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Edited by:

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Paola Forte
Miha Boltežar
Michael J. Brennan
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Proceedings of the

XI International Conference on Recent Advances in Structural Dynamics

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XI International Conference on Recent Advances in Structural Dynamics

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Preface

On behalf of the Organising Committee, it is a pleasure to welcome you to Pisa for the XI International Conference on Recent Advances in Structural Dynamics (RASD 2013). Some of you may have attended many of the previous conferences and may be surprised that this time we are not meeting in Southampton! We really hope that bringing RASD 2013 to Pisa will be stimulating and that all of you will have an enjoyable conference.

The conference is devoted to theoretical, numerical and experimental developments in structural dynamics and their application to all types of structures and dynamical systems. The conference will reflect the state-of-the-art structural dynamics and dynamical systems in science and engineering practice and is an opportunity to exchange scientific, technical and experimental ideas.

The Conference Proceedings include 127 papers by authors from over 25 countries and are contained on a USB memory stick attached to your lanyard. You will find this inside the conference folder together with the book of abstracts and this programme which may help you in planning your attendance.

The conference will be held at the Polo Didattico Universitario Fibonacci (Ex Marzotto, Via Buonarroti 4, 56127 Pisa, Italy), which is close to the Leaning Tower and the Cathedral of Pisa. Registration will take place from 5:00pm to 7:00pm on Sunday 30 June in the main entrance hall on the first floor of the conference venue (RASD 2013 registration desk, tel: +44 (0)7786277986 or +39 3773213562). Further registration will take place from 8.00am on Monday 1 July. Please enter the building by the main entrance on Via Filippo Buonarroti and follow the RASD 2013 signs to the registration desk.

The four lecture theatres being used are the Auditorium and Rooms 1, 2 and 4. To locate the lecture theatres refer to the floor plan of the Polo Didattico Universitario Fibonacci on the last page of this programme. Tea and coffee will be served on the first floor in the morning and between the two technical sessions in the afternoon. Lunch will be served in the same area. You will also be able to buy tea, coffee and light refreshments from a kiosk café just outside the venue from 10:00am to 3:00pm.

Following the afternoon session on Monday, there will be a conference reception at the 'Palazzo del Consiglio dei Dodici', in Piazza dei Cavalieri, which is a short walking distance from the conference venue. The conference reception is for all delegates and accompanying persons. On Tuesday evening there will be a conference dinner at the 'Chiostro della Chiesa di Santa Maria del Carmine' in Corso Italia, 85. Again this is walking distance from the conference venue, just the other side of the river Arno.

I would like to thank the members of the Organising Committee and the Conference Secretariat for their considerable help. In particular I would like to thank the DICI (Department of Industrial and Civil Engineering) of the University of Pisa for hosting this conference.

I hope you will all have an interesting and exciting meeting and a pleasant stay in Pisa.

Emiliano Rustighi

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XI International Conference on Recent Advances in Structural Dynamics

Abstracts

Plenary Sessions

09:00

Dynamic Simulation and Analysis for Sustainable Transport Systems

Suda, Y. *, University of Tokyo, Japan.*

For the achievement of sustainable society, the energy efficiency of transportation system has become more important. “Low Emission & Energy Saving”, “Safety & Security” and “Comfort & Healthy” are important target for the sustainable transportation. The activities of the Advanced Mobility Research Center established in the Institute of Industrial Science, The University of Tokyo for the integrated research of human-vehicle-infrastructure in April 2009 concentrated to the following three topics: Research and development of ITS (Intelligent Transport System) for road traffic and automobiles, Advanced Public Transit System, and Personal Mobility.

For these topics, the research and development of various types of vehicles are made using dynamic simulation and analysis have been conducted. The use of motion simulator and analyses using hardware-in-the-simulation technologies are useful methods in these research areas, and it requires real-time simulation and detailed modeling in the vehicle motion. The application of control technology to improve vehicle behavior and ride comfort becomes very important. The modeling for vehicles for controlling is required by the simple and reduced degrees of freedom, however, the precious multibody dynamic simulation are also necessary to confirm the availability and check the control performance. Especially, the modeling of interface of road and tire in automobiles, rail and wheel in railway vehicles are key points for modeling. The validation of dynamic simulation is also important process for development of advanced mobility. Scaled model experiments and full scale experiments should be made under the fixed conditions of parameters affected to the vehicle motion.

In this presentation, the author will show examples of dynamic simulation and analysis using various modeling and simulation.

