiple-exciter system can be classified as open-loop, iterative closed-loop and real-time closed-loop (e.g., Hamma et al. 1996). These systems are briefly described here for completeness.

Open-Loop Control

In an open-loop control scheme, the signals used to drive the actuators do not benefit from any observed output of the system; rather these are generated directly by prescribed function generators. This type of control systems may be suited for very low frequency type loading signals and are not recommended for any dynamic testing involving higher frequencies due to potential instabilities.

Iterative Closed-Loop Control

Traditionally, iterative closed-loop control schemes have been used extensively to control MASA/MAMA systems (e.g., Fletcher 1990). The central design of iterative closed-loop schemes is outlined in Fig. 3. The function $H_{yu}(\omega)$, which defines the transfer function between measured forces (output) and control forces (input) to the servomotors, is estimated for the closed loop system. The error between the desired and measured system response is iteratively minimized by sequentially updating the driver signal. It is important to note that the impedance matrix calculation requires clipping at low frequencies prior to matrix inversion, which is necessitated by the influence of measurement

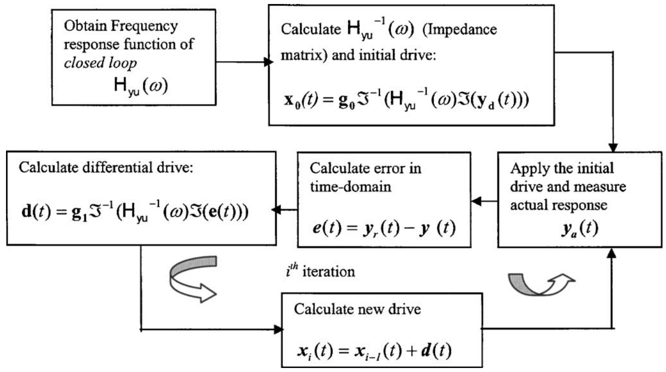

Fig. 3. Iterative scheme for multiactuator control

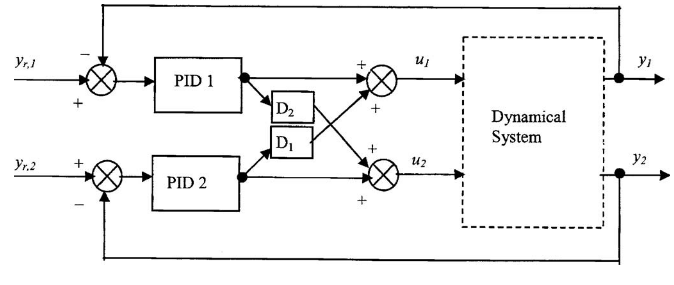

Fig. 4. Decoupled control strategy

noise at low frequencies. Consequently, the peak in the inversed impedance matrix is not well defined, which my lead to serious overexcitation of the system.

Iterative schemes are very attractive in accounting for the nonlinearities introduced by the simulator dynamics and simulator-structure interactions. These schemes have also been employed successfully in wind tunnels and wave tanks (Cao et al. 2002; Chakrabarti 1994). However, in this study the focus is on the development of *online* strategies, which rely on measurements to adjust the driver signal in real-time to achieve the simulation of target time histories. These schemes are discussed in the following section.

Real-Time Closed-Loop Control

An attractive approach in designing MIMO systems is to decouple the interaction terms using "decouplers" that are essentially feedforward elements. These types of systems are referred to as decoupled control systems (DCS). Additional details on decoupling control can be found in Wang (2003). Once the system is effectively decoupled, it is reduced to a multiple SISO system for which individual PID controllers can be designed in a straightforward manner (e.g., Astrom et al. 1992). Consider a typical 2-input 2-output system described by the following open-loop system:

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} H_{11}(s) & H_{12}(s) \\ H_{21}(s) & H_{22}(s) \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} \tag{1}$$

In this case, the design objective is to introduce an input that changes u_1 by an amount so as to negate the interaction effect of u_2. This strategy would effectively decouple the first output y_1 from the cross-coupling influence of the second input u_2. This element can be written as (Stephanopoulos 1984)

$$u_1(s) = -\frac{H_{12}(s)}{H_{11}(s)} u_2(s) = -D_1(s)u_2(s) \tag{2}$$

Similarly, the changes in u_2 by an amount sufficient to cancel the interaction effect due to u_1 are related by

$$u_2(s) = -\frac{H_{21}(s)}{H_{22}(s)} u_1(s) = -D_2(s)u_1(s) \tag{3}$$

This decoupling feature is shown in Fig. 4, where the "decoupler" D_1 measures the changes in u_2 and takes appropriate action to cancel the effect u_2 would have on y_1.

