

## **Engineering Technology Laboratory for Structural Control of Structures**

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### Abstract

Structural protection using active control systems is becoming common practice due to three factors: 1) safety, in order to protect the lives of occupants; 2) the high cost of reconstruction or repair of structures including the social cost incurred while the structure is out of service; and 3) the low cost of reliable electro-mechanical systems required for implementation of an active control system.

Structural Analysis and Design (SAD) and Control and Instrumentation Electronics (CIE) are two University of Houston-Downtown Engineering Technology B.S. degree programs that are ideally related in the field of active control of civil structures. SAD deals with the analysis and design of structures, their loads, and failure modes. CIE deals with the design of systems for control of processes. The study of how to design active controls for structures that respond favorably to imposed loads and deformations is a problem that naturally connects the two disciplines.

The Engineering Technology Department at the University of Houston-Downtown (UHD) has a structural laboratory that was developed with funds provided by the National Science Foundation (NSF). After the NSF grant was implemented, the laboratory developed additional facilities for testing and determining the behavior of structures. During Fall 2001 a student appointed as a Shell Scholar (Shell Scholars are student assistants that are assigned activities that benefit other students) developed a test rig for active control of structures. The paper presents the factors used for design of the test rig and illustrates specific examples of active control of structures in the laboratory. This paper also shows how two seemingly different engineering technology majors can function in a synergistic environment for the benefit of students in both programs.

### Introduction

This paper deals with a new and challenging field that results from the overlapping of the realms of structural engineering and control system engineering. The field that was in the past a theoretical dream has become a reality due to economic factors and society's demands. Structures of significant size and importance for every day life are found everywhere. Bridges, buildings, communication towers, and dams are called civil structures because of their close interaction with community activities. Society requires a high level of unsupervised or autonomous safety in the use or operation of these civil structures.

It is interesting to compare the operational safety of a ship to that of a bridge. Ships and bridges are structures that may be subjected to the action of environmental effects affecting their

behavior including failure causing significant loss of human lives and high economic costs to society. However, their mode of operation is completely different. A ship is under constant human control and supervision and it is not expected that it will withstand unexpected loads without assistance from human operators. Economically efficient design implies human participation and control for avoidance of collisions and impact from rocks and sand bars when the ship runs aground. Thus, humans are part of the ship system because operators participate in performing the required actions to protect the system from overloads of many types.

A bridge is built and left alone to withstand all sort of actions from the environment. The structure is supposed to resist overloads due to road traffic, earthquakes, hurricanes, and collision impacts to the piers from ships and barges. This concept that was operational in the past is not satisfactory at present. New challenging structures such as the Akashi Kaikyo bridge with a span of 10,000 ft, close to twice the span of the Golden Gate Bridge, could no be built without provisions for automatic response to environmental forces<sup>1</sup>.

Structures that are designed with the ability to respond to the action of unexpected agents by triggering counteracting responses that alleviate the effect of these agents are called “active structures”. In this paper the authors concentrate on dynamic loads applied to structures. There are other external actions that trigger structural response such as the case of “smart concrete” in corrosive environments where the concrete triggers autonomous chemical reactions that protect the structural element. These cases are outside of the scope of this paper.

The Engineering Technology Department at the University of Houston-Downtown (UHD), and specifically the programs in Structural Analysis and Design (SAD) and in Control and Instrumentation Electronics (CIE) instruct students on the state-of-the-art technologies in order to prepare students that are very desirable for industrial employment in the Houston Area. According to this educational goal, the subject of active structural controls is being introduced into the programs in progressive steps.

The first step was to design testing rigs and data acquisition systems. Students of the two programs performed these tasks in Directed Study (individual project) courses. Students in Structural Analysis and Design concentrated on the design and fabrication of the testing devices that apply forces while Control and Instrumentation students dedicated their efforts to design of the data acquisition and control systems.

