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Human-Structure Interaction
-- Applying body Biodynamics into Structural Dynamics

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1. The grant

The project was started from 1 April 2003 and completed on 31 July 2006 including a three-month extension without increasing the budget. The extension was granted in 2004 due to the unexpected changes of the researchers.

An EPSRC project, *predicting floor vibration induced by walking loads and verification using the available measurements*, was awarded for a two-year period between 1 August 2004 and 31 July 2006. Both the Leverhulme and EPSRC projects were allocated costs for a part-time technician. As we had a PhD student being involved in the study for conducting tests, it would be beneficial to the two projects if an additional RA post could be created using the costs allocated for a technician. Approved by the Leverhulme Trust, EPSRC and the head of Department, an additional RA (Dr Ding Zhou) was appointed to conduct research on the two projects. The researchers and their working periods on this project are listed as follows:

Dr Zemin Geng	RA	01/04/2003 – 31/12/2003	Full time
Dr Dongwei Wang	RA	12/04/2004 – 14/08/2005	Full time
Dr Ding Zhou	RA	10/08/2004 – 31/07/2006	25% 15/08/2004 – 31/12/2005 Full time 01/01/06 – 31/07/06
Mr Ernesto Duarte	PhD student	01/01/2004 – 31/03/2007	Full time sponsored by the Mexican Government, subsistence was provided from the project
Dr Brian Ellis	Consultant	provided advice on the development of the project	

Although it was disappointing in the first year of the project, measures were then taken, which included the appointment of an additional RA shared with the EPSRC project and involvement of a PhD student in the project. For fully realising the researchers' potentials, Dr Zhou is arranged to conduct theoretical study; Mr. Duarte experimental investigation and Dr Wang involved in both theoretical and experimental studies. All researchers worked at the site of the University. The actual expenditure of the project is less £10 overspending.

2. Objectives

The following was quoted from my proposal for the application in 2002:

This project aims to develop the new topic, human-structure interaction, which links body biodynamics and structural dynamics. The new topic will be developed by applying existing knowledge in body biodynamics to structural dynamics, identifying some dynamic characteristics of human whole-body and investigating systematically several issues of structures relating to human body models as an individual and as a crowd. The specific objectives are:

a) to apply available body biodynamics knowledge into structural dynamics
b) to obtain basic dynamic characteristics of the human whole-body in sitting and standing positions
c) to establish the basic theory of human-structure vibration
d) to understand the effects of different human whole-body models in structural vibration
e) to identify global response of the human whole-body to structural vibration
f) to examine the possibility of natural reduction of the human induced structural vibration

The investigator is pleased to report that five (*a*, *c*-*f*) of the six objectives have been successfully achieved, which is reflected in a series of publications listed on the last page of the report. People in seated positions listed in Objective b have not been tested in this project due to the limitation of the test rig. On the other hand, we have conducted much more work which was not described in the proposal due to the progress of the research.

Some research outcome is more significant than expected when the proposal was written, which will be detailed in Section 4. The project was benefited by having two RAs for some months, they had effectively contributed to the project. A PhD student was arranged to participate in the project for completing his thesis. It was beneficial to the student for being involved in the research of a challenging topic and to the project from the student's contribution.

3. Research Activities

A research team, the principal investigator, two Research Associates and a PhD student, was formed to work on the project. Two internal seminars were organized to report and comment on the research progress made by each individual. This not only helped to improve the presentation skills of the RAs and the PhD student but also enhanced the communication between the researchers.

As the project concerns both human bodies and structures, the study was conducted taking an integrated approach of both body biodynamics and structural dynamics, and both theoretical and experimental investigations. Some fundamental questions/problems were addressed on which the research had focused. These questions include:

- A crowd on a structure is often represented by a two degrees-of-freedom system for analysis where the crowd and the structures are modeled as two single degree-of-freedom systems respectively. Is this simplification correct? What is the relationship between the actual continuous models and the simplified discrete models?
- It has been identified that a stationary body acts as a mass-spring-damper and a person jumping acts as a loading solely. What are the body models in structural vibration when people moves between stationary and jumping, such as bouncing/bobbing or walking?
- What are the human body models in structural vibration? Can the models developed in the study of body biomechanics be applied into structural vibration?
- Why were only one resonance frequency observed in site and laboratory experiments while a human-structure system is considered as a two degrees-of-freedom system?
- What is the significance when human-structure interaction is considered in engineering practice?

Seeking the answers of the above questions and adopting appropriate methods for solutions made the research progress in a right track.

4. Conclusions and Achievements

The most significant findings of the project include:

(1) The qualitatively exact human body models are established based on a vibrating environment [8, 14] while all other body models in body biodynamics and structural dynamics were developed based on a non-vibrating or semi-vibrating environment;
(2) Human body models in vertical and lateral structural vibrations for standing, bouncing (vertical vibration only) and walking are experimentally identified based on over 700 tests [4, 12, 16]; and
(3) The relationships between continuous and discrete human-structure systems are established [1, 2]. These provide fundamentals for using the simplified discrete models in the study of human-structure interaction.