It is noteworthy that the DCS strategy works better for stationary disturbances because the "decouplers" are tailored on the basis of steady-state transfer functions. As the objective of this study is to develop a testing facility that is capable of incorporating dynamic and transient loading features, a more robust control system is desired. In order to address these needs, this study introduces a new type of CCS, which successfully eliminates cross-channel coupling. Its details are described in the following section.

Coupled Control System

Central to the idea of coupled control systems is the design of a MIMO-PID controller under certain constraints to compensate for the cross-channel coupling. This kind of constrained optimization can be automated using the Nonlinear Control Design (NCD) toolbox of MATLAB (e.g., Potvin 1993). The primary difference between the NCD and the conventional optimal control LQG/H_2 type approaches lies in the manner in which the control design is framed. For example, the LQR/LQG based schemes involve minimization of various norms of the weighted transfer functions and tuning of the response by tweaking the weights, i.e., Q and R matrices, whereas the NCD approach utilizes the time domain based constraint paradigm. The NCD toolbox essentially transforms the constraints and simulated system output into an optimization problem of the form

$$\min_x \gamma \text{ s.t. } \mathbf{g}(\mathbf{x}) - \mathbf{w}\gamma \leqslant 0; \quad x_l \leqslant x \leqslant x_u \tag{4}$$

where $\mathbf{x}$=vector of tunable variables with $\mathbf{x}_l$ and $\mathbf{x}_u$ the lower and upper bounds, respectively; $\mathbf{g}(\mathbf{x})$=vector of the imposed constraints; and $\mathbf{w}$=weighting vector.

The first step in this regard is to establish the transfer function matrix of the open-loop system. This is customarily accomplished by introducing a band-limited white noise excitation to each input of the system and subsequently monitoring the system outputs. The transfer functions are curve-fitted using a constrained iterative method based on the coherence of the transfer function as a weighting factor where the following objective function is minimized:

$$\text{minimize } \mathbf{J} = \left(\sum_{i=1}^{N} \left(\frac{a_1 s^n + a_2 s^{n-1} + \cdots + a_n}{s^m + b_1 s^{m-1} + \cdots + b_m} \right) - H_i \right)_{f_i} \times \boldsymbol{w}_c \tag{5}$$

where N=total number of frequency points; $\mathbf{w}_c$=coherence weighting function; and n and m are the orders of the polynomials in the numerator and denominator of the fitted transfer function. As shown in Fig. 5, the fitted transfer functions provide a good match with the frequency response data.

Next, the control system is designed for the closed-loop system. The error between the measured force and the applied force is corrected using a conventional PID controller. SISO-PID controllers have robust performance under a wide range of operating conditions and are relatively simple in design and implementation

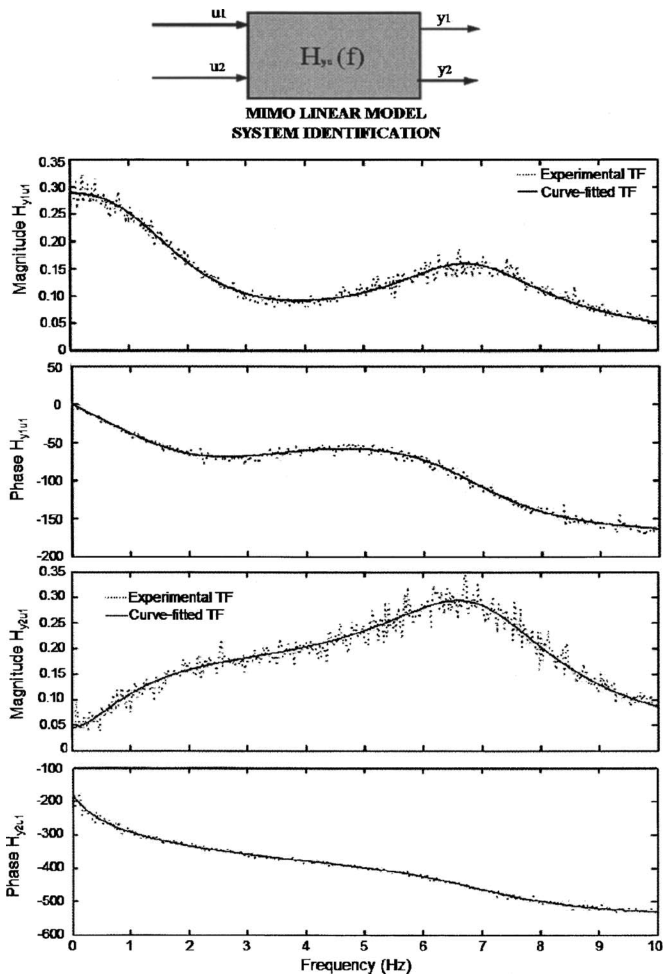

Fig. 5. Open loop transfer functions (experimental and curve fitted)

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. Whereas, a general MIMO PID controller can be described by the following transfer function

$$\mathbf{u}(s) = \left[\mathbf{K}_p + \frac{\mathbf{K}_i}{s} + \frac{\mathbf{K}_d(100s)}{(s+100)}\right]\mathbf{e}(s) \tag{6}$$

where $\mathbf{e}(s)$ = error between the reference or desired output and the measured output. The scalar PID gains now become matrix gains. However, as alluded to earlier, tuning the gains for MIMO-PID controllers is a difficult task as there are no well-defined tuning rules similar to those available for SISO-PID controllers.