This paper presents the fundamental concepts of active control of structures and describes the work that has been done up to the present in active control of structures at Structures Laboratory of the Engineering Technology Department, University of Houston-Downtown. A significant portion of the work remains to be performed in the near future due to the interdisciplinary nature of the subject matter.

#### Active Structures: General principles

The concept of active structures implies systems that are able to respond to external agents with an action that alleviates the effects of the external agent. It was introduced initially to mitigate the effects of resonance in structures under the action of wind forces<sup>2</sup>. Antenna towers that had

the tendency to resonate with cross winds were provided with “spoilers”, small pieces of tread that preventing the formation of von Karman eddy.

The stabilizing systems of cruise ships are also examples of active controls systems. Ships used for pleasure cruising include hydraulic systems that move water back and forth to counteract the action of the waves. Using this stabilizing system, the ship moves through rough sea without disturbance to the passenger. It is important to observe that this stabilizing system is completely autonomous and responds to an external agent that has a random nature.

Earthquake or seismic effects present the first demand for active systems. Earthquakes produce ground accelerations that induce significant dynamic forces on structures. The first reaction of the designer is to make the structure stronger which implies a heavier and stiffer structure. However the heavier and stiffer the structure is, the larger the dynamic forces generated. The question arose in the field of seismic design for regions of high seismic activity: Is there an alternative?

The first response to this question was to make structures more flexible mimicking the behavior of a wheat straw flexed by wind. This behavior illustrates the fundamental principle of active response of structures: The system autonomously takes an action that alleviates the effect of the wind force.

The next step is to make the structure react to the external force. Professor Shuszo Ishida at the Kyoto Institute of Technology explains the behavior of a pagoda during an earthquake as follows: “The pagodas which are tall buildings rising as much as 180 feet have been rattled by countless earthquakes and still they stand as they were built 500 years ago. At first sight pagodas seem unstable since one of the many roofs carry heavy tiles. Figure 1 shows a floating central pole, the trunk of a heavy cedar tree that is the core of the structure. When an earthquake shakes the pagoda the central pole acts as a gate bar that dampens the ground vibrations and dissipates the seismic force<sup>3</sup>.



Figure 1 - Pagoda with central floating pole at the top.

The projects that have been completed at the Structures Laboratory are related to damping of excessive vibrations. The theoretical model that is currently being studied represents a bridge under the action of a moving truck. There are many anecdotic references to dramatic shakes of highway bridges under the action of insignificant loads. Professor Eugene Ripperger, a member of the Aerospace and Engineering Mechanics at the University of Texas and supervising professor of the doctoral dissertation of one of the authors of this paper, Dr. Alberto Gomez-Rivas, used to present the following case: He was doing research on bridge vibrations for the Southwest Research Institute in San Antonio Texas. As part of his work he had a bridge fully instrumented to record deflections and vibrations due to highway traffic, mostly cars and trucks. While he was performing the measurements, a Mexican farmer crossed the bridge on a donkey cart. The vibrations of the bridge were the largest recorded to the point that it appeared that the bridge was going to collapse. After that event, the farmer was hired to test the bridge again but after hundreds of tries the initial gallop that almost destroyed the bridge could not be reproduced.

This example is ideal to illustrate the need for active controls of structures. This bridge was subjected to a load and frequency that the designers did not consider. If the bridge were to include active controls, the large vibrations could trigger a damping system that would immediately reduce the vibration intensity. However, not all vibrations can to be reduced because the damping mechanism may deteriorate rapidly through time<sup>4</sup>.

#### Wind-Tunnel Test of a Bridge with Active Vibration Control

The application of active control systems to reduce wind vibration in bridges is a new area of research. H. L. Hansen, et al, presented the results of a set of wind tunnel tests on a bridge model equipped with active movable flaps<sup>5</sup>. Based on the monitored position and motion of the deck, the flaps are regulated by a control algorithm so that the wind forces exerted on them counteract the deck oscillations.

