

# Modeling the Vibrations and Energy Flows in Complex Dynamic Systems

WENLONG LI<sup>1</sup>, and HONGAN XU<sup>2</sup>

<sup>1,2</sup>Mississippi State University, Mississippi State, MS 39762, USA.

E-mail: li@me.msstate.edu

*ABSTRACT: This international research cooperation is aimed to further and widen the scope of the ongoing research about developing a general methodology for the vibration and energy flow analyses of complex dynamic systems. The unique advantages of this modeling technique are explored and demonstrated through employing it to active control of structural vibrations. In the process, some important questions and concerns in active vibration control have been discussed which include how the modal truncation errors affect the number of control forces, how to select the appropriate number of error sensors, what are the optimal control locations, and so on. In addition, the control of power flows in dynamic systems is studied in terms of smart joints which apply both active forces and moments for improved performance and efficiency. A new control strategy based on the concept of vibration-free state is also proposed to reduce vibrations and confine disturbance sources. The significance and impact of this international research experience is not limited to the technical achievements. It also gives American researchers and students the opportunities of acquiring research skills, developing long-term relationship with world-leading researchers, learning about different cultures, and understanding diversity issues. In view of the global economy and the increasing speed of globalization in other aspects, the international cooperation experience is critical to maintaining our world leader position from economy to international affairs. We firmly believe this IREE international cooperation program represents a time- and cost-efficient means of promoting intellectual, educational, social and cultural exchanges between American researchers, students and institutions with their international counterparts.*

## INTRODUCTION

The work being carried out at Mississippi State University under the current NSF award is to develop a general and sophisticated method for the dynamic analysis of built-up structures. It is also aimed at filling the long existing mid-frequency gap in structural dynamics analysis. The general approach of the research is to divide a complex structure into a number of subsystems, based on an innovative idea in which the solution on each individual subsystem is sought in the Fourier space rather than in the conventional physical (or Euclid) space as adopted by most existing methods. Since started in September, 2005, this research has progressed significantly regarding solution

algorithms, basic component-level models and the interactions of components under most general boundary or coupling conditions. The unique advantages and excellent numerical characteristic of this modeling methodology have been demonstrated repeatedly for different structural dynamics problems.

In order to broaden the impact and the dissemination of the research results, we believe it is critical to extend this new technique to active vibration control research. This is not only because the fact that active vibration control continues to attract substantial attentions and efforts, but also due to its constant demanding and searching for more accurate and more effective models. Thus, it is of technical merit and challenge to be able to demonstrate the unique advantages of this new technique successfully for active vibration control problems.

The host laboratory is the ANVC Group in the School of Mechanical Engineering at University of Adelaide in Australia. The ANVC Group is well known for its work of international significance in the field of active noise and vibration control as well as for its work on various other aspects of control and acoustics. ANVC group is one of the largest of its kind in the world and it regularly hosts visitors from overseas institutions and has become a place of choice for well-known academics to spend their sabbatical leave. The ANVC group meets every 2 weeks during which a seminar from one of the group members is presented. So there exists a stimulating intellectual environment which also contributes substantially to the education of the twelve graduate students who are part of the group. In addition to the graduate students, the group consists of three full time academic teaching staff and five full-time research fellows. The University (city) of Adelaide boasts a vibrant cultural heritage and multi-ethnic mix which attract visitors from all over the world.

This international experience also provides an opportunity for American researchers and students to evaluate and learn from other educational systems with respect to both research and teaching. In particular, we like to start and establish, through this international collaboration experience, a long-term research and education partnership between these two research groups, and eventually between the two institutions. Two U.S. researchers, Dr. Wen Li and Mr. Hongan Xu (Ph.D. student) traveled to University of Adelaide in Australia. They worked closely with the ANVC group for three months last summer from May 9 to August 9. This cooperation is an experience valued highly by us and by our Australian counterparts as well.

## **RESEARCH ACTIVITIES AND ACCOMPLISHMENTS OF THE INTERNATIONAL COOPERATION**

The international research cooperation was focused on demonstrating the advantages and exploring new opportunities through applying this new methodology to active vibration control research. The program is highlighted below:

### 1) Wave vs. Modal Descriptions

Modal and wave approaches are the most widely used in active vibration control research, each of them has advantages and disadvantages depending upon the

applications and performance requirements. However, these two approaches sometimes appear to lead to different conclusions or observations from control implementation to the performance. Understanding the difference is important to controller design, control implementation and performance. The errors in a modal model and the corresponding effects on the spatial derivative and energy flows were studied against the truncation schemes, the number of error sensors, and their locations. For instance, the convergence behavior of the modal approach is shown in Figure 1 for various truncation schemes when a single control force is applied to a beam structure. It is seen that as more modes are included the displacement expansion, the modal solution will approach to the wave solution which is exact in this case.