The MIMO-PID controller parameter-tuning problem was addressed utilizing the NCD toolbox in MATLAB. The control design scheme is shown schematically in Fig. 6. The optimization loop iteratively searches for the optimum set of tuning parameters that satisfy the time-domain constraints in the output response. The MIMO-PID controller for tracking problems involves sequentially inputting a step command. When the first channel steps (i.e., a step input is applied), the first output should track the step while the other channels should reject this input and vice versa. Fig. 7 shows the tuning of the system parameters before and after optimization. Before optimization, the system response is coupled and does not meet the requirements introduced by constraints.

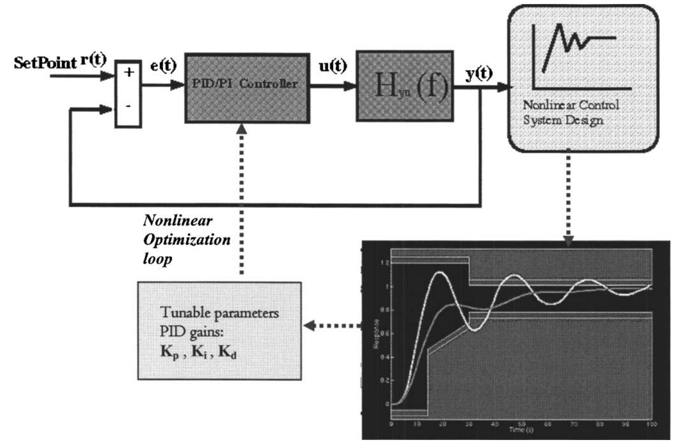

Fig. 6. Nonlinear control design methodology

This means that when the input step is introduced at the first actuator, the second actuator also produces a response to the excitation as noted in Fig. 7(a). On the other hand, when the proposed optimization is introduced, the NCD toolbox effectively tunes 12 parameters (4 parameters each in $\mathbf{K}_p$, $\mathbf{K}_i$, and $\mathbf{K}_d$ matrices) under a total of 6,012 constraints to provide the solution, which results in an optimum performance. As noted in Fig. 7(b), with optimization in place, the two actuators respond to step inputs independent of each other. The nonlinear control systems toolbox also permits inclusion of inherent uncertainties in the various plant parameters, which results in a more robust design. Uncertainties were not explicitly considered as a part of this study as the transfer function of the system was estimated experimentally. The MIMO-PID gain matrices before and after optimization are given as

- Before optimization

$$\mathbf{K}_p = \begin{bmatrix} 4.0 & 0 \\ 0 & 3.0 \end{bmatrix}; \quad \mathbf{K}_i = \begin{bmatrix} 1.0 & 0 \\ 0 & 1.0 \end{bmatrix}; \quad \mathbf{K}_d = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.1 \end{bmatrix}$$

- After optimization

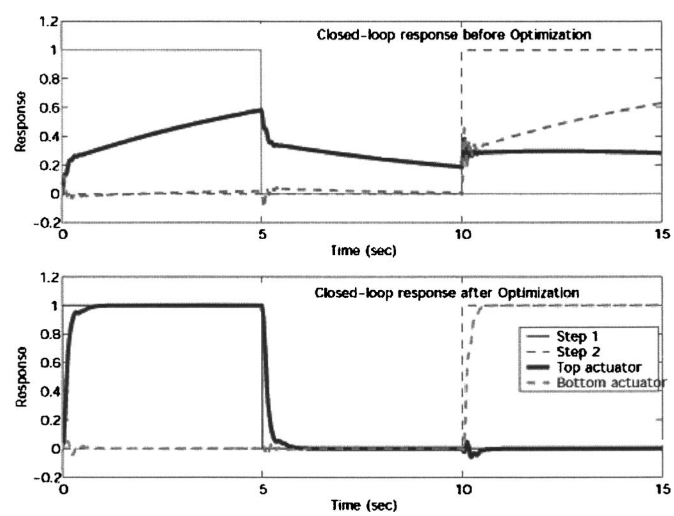

Fig. 7. Closed loop response of two outputs to sequential step loading prior to and after optimization