Modern suspension bridges may develop large amplitude vibrations even under moderate wind speeds, which lead to frequent closing of the bridge to traffic and the associated social and economic costs. In order to solve this problem, a new strategy is being investigated and implemented by engineers throughout the world. This strategy consists of installation of active control systems that are activated under bridge vibration situations in order to reduce vibration to acceptable levels and thus, guarantee the serviceability of the structure.

Figure 2 presents the model of the bridge deck consisting of the deck for traffic and two flaps running along the sides of the deck. These flaps are moved by servomotors in response to specific conditions of displacement and acceleration of the deck. The displacements and acceleration are measured by accelerometers attached to the model. The deck panel is supported at the ends by sets of springs that represent the boundary conditions of the panel as part of the total bridge.

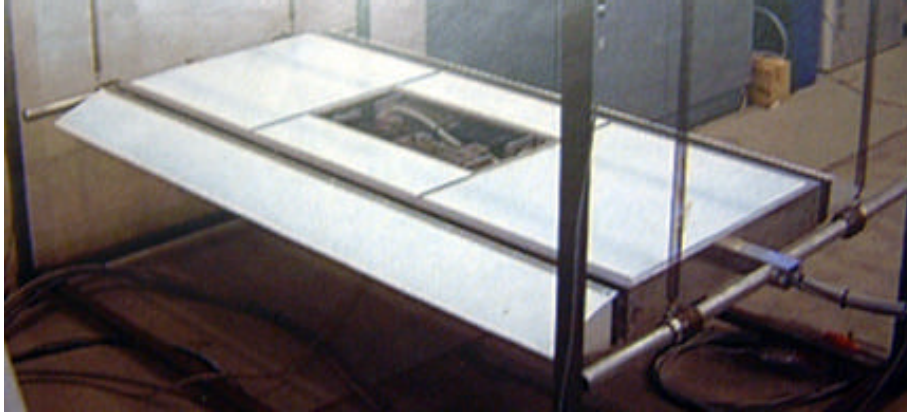


Figure 2 - Panel of the deck of the bridge model with flaps at the ends.

The regulation system to move the flaps consists of two servo systems and includes the regulation software to position the flaps and the control software to calculate the desired position of the flaps. Each servo system consists of a servo amplifier, a servomotor and reduction gear. Two servo systems are used because the flaps are regulated independently. The position regulator is basically a proportional integral derivative (PID) in the servo amplifier. Only software can regulate the flaps, i.e. there is no manual control during the experiments.

Test results indicated that the model with some configurations of the flaps produced dynamic damping far superior to the expected theoretical computations. A possible explanation for this difference is that the theoretical computations assume static positions of the flaps while the model was continuously moving the flaps, like a bird during flight, thus damping the vibrations in a more effective manner.

The results of this experiment present what is perhaps the main advantage of active vibration control. Theoretical computations by necessity assume a steady wind action and a fixed configuration of the flaps. Algorithms for active vibration control can be developed and fine-tuned to respond to a variety of situations. Therefore, it is only necessary to specify limiting conditions of displacement, acceleration and the magnitude of the corrective action.

Generic algorithms, that is, algorithms that can change themselves based on previous observations or experience, are used today in computer software that requires improvement in the event of an unexpected situation. The application of generic algorithms to active control of structural vibrations may provide safer structures that operate under uncertain environmental conditions.

#### Examples of Active Structural Control

##### \* Moby Dick Project

Professor Yukio Meada, Honorary Member of the International Association for Bridge and Structural Engineering (IABSE) considers that “Control Technology” is a critical discipline for structural engineering<sup>6</sup>. He wrote:

“In his paper at the 12<sup>th</sup> IABSE Congress in Vancouver in 1984 T. Y. Lin pointed out the importance of structural control. Engineers are being asked to design and build ever more ambitious and complex structures and to assure that they are safe, economically practicable, and environmentally acceptable. One of the best approaches to these challenges is *Control Technology*.