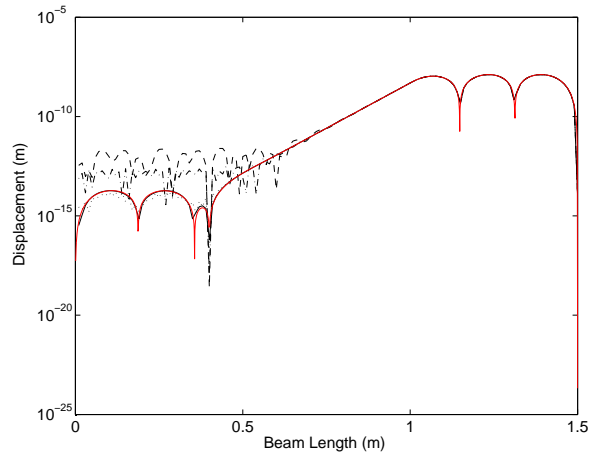


Figure 1. Comparison of control performance between modal and wave approaches for a beam structure under the action of a single point force.

## 2) Vibration-Free State and Source Confinement

The concept of vibration-free state was recently proposed for active control of beam vibrations through creating artificial boundary conditions. It is shown that the vibration-free state exists on a section of beam regardless of the exact location of the artificial B.C. This implies that the control effort will at most depend only upon the actuator locations. We extended this active control idea by replacing artificial B.C. with a much simpler and more effective control goal in which the vibrations are to be suppressed at two selected locations. The issue of optimal actuator locations is also studied to minimize the control effort. The genetic algorithm (GA) was used to seek the best actuator locations. For active beam vibration control, only two actuators will be needed and their optimal placements are identified, as illustrated in Figure 2.

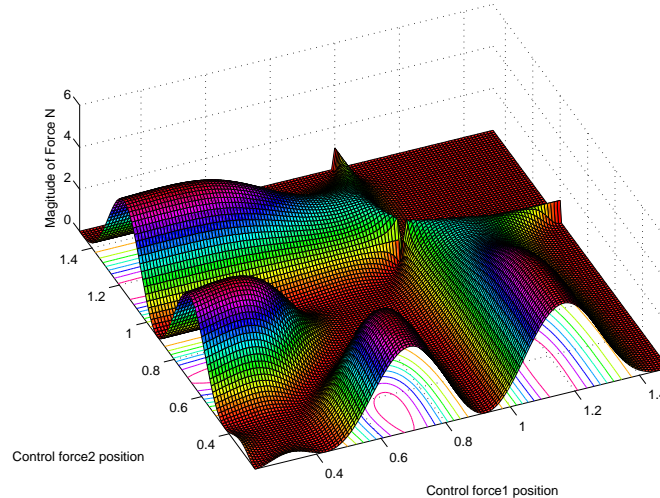


Figure 2. The optimal combination of control locations determined based on genetic algorithm.

### 3) Active Joints to Regulate Power Flows

Instead of suppressing vibrations at selected locations, minimizing and regulating the vibratory power transmissions may often constitute a more effective means to actively control structural vibrations. In this study, an active or smart joint was used to regulate the power flows and vibration distributions in a dynamic system. The smart joints, in comparison with the existing ones, can simultaneously apply both forces and moments to the connecting structures to maximize the control performance.

Throughout the entire visit, the interactions between visiting and host researchers are intensive and multi-faceted. First of all, the researchers have given the complete access to internet, library, lab facilities, and the technical documents (papers and reports) and database. Many of the aforementioned tasks will be impossible without the active involvement, and the full cooperation and supports from our hosts, especially in the experimental studies which are not explicitly described here due to space limit. We also received valuable helps from graduate students at the host institution from answering simple questions to assisting test setup. By routinely attending departmental seminars and participating in and reporting progresses at group meetings, we feel and are treated like a regular member in the host laboratory.