The other contributions from the research include:

(1) Explanations are provided why only one resonance frequency can be measured in practice and the necessary condition for observing the two resonance frequencies of a human-structure system is provided graphically [17].
(2) The frequency characteristics of a highly damped human-structure system are investigated and the relationships between the resonance frequency and natural frequency of the system are provided graphically [6].
(3) The outcome of the project has been linked to the design of sports structures and floors where a crowd is involved [15].

5. Publications and Dissemination

The current research has generated three journal papers published or in press [1-3], five other journal papers submitted [4-8] and five conference papers presented [10-14]. An invited journal article (not refereed) about human-structure interaction was published for providing the basics to engineers [9]. The full list of the publications is given on the last page of the report.

The other disseminations include:

- providing a poster, *Grandstands and Spectators*, at the UK-Singapore: Sports Science and Engineering, in Singapore starting from 17 June 2005, through the International Office of the University of Manchester.
- giving an invited plenary lecture, *Grandstands and Spectators*, at the 11th National Conference on Spatial Structures, Nanjing, China, 22-25 June 2005.
- delivering an invited lecture, Sports Structures Used for Pop Concerts [13], at the IASS (International Association for Shell and Spatial Structures) Symposium, New Olympic, New Shell and Spatial Structures, Beijing, 16-19 October 2006.
- A section, Human Bodies in Structural Vibration, partly abstracted and complied from this project has been added into our website, *Seeing and Touching Structural Concepts* [W1], for students, lecturers and engineers in civil engineering and related disciplines.
- A website about the project was created when the project was awarded. The summary and outcome of the project are now added into the website [W2].

Consultancy was provided on the measurement of natural frequencies of the Goven stand of the Ibrox stadium before and after its extension and on the vibration assessment of the Wembley National Stadium.

6. Further Research

A proposal, *Serviceability and Efficiency of Sports Structures for the London Olympic Games*, has been submitted to the EPSRC for applying for a Senior Research Fellowship. Two of the four tasks in the proposal are developed based on the Leverhulme Trust project.

A new PhD student has been arranged to continue the study of human-structure interaction since October 2006.

7. Key Words

Human-structure interaction, body biodynamics, structural dynamics, body models, experimental identification.

List of Publications

Journal Papers (refereed)

1. *Zhou, D and Ji, T, (2006), Dynamic characteristics of a beam and distributed spring-mass system, International Journal of Solids and Structures, Vol.43, No. 18-19, 5555-556.
2. *Zhou, D and Ji, T, (2006), Free vibration of rectangular plates with distributed spring-mass, International Journal of Solids and Structures, Vol.43, No.21, 6502-6520.
3. *Zhou, D and Ji, T, Estimation of dynamic characteristics of a spring-mass-beam system, Journal of Shock and Vibration, in press.
4. *Ernesto, E and Ji, T, The action of individual bouncing on structures, submitted to Structures and Buildings, The Proceedings of the Institution of Civil Engineers.
5. *Zhou, D and Ji, T, Dynamic characteristics of rectangular plates attached with discrete sprung masses, submitted to the Journal of Sound and Vibration.
6. *Wang, D and Ji, T, Dynamic characteristics of a highly damped two degrees-of-freedom system, submitted to the Journal of Sound and Vibration.
7. *Zhou, D and Ji, T., Mathematical Modelling of a Human-Structure System: Standing Body, submitted to Applied Mathematical Modelling
8. *Ji, T and Zhou D, Models of a standing body in a vertical vibrating environment, submitted to the Journal of Sound and Vibration

Journal Paper (not refereed)

9. *Ji, T., (2003), Understanding the interactions between people and structures, The Structural Engineers, Vol.81, No.14, pp.12-13.

Conference Papers

10. *Ji, T. and Wang, D, (2004), The natural frequency of a seated person in structural vibration, The 39th United Kingdom Group Meeting on Human Response to Vibration, Ludlow, England, 15-17 September 2004.
11. Duarte, E and Ji, T, (2005), Bouncing loads induced by an individual, The 6th European Conference on Structural Dynamics, Paris, September 2005.
12. *Duarte, E and Ji, T, (2006), Measurement of human-structure interaction in vertical and lateral directions: a standing body, ISMA International Conference on Noise and Vibration Engineering, Leuven, Belgium, September 18-20 2006.
13. *Ji, T and Ellis B R (2006), Sports stadia used for pop concerts, International Association for Shell and Spatial Structures Symposium: New Olympics, New Shell and Spatial Structures, Beijing, China, 16-19 October 2006
14. *Ji, T, (2006), Qualitative comparison of human body models in a vibrating environment, The 41st United Kingdom Group Meeting on Human Response to Vibration, Farnborough, England, 20-22 September 2006.

Special Publications

15. Ellis, B R and Ji, T, (2004), BRE Digest 426, Response of Structures Subject to Dynamic Crowd Loads, ISBN 1 86081 1744, 12 pages, second edition.

Papers to be submitted

16. Duarte, E and Ji, T, Experimental identification of human body models in structural vibration: standing, bouncing and walking, to be submitted to the Journal of Sound and Vibration.

Websites

W1: Ji, T and Bell A J, (2006), Seeing and Touching Structural Concepts, www.structuralconcepts.org
W2: *http://personalpages.manchester.ac.uk/staff/tianjian.ji/research/hulme/human.htm

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