In Japan, my group is working to plan and design a large floating complex called the *Moby Dick* Project. It covers a circular area about 600 m in diameter and is intended as a multifunction sports, recreation and conference center with its own solar energy-generation system and water purification plant.

*Moby Dick* must be stabilized even against the most violent pitching and rolling of the sea and wind. There are many questions at the conceptual design and planning stages: active or passive control; strong or weak control; how to monitor and assess; and if devices do not exist how to create them. This project is not a single structure, but a multi-purpose system of structures. Its design, construction and operation need input from structural, electrical, biochemical, naval, and environmental engineers. Above all, control technology is the most challenging engineering task monitoring, interpreting and acting upon information gathered. The needs to assess the complex forces affecting such mega-structures and to coordinate any actions in response to those forces are challenges that call for the input from structural engineers.

Tomorrow’s structures will be even more complex to satisfy various functions and requirements. Indeed, they will become more like machines. Structural engineers have a critically important supervisory role to play. They are gaining experience with control technology and this experience has to be exchanged and discussed for the progress of future structures.”

\* The Osaka World Trade Center

This structure shown in Figure 3 stands on reclaimed land in the Osaka Bay. The building is 256 m tall with 55 floors above ground and three below. Discomforting vibrations and swaying are two problems confronting designers of high-rise structures. With buildings over 200 meters tall, wind loads rather than earthquake loads determine the design of the main structural members. Design wind loads were determined in wind tunnel experiments<sup>7</sup>.

As an additional measure to assure the comfort of the occupants, two tuned mass dampers (TMDs) were installed on the roof to reduce wind-induced motion. A pendulum weighting 50 t is computer-controlled so that its swing period counteracts that of the building. The devices were installed in opposite corners of the roof. When the average wind velocity is approximately 20 m/s, the TMDs reduced the response acceleration of the building by 50 percent.



Figure 3 - Osaka World Trade Center

#### Active Control at UHD

One of the goals of our future research effort is to include additional studies dealing with structural control systems. This is an interdisciplinary area that has profound impact on industrial applications as well as research and development. There are a number of articles in various journals reporting successful experiments and applications of structural control systems used in high-rise buildings, bridges, and other civil structures.

A function block diagram as shown below in Figure 4 can represent a structural control system. In the block diagram, there are five elements that are represented by the blocks: Structural system, Measurement, Error detector, Controller, and Actuator. Arrow-headed lines represent system variables and signals. The five elements are connected into a feedback loop with the measurement device providing the feedback signal. The main objective of a properly designed closed-loop control system is to stabilize the overall structure in the presence of environment disturbances, for example wind-induced motion or seismic impact.

Several PC-based measurement and data acquisition systems have been implemented at UHD as discussed in the following section of this paper. The immediate next step will be focused on the design and implementation of a closed-loop control system that attenuates the vibration of an aluminum beam. The controller hardware will be PC based with a DAQ (data acquisition) card from National Instrument. A number of control algorithms will be explored, starting with the conventional three-term PID (proportional-integral-derivative) control. It is felt that advanced

methods such as Genetic Algorithm may offer significant improvement on the performance over the basic on-off or PID controllers.