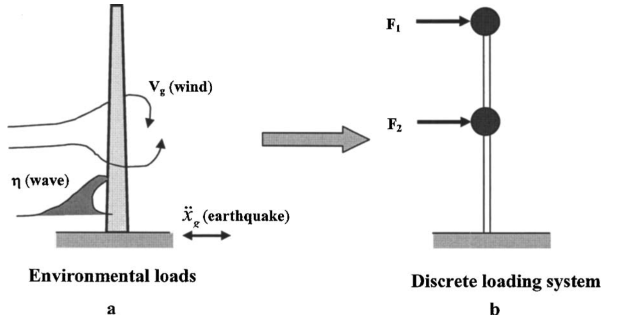

Fig. 8. (a) Environmental loading; (b) discrete loading system

$$\mathbf{K}_p = \begin{bmatrix} 4.16 & -9.7 \\ 0.80 & 4.2 \end{bmatrix}; \quad \mathbf{K}_i = \begin{bmatrix} 4.2 & -0.11 \\ 4.93 & 8.96 \end{bmatrix};$$

$$\mathbf{K}_d = \begin{bmatrix} 0.43 & -0.17 \\ -0.15 & 0.09 \end{bmatrix}$$

It is noteworthy that the gains matrices in the MIMO controller are fully populated, where the off-diagonal terms are responsible for compensating the cross-channel coupling.

Applications

In order to demonstrate the proposed scheme to control multiple actuators, representative loading time histories are generated utilizing the DLS. It is important to bear in mind that unlike conventional test facilities, e.g., wind tunnels, wave tanks, shaking tables etc., where distributed space-time variations of the aerodynamic, hydrodynamic pressure fields or inertial loads are introduced, the DLS provides discrete point loads to produce global load characteristics by taking into account the overall spatiotemporal correlation (Fig. 8). Accordingly, the load simulator is ideal for structural components and for systems that can be idealized as lumped mass systems. A suite of different loading cases including sinusoidal, wind loading with high and low correlations, seismic loading and non-Gaussian loading were investigated.

Sinusoidal Loading

The initial testing of DLS was conducted using sinusoidal loads with potential application to cyclical fatigue testing of components. Fig. 9 shows the desired signals applied to the two actuators with sinusoidal frequencies of 1.5 and 1.0 Hz. It is noted that the force tracking, i.e., actual output signals measured by the force transducers, match the input signals quite well with the exception of slight attenuation in the amplitudes around the peaks.

Wind Loading

As wind flows past a structure, it manifests loads through spatiotemporally distributed fluctuations in surface pressure. For a load bearing structural system, a pointed load at each floor level is estimated based on the tributary area and appropriate correlation of the fluctuating pressure. For the time history analysis, these load fluctuations can be synthesized through wind tunnel tests utilizing pressure models equipped with multi-scanning systems. Alternatively, the time histories may be digitally simulated based on prescribed spectral correlation.

In this study, time-histories for numerically simulated fluctuating components of wind forces for a two degrees of freedom (2DOF) system were introduced as input to the DLS system. The time histories of wind forces were generated using a multivariate simulation based on the prescribed power spectral density matrix with prescribed correlation structure (Gurley and Kareem 1998). Two loading cases were considered: wind loads with high and low correlation. 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. Fig. 10 shows the target and simulated records, which demonstrates that the two actuators reproduced the two input signals with their respective correlation level in each case with high fidelity.

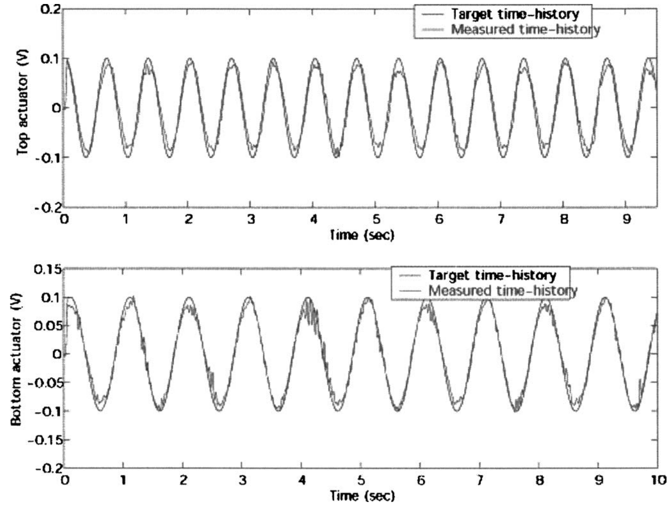

Fig. 9. Sinusoidal load simulation with actuator frequencies: Top—1.5 Hz and bottom—1.0 Hz

Earthquake Loading

The motion of a structural system subjected to ground motion $\ddot{x}_g$ is given by

$$M\ddot{X}(t) + C\dot{X}(t) + KX(t) = -M\ddot{x}_g \tag{7}$$

in which M, C, K=mass, damping, and stiffness matrices, respectively. $X(t)$ and its derivatives represent relative motion components of the different degrees of freedom with respect to the ground. A system subjected to a base motion may be replaced by an equivalent fixed-base structure with the effective force $F_{\text{eff}}(t)$ applied to structural lumped masses. This is similar to the EFT utilized in Dimig et al. (1999). In this manner, the effective forces are applied directly to a fixed-base structural model using actuators operated under a force control scheme. A major advantage of this scheme lies in the fact that since the effective force at each level depends only on the ground acceleration and the structural masses; it is independent of any nonlinearity that may exist in the structural behavior under loads. Therefore, these loads can be ascertained in advance, precluding the need for any online computations. An added advantage is that since loads at each level are fully correlated, the need for coupled control schemes is eliminated.