#### **BROADER IMPACTS OF THE INTERNATIONAL TRAVEL**

The research activities described above are directly related to the objectives of the research conducted under the current award. This international collaboration has greatly enriched and extended the scope of the current work, and significantly broadened its impact on both research and education. Active vibration control, through decades of

intensive research, has progressed substantially in terms of both technologies and applications. Hardware including sensors and actuators has in particular fueled the rapid advancement of active control technology. However, the ways in which the dynamic behavior of a structure is modeled have not changed much in comparison, even though a better modeling method is in critical need to improve control algorithms, implementation, and performance. The new methodology developed under the current award offers a great potential to advance active vibration control in terms of both research and applications.

Through this international experience, the two research groups are effectively bonded together to form an international team to tackle the problems of broader interest and concerns. This international experience has promoted diversity which can be defined in a broader sense to also include different styles and skills related to research and learning. Living and working in other countries is an effective way to learn and assess the advantages and effectiveness of different educational systems and research practices. During the visit, we have an opportunity to meet many people and talk with them about various subjects from local news to an event of international interest. Through these contacts, we have also directly or indirectly promoted the international awareness about the research and education programs at the awardees institution.

#### **DISCUSSION AND SUMMARY**

The current research has been significantly expanded and enriched by applying the new modeling method to the active control of structural vibrations. Its unique advantages are successfully explored and demonstrated through addressing several important issues and concerns in active control research and applications. First, the truncation errors in a modal description are studied with respect to their effects on the selection of an optimal number of actuators, the locations of error sensors, and the control strategies and performance. The newly proposed concept of vibration-free state is extended to confining the disturbance sources, and to regulating the vibratory power flows in a structural system. The genetic algorithm is employed to determine the optimal actuator locations to minimize the control effort. An active control of power flows is also investigated through the use of active or smart joints which exert both control forces and moments for improved performance and efficiency. The active forces can be applied differently at the upper and lower terminals of each joint. The above investigations have not only meaningfully extended the scope of the current work, but also significantly broadened its impact to active vibration control research and applications. A series of experimental tests were conducted at the host laboratory to verify the research results and findings.

In addition to the aforementioned accomplishments, this international cooperation is considered very valuable from other non-technical perspectives. This IREE Program provides an avenue and short-cut for American researchers and educators, especially those in their early careers, to associate themselves with the best researchers and institutions in the world. Of equal importance, it also gives American students an opportunity of developing research skills, working with foreign researchers and students, learning about different cultures, and understanding diversity issues. In view of the increasing speed of globalization including global economy, such an international

experience for American educators and students is critical to maintaining our country's influence and leader position in the world from economy to international affairs. The U.S. researchers and students, through this international experience, have generated an international awareness about the research and education programs at the awardees institutions. We believe this IREE program represents a time- and cost-effective means to promote intellectual, educational, social and cultural exchanges between American researchers, students and institutions with their international counterparts.

### ACKNOWLEDGEMENTS

This research is supported by NSF Grant CMS-0528263 under the supervision of Dr. Eduardo Misawa.

### BRIEF BIOGRAPHIES OF RESEARCHERS

**Wen Li** received the B.S. degree in Physics in 1982 from the Liaoning Teachers University in Dalian, China, and M.Eng. in 1984 from Beijint Institute of Technologies in Beijing, China. He received his Ph.D. degree in Mechanical Engineering from University of Kentucky in 1991. He is currently Associate Professor in Mechanical Engineering at Wayne State University. He was Associate Professor at Mississippi State University from 2004-2007. Before that, he worked as: *Principal Engineer* at United Technologies Research Center (1/2002-8/2004); *Senior Staff Engineer* at Carrier Corporation (5/1995-12/2001); *Technical Specialist* at Case Corporation (11/1992-4/1995). His research interests include dynamic systems, acoustics, noise and vibration control, and numerical methods.

**Hongan Xu** received the BS and M.Eng. in Mechanical Engineering from Beijing Institute of Machinery Industry in 1998 and 2001. Mr. Hongan Xu came to the U.S. in August, 2005 to become a Ph.D. student in the Department of Mechanical Engineering at Mississippi State University. He received his Master degree in 2001 from the Department of Mechanical Engineering and Applied Electronics Technology at Beijing Institute of Machinery, Beijing, China. From 2001-2005, he was a research associate in the Department of Mechanical Engineering at Beijing University Technology, working on machining dynamics, cutting mechanics and mechanistic process modeling techniques.