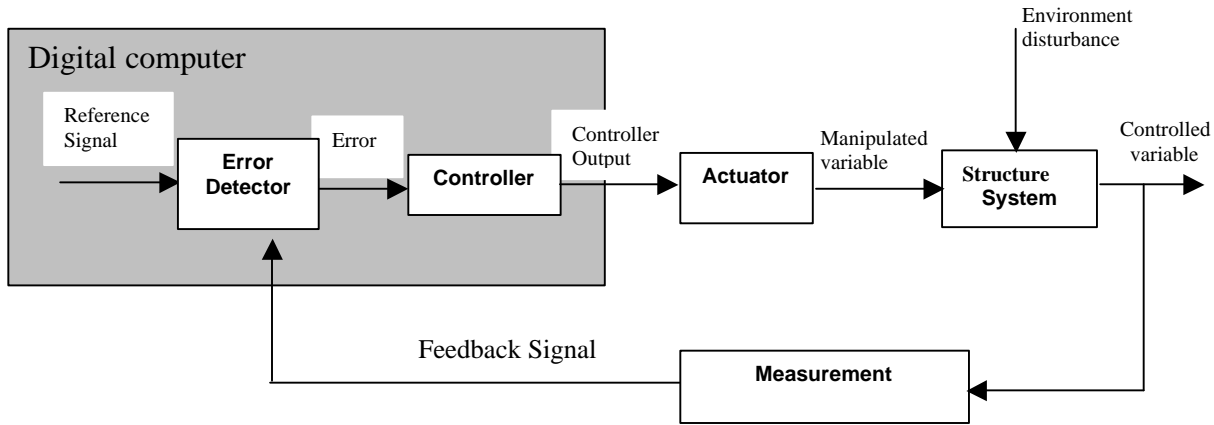


Figure 4 - Diagram of a structural control system.

#### Factors that Justify Active Control of Structures

There are two sets of factors that make active control of structures possible today and determine the feasibility of projects involving active control: cost and reliability. The first set deals with economic considerations. It is important to remember that engineering alternatives that are not optimal in overall cost, including construction and maintenance, will not be adopted in common practice. Structures with disproportionate cost of construction or maintenance will not be considered as possible alternatives. The cost of active structures can be divided into the cost of the structure and the cost of the control system. The cost of the structure should be lower than that of other alternatives in order to compensate for the additional cost of the control system.

The relative low cost of installation and maintenance of electronic equipment combining hardware and software is the factor that makes active structures economically feasible today. Control systems for active structures are based on software systems that are economical and easy to develop and program. The low cost of software is the main reason for the current application of these systems.

The second set of factors is related to the reliability of the control system. Software systems of control do not have to be soft in the sense that they will be easy to damage or erase. The logic of the controlling algorithms is built into chips with high reliability and very little or no maintenance at all.



## Programs Involved in Active Structures at UHD

Often the so-called interdisciplinary studies are forced marriages of disciplines that do not complement each other. This is not the case for structural control systems. Structural implies the field of structural engineering, one of the most traditional fields of Civil Engineering. Control in this case refers to control of dynamics systems by electronic systems integrating hardware and software components, a well-defined field within the realm of Electrical Engineering Technology.

The University of Houston-Downtown offers two programs that make for a perfect fit of the interdisciplinary field of structural control systems: Structural Analysis and Design Engineering Technology (SAD) for the structural component and Control and Instrumentation Electronics Technology (CIE) for the control part of the field. The two programs are focused in each one of the two fields: structures and control<sup>5</sup>.

SAD is a unique program dedicated to the analysis and design of civil structures including bridges, buildings, and towers, which are the structures more sensitive to dynamic loads<sup>8</sup>. Students in the program receive an education in structures that is more advanced than the one that is offered in undergraduate programs in civil engineering because of the focus on the narrower field of structures. Concentration in one field allows for intensive computer applications and laboratory testing in all courses in the program. The exposure of students to computers and testing give them an excellent background for the field of structural control. Figure 5 shows two students working on the installation of the structural control-testing rig.