As illustrated here, the response of a system to a given ground motion may be replicated exactly by applying an effective force to each mass of the system, which is equal to the product of the mass at that level and the ground acceleration. In order to validate

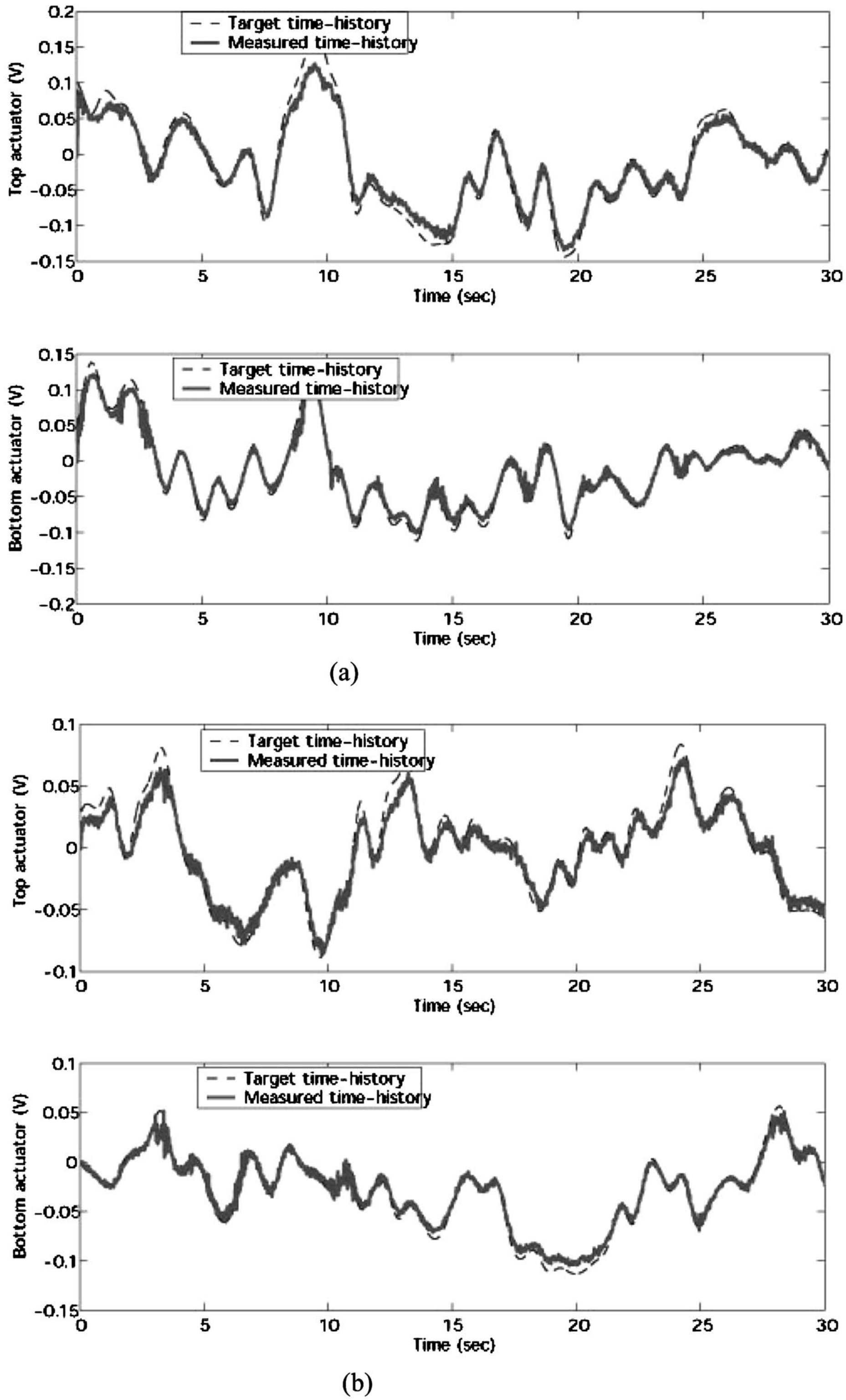

Fig. 10. Simulation of wind loading: (a) high correlation; (b) low correlation

the simulation of seismic loads using the DLS system, the first 10 s of the El Centro Earthquake time history were used as an input at both levels of the DLS system (Fig. 11). The results demonstrate that the system was able to reproduce the transient earthquake loading with high accuracy.

Non-Gaussian Loading

The preceding example of wind loading signals was characterized by Gaussian fluctuations. However, some of the local pressure fluctuations on buildings may exhibit strong non-Gaussian features, which are distinctly different from Gaussian. These features are characterized by skewness and kurtosis (Gurley et al. 1997). It is also noteworthy that the load fluctuations derived from the synthesis of these pressure fluctuations may still exhibit strong non-Gaussian features as the spatio-temporal correlation of these pressure fields over structural surfaces precludes validity of the Central Limit Theorem. In order to examine the ability of the

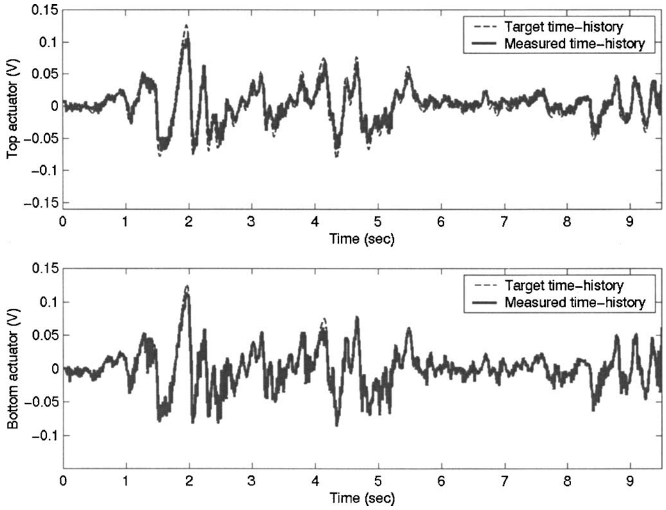

Fig. 11. Simulation of earthquake loading

DLS to faithfully track force fluctuations characterized by the non-Gaussian aspects, simulated records based on the prescribed spectral and probabilistic features were utilized to derive the DLS actuators. Fig. 12 demonstrates the high quality of load simulation as it chronicles two target correlated non-Gaussian pressure fluctuations [Fig. 12(a)]. Comparisons of simulated and target signatures zoomed for two representative regions in Figs. 12(b and c). It is noteworthy that the actuators capture the non-Gaussian features with high fidelity. An example of wave induced loads on structures for either linear (Gaussian) or nonlinear (non-Gaussian) wave has not been included here, but such applications are immediate as demonstrated here for a similar loading signature (Kareem et al. 1998).

Conclusions

The development of a small-scale bench-top testing facility, namely the DLS, was described in this paper. Various types of control strategies used for controlling single/multiple actuators in a testing facility utilizing force-feedback were examined. A new type of CCS using the nonlinear control system toolbox in