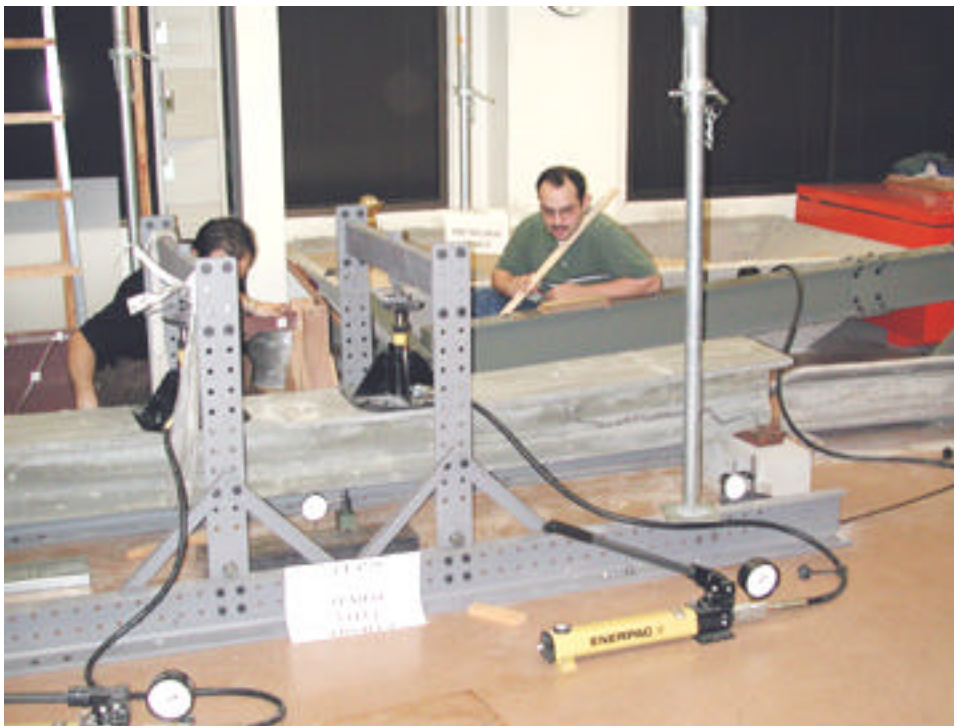


Figure 5 - Students working in installation of testing rig.

CIE on the other hand is a program with intensive concentration on the application of electronics to the problems of control and instrumentation in industrial processes. Participation in the interdisciplinary field of structural control gives students in the program a new and challenging task. Because of the concentration in instrumentation and control, students in the program have a significant comparative advantage in the field of structural control. The technology nature of the two programs makes them complimentary and oriented towards projects that can be used in practical industrial applications.

The two aspects of structural control systems discussed in this paper: structural testing and instrumentation for control correspond to SAD and CIE respectively. The fact that the laboratories for these two programs have been integrated through the applications of structural control is the first and productive byproduct of the activities in structural control at the Engineering Technology Department of the University of Houston-Downtown. Faculty from both programs work in close relationship and develop advanced knowledge of each other's fields.

The interaction of the faculty and students in the structural control program has been very enlightening and productive. Previous to the initiation of the structural control project, the CIE and SAD programs did not have anything in common. They were two isolated disciplines working in two laboratories not more that twenty feet apart. Now we consider the joint laboratory common ground and participants are very interested in the activities of the other program. Student and faculty in CIE are all of the sudden interested in structural testing and SAD personal are observing and learning operation of control systems. This cooperation makes the project highly worthwhile for the participants.

### Structural Testing Facilities

The SAD program is intensive in laboratory testing in all courses. The program has a laboratory that was developed with a grant for laboratory improvements from the National Science Foundation. The strength of the testing facilities arises from the extensive testing experience of the faculty and the cooperation of students with industrial experience in the design and construction of the equipment. One testing rig use for this project is presented in Figure 6.



Figure 6 - Testing rig for the structural control project.

This device was designed and built by a student in the SAD program. It is important to emphasize that UHD is a teaching university and that research is always oriented towards teaching modern technologies. Students gain experience that makes them very desirable in industry when they design and construct equipment as part their university studies.

#### Control and Instrumentation Laboratory

The CIE program has a laboratory with excellent hardware and software for control and simulation of processes as typically found in petrochemical, oil refining, and other industries. Faculty and students in the program develop control systems using industrial standard packages such LabView, which includes hardware and software components. What is more interesting is the intensive development of control systems using Visual Basic and that are developed from scratch by teams in the control laboratory. A good example of the control applications is a temperature-sensing system that transmits data to all computers in the laboratories by a wireless network. This network is in process of development to achieve a goal that the program developed several semesters ago: To do wireless process control.

The control laboratory and in general all laboratories in the department are more workshops than science laboratories because they are used to teach students modern technologies and to provide students with opportunities to gain valuable practical experience. This fact makes the laboratories very attractive to students that can demonstrate their creativity in development of modern technological applications. Figure 7 shows a member of the faculty developing software for active control devices. Figure 8 shows a student calibrating a LabView system for applications in control of a structural system.



Figure 7 - Software development for instrument used in active control testing.





Figure 8 - Student using LabView during structural control testing.

Students and faculty work in the structural laboratory in close contact. Figure 9 shows students during presentation of a final project in a course in control and instrumentation.



Figure 9 - Presentation of final project in control and instrumentation

## Conclusions and Future Developments

- \* Structural Analysis and Design (SAD) and Control and Instrumentation Electronics (CIE) are two University of Houston-Downtown Engineering Technology B.S. degree programs that are ideally related in application of active control of civil structures. This paper also shows how these two seemingly different engineering technology majors can function in a synergistic environment for the benefit of students in both programs.
- \* The two aspects of structural control systems discussed in this paper: structural testing and instrumentation for control correspond to SAD and CIE respectively. The laboratories for these two programs have been integrated through applications of structural control.
- \* Faculty from both programs work in close relationship and develop advanced knowledge of each other's fields. The interaction of faculty and students in the structural control activities has been very enlightening and productive. Student and faculty in CIE have become interested in structural testing and SAD personnel are observing and learning operation of control systems.
- \* The paper describes the factors used for design of a test rig used by engineering technology students where structural control methods are applied. Other specific examples of active control of structures in the laboratory and in the field are discussed.
- \* This paper serves as a planning tool for future activities of the structural control project. In the immediate future, instrumentation will be improved by inclusion of additional sensors and the incorporation of LabView in the system. Students and faculty continue to present projects during their participation in the Advanced Design Project program sponsored by the Texas Space Grant Consortium in which the Engineering Technology Department at UHD has participated for the last seven years.
- \* A specialized course in the field "Structural Control Systems" will be offered in the next academic year. The course will be open to students in the Structural Analysis and Design and the Control and Instrumentation Electronics programs.
- \* Proposal for grants to continue the project and at the same time improve the laboratories are being prepared taking into consideration applications of structural control for the Houston area where offshore and land structures are frequently subjected to high velocity wind gusts of tropical storms. Another positive factor is the positive track record of the structural laboratory that was initially developed several years ago through a grant from the National Science Foundation.

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## Biographical Information

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Alberto Gomez-Rivas is Professor of Structural Analysis and Chair of Engineering Technology. Dr. Gomez-Rivas received Ph.D. degrees from the University of Texas, Austin, Texas, in Civil Engineering and from Rice University, Houston, Texas, in Economics. He received the Ingeniero Civil degree, with Honors, from the Universidad Javeriana in Bogotá, Colombia. He also served as Chief of Colombia's Department of Transportation Highway Bridge Division.

### WEINING FENG

Weining Feng, PhD, is Associate Professor of Process Control and Instrumentation in the Engineering Technology Department, University of Houston-Downtown. Dr. Feng received a Ph.D. from the Department of Electrical and Electronic Engineering, University of Strathclyde, Scotland, in 1990. She is in charge developing UHD's Control and Instrumentation laboratories and serves as director of the Process Control and Instrumentation program.

### GEORGE PINCUS

George Pincus is Dean of the College of Sciences and Technology, and Professor at the University of Houston-Downtown (1986-date). Prior service includes Dean of the Newark College of Engineering and Professor, New Jersey Institute of Technology (1986-1994). Dean Pincus received the Ph.D. degree from Cornell University and the M.B.A degree from the University of Houston. Dr. Pincus has published over 40 journal articles, 2 books and is a Registered Professional Engineer in 5 states.