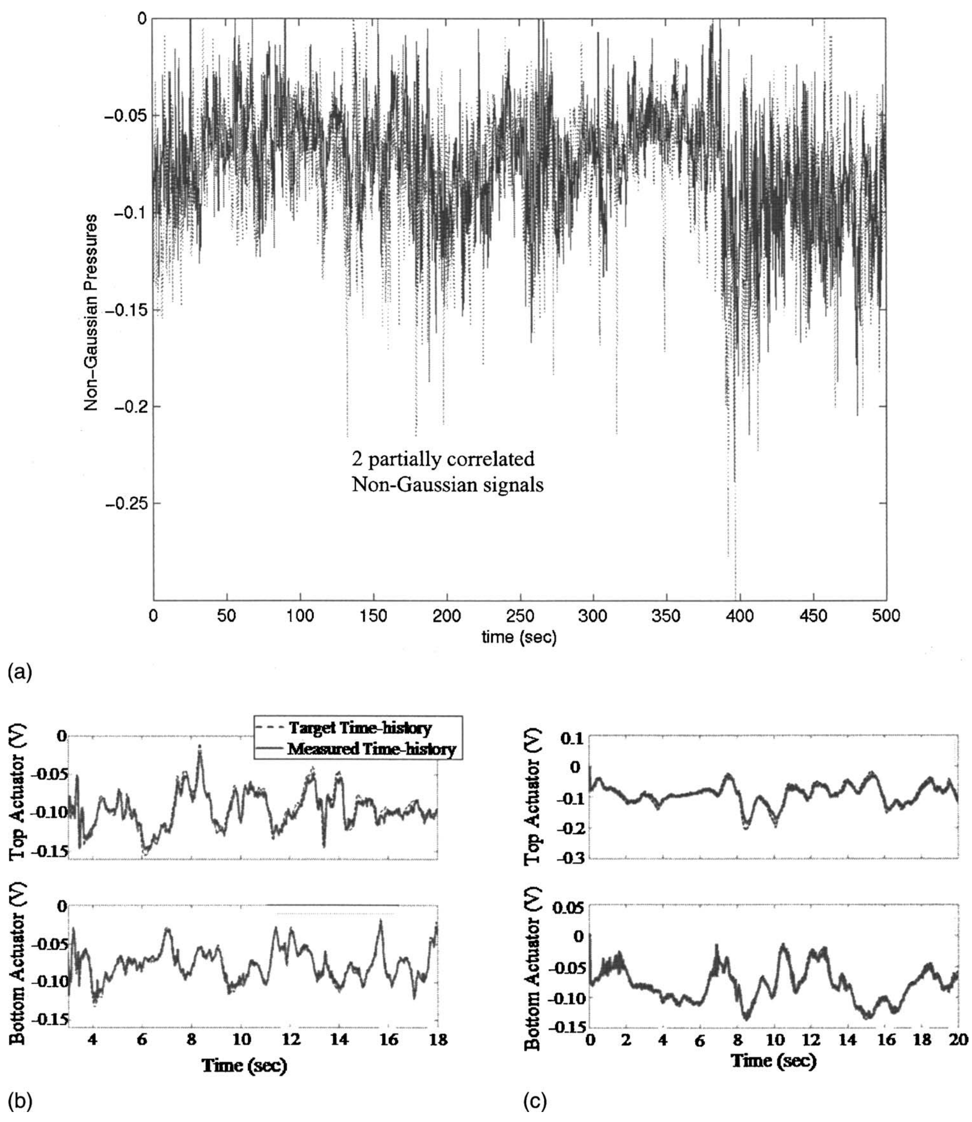

Fig. 12. (a) Original time histories of two partially correlated nonGaussian signals; (b) and (c) zoomed comparisons between target and measured

MATLAB was introduced in this study. In this approach, the time-domain control parameter-tuning problem was solved as a constrained optimization problem. A suite of loading protocols that included sinusoidal, wind loading with high and low correlation, earthquake loading and non-Gaussian type loading was simulated and verified experimentally on the DLS system. The generated loads exhibited a good agreement with the desired target load signatures. An immediate extension of this concept may be realized by placing multiple actuators at a closely spaced grid to further accentuate spatial correlation of loading. Applications to wave-related processes are immediate. The demonstrated success in generating a wide range of signals with high repeatability and robustness suggests that the DLS concept will be ideal for testing structural components under multiple-correlated loads. Further, it also holds promise of prototyping this small-scale system to a large-scale real-time DLS that utilizes high capacity electromechanical actuators with existing reaction-support systems in structural testing laboratories. Such systems would be invaluable tools for testing performance of structures under the demand posed by wind, wave and earthquake loads. The robustness in the performance of such a loading system for components or systems that experience yielding needs to be further investigated.

Acknowledgments

The writers were supported in part by Grant No. CCS622895 by the Lockheed Martin Idaho Technologies and the NSF Grant No. CMS 95-03779. This support is gratefully acknowledged. Any opinions, findings, or recommendations expressed in this paper are those of the writers and do not necessarily represent the views of the sponsors.

References

Astrom, K. J., Hang, C. C., Persson, P., and Ho, W. K. (1992). "Towards intelligent PID control." *Automatica*, 28(1), 1–9.

Bartlett, M. (2002). "Testing load paths in full-scale houses." *Proc., Workshop on Mitigating Housing Losses in Extreme Natural Events*, Institute for Catastrophic Loss Reduction, Toronto.

Cao, S., Nushi, A., Kikugawa, H., and Matsuda, Y. (2002). "Reproduction of wind velocity history in a multiple fan wind tunnel." *J. Wind. Eng. Ind. Aerodyn.*, 90(12–15), 1719–1729.

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 Research Council, National Academy Press, Washington, D.C.

Chakrabarti, S. (1994). *Offshore structural modeling*, World Scientific, River Edge, N.J.

Cook, N. J., Keevil, A. P., and Stobart, R. K. (1988). "BRERWULF—The big bad wolf." *J. Wind. Eng. Ind. Aerodyn.*, 29(1–3), 99–107.

Cruz, I. S. (1997). "Linear motors: A good choice for motion and position control." *I&CS* (10), 53–56.

Darby, A. P., Blakeborough, A., and Williams, M. S. (1999). "Real-time substructure tests using hydraulic actuator." *J. Eng. Mech.*, 125(10), 1133–1139.

Dimig, J., Shield, C., French, C., Bailey, F., and Clark, A. (1999). "Effective force testing: A method of seismic simulation for structural testing." *J. Struct. Eng.*, 125(9), 1028–1037.

Dorf, R. C., and Bishop, R. H. (1998). *Modern control systems*, Addison Wesley, Reading, Mass.

Fletcher, J. N. (1990). "Global simulation: New technique for multiaxis control." *Sound Vib.*, November, 1990, 26–33.

Gurley, K., and Kareem, A. (1998). "Simulation of correlated non-Gaussian pressure fields." *Meccanica*, 33(3), 309–317.

Gurley, K., Tognarelli, M. A., and Kareem, A. (1997). "Analysis and simulation tools for wind engineering." *Probab. Eng. Mech.*, 12(1), 9–32.

Hamma, G. A., Stroud, R. C., Underwood, M. A., Woyski, W. B., Tauscher, R. C., and Cappel, K. L. (1996). "A review of multi-axis/multiexciter vibration technology." *Sound Vib.* April, 1996, 20–27.

Horiuchi, T., Nakagawa, M., Sugano, M., and Konno, T. (1996). "Development of real-time hybrid experimental system with actuator delay compensation." *Proc., 11th World Conf. on Earthquake Engineering*, Paper No. 660, International Association for Earthquake Engineering.

Isermann, R., Schaffnit, J., and Sinsel, S. (1999). "Hardware-in-the-loop simulation for the design and testing of engine-control systems." *Control Eng. Pract.*, 7(5), 644–653.

Kareem, A., Hsieh, C., and Tognarelli, M. (1998). "Frequency-domain response analysis of offshore platform in non-Gaussian seas." *J. Eng. Mech.*, 124(6), 668–683.

Kareem, A., Kabat, S., and Haan, F. L., Jr. (1997). "Dynamic wind load simulator." *Proc., 8th U.S. National Conf. on Wind Engineering*, Baltimore, Md.

Mahin, S. A., Shing, P. B., Thewalt, C. R., and Hanson, R. D. (1989). "Pseudodynamic test method-current status and future directions." *J. Struct. Eng.*, 115(8), 2113–2127.

Nakashima, M. (2001). "Development, potential and limitations of real-time online (pseudodynamic) testing." *Philos. Trans. R. Soc. London, Ser. A*, 359(1786), 1851–1867.

Potvin, A. F. (1993). *Nonlinear control design toolbox*, The Mathworks Inc., Natick, Mass.

Reardon, G. F. (1988). "Simulated wind loading on houses." *Proc., Int. Conf. Housing and Construction in the Age of Technology*, Gold Coast.

Reinhorn, A. M., Sivaselvan, M. V., Liang, Z., and Shao, X. (2004). "Real-time dynamic hybrid testing of structural systems." *Proc., 13th World Conf. on Earthquake Engineering*, Vancouver, B.C., Canada, Paper No. 1644, International Association for Earthquake Engineering.

Reinhold, T. A., and Kareem, A. (1996). "Next generation of wind test facilities: A feasibility study." *Proc., 2nd Int. Workshop of Structural Control, Next Generation of Intelligent Structures*, International Association for Structural Control, Hong Kong.

Spencer, B. F., and Yang, G. (1998). "Earthquake simulator control by transfer function iteration." *Proc., 12th Engineering Mechanics Conf. Engineering Mechanics: A Force for the 21st Century*, E. H. Murakami and J. E. Luco, eds., 766–769.

Stephanopoulos, G. (1984). *Chemical process control: An introduction to theory and practice*, Prentice Hall, Inc., Englewood Cliffs, N.J.

Takanashi, K., and Nakashima, M. (1987). "Japanese activities on on-line testing." *J. Eng. Mech.*, 113(7), 1014–1032.

Wang, Q.-G. (2003). *Decoupling control*, Lecture Notes in Control and Information Science, Vol. 285, Springer, New York.

Williams, M. S., and Blakeborough, A. (2001). "Laboratory testing of structures under dynamic loads: An introductory review." *Philos. Trans. R. Soc. London, Ser. A*, 359(1786), 1651–1669.

Yalla, S. K. (2001). "Liquid dampers for mitigation of structural response: Theoretical development and experimental validation." Thesis, Dept. of Civil Engineering, Univ. of Notre Dame, Notre Dame, IN.

Yalla, S. K., and Kareem, A. (2001). "Hardware-in-the-loop simulation: A case study for liquid dampers." *Proc., Joint Applied Mechanics and Materials Summer Conf.*, ASCE/ASME, San Diego.

Yalla, S. K., Kareem, A., Kabat, S., and Haan, F. L., Jr. (2001). "Dynamic load simulator: Development of a prototype." *J. Eng. Mech.*, 127(12), 1310–1315.

Zhao, J., French, C., Shield, C., and Posberg, T. (2004). "Effective force testing with nonlinear velocity feedback compensation." *Proc., 13th World Conf. on Earthquake Engineering*, Vancouver, B.C., Canada, Paper No. 268, International Association for Earthquake Engineering.