Notes

13:40

Development, Evaluation and Application of a Wake-Oscillator Model for Vortex-Induced Vibrations of Marine Risers

Metrikine, A., *TU Delft, The Netherlands.*

This presentation is devoted to bending vibrations of vertical, submerged pipelines (risers) in marine currents. The focus is placed on the phenomenon of vortex-induced vibrations (VIV), whose origin is as follows. When a sea current flows about a riser, the streamlines separate from its outer surface and vortices are formed in the downstream wake. The alternate shedding of the vortices results in oscillating lift and drag forces. The lift force oscillations have zero mean value and their frequency follows the Strouhal relation and increases proportionally to the flow velocity as long as the riser does not move significantly. The drag force has a significant mean value and oscillates around it with twice the Strouhal frequency. The above-described regime takes place provided that the frequency of lift force is not close to one of the resonance frequencies of the riser. Otherwise, the riser may start to vibrate predominantly in cross-flow direction with a perceptible, yet being a fraction of its diameter, amplitude. This vibration cardinally changes the vortex pattern and causes the vortices to shed with a constant frequency equal to the resonance frequency at a wide range of the flow velocities. This nonlinear phenomenon is called frequency lock-in. It should be noted that VIV of marine risers is an undesirable phenomenon indeed as it significantly shortens the service life of the risers.

Several approaches can be used to model VIV of marine risers. In this presentation a family of the so-called wake-oscillator models will be discussed. Those models are phenomenological and, therefore, should be checked against a carefully chosen set of experiments. The experiments, which the wake-oscillator models should satisfy will be discussed in the presentation and then the validity of existing wake-oscillator models will be evaluated. As the wake-oscillator models are nonlinear, a criterion will be proposed for the assessment of the physical correctness of the chosen nonlinearity. Thereafter, a recently developed wake-oscillator model will be presented that takes into account both drag and lift forces. Finally, the latter model will be applied to model VIV of a deep-water riser with intermediate constraints.

<u>Session 1</u> Nonlinear Vibrations I

10:30

On the Behavior of Post-Buckled Plates (838)

Virgin, L.N. and Lyman, T., *Department of Mechanical Engineering, Duke University, Durham, USA.*

When loaded beyond their initial critical loads, plates continue to exhibit positive stiffness, and it is useful to gain some insight into possible equilibrium configurations, natural frequencies and vibration mode shapes in the post-buckled regime. In this paper use is made of continuation methods, whereby a solution to an underlying problem is tracked including into the heavily post-buckled regime. The stability of resulting equilibrium paths is automatically assessed since the method relies on the computation of local Jacobian matrices. When paired with a Galerkin approximation, continuation methods are shown to be well suited to solving non-linear buckling problems. In addition to providing a robust solution method for nonlinear equations, it is relatively easy to extend the continuation approach to extract natural frequency and mode shape information. Using the continuation package AUTO, primary and remote secondary equilibrium branches are identified, and followed as a function of axial load. The effect of initial geometric imperfections are included together with some comparisons with experimental data.

<u>Session 2</u> Vibroacoustics I

10:30

A Comparison of Two In-Situ Transfer Path Analysis Methods (1030)

Moorhouse, A.T., Zafeiropoulos, N., Mackay, A. and Senapati, U., *Acoustics Research Centre, University of Salford, UK.*

The need for improving fuel efficiency and driving dynamics has an effect on modern vehicles structures. Currently most of them are assembled by various mechanical parts, like suspension systems, mounts, chassis and body structure that differ in terms of structural dynamics. The integration of all these parts results in a mechanical system that can be prone to structureborne noise. Advanced vibro-acoustic measurement techniques are used to identify the structural sources that cause the low frequency noise in the compartment. There are advantages in methods not requiring disassembly of the vehicle structure, e.g. OTPA, iTPA (in-situ TPA) the latter has been also proven recently to provide reliable results on vehicles and other complex structure. Here another Transfer Path Analysis approach is investigated that does not require any physical blocking or disassembling of the structure. The concept of blocked transfer paths was proposed by F. X. Magrans in the early ’80s and is referred as Advanced Transfer Path Analysis (ATPA). This method allows the identification of the transfer paths between two parts of the vibro-acoustic system under blocked conditions at the interface between the source and the receiver structures. Therefore this method is potentially a useful tool for structureborne noise analysis in vehicles, where many tests are necessary for identifying the structural characteristics of individual transfer paths that contribute to the noise in the compartment. The validity of ATPA is compared with experimental results from iTPA that were obtained from a beam-plate structure.

<u>Session 3</u> Structural Health Monitoring

10:30

Reflection and Transmission Coefficients from Rectangular Notches in Pipes (885)

Popplewell, N., Stoyko, D.K., and Shah, A.H., *Department of Mechanical and Manufacturing Engineering, University of Manitoba, Canada.*

The use of a single, non-dispersive ultrasonic guided wave mode is one important approach to monitoring a structure's health. It is advantageously non-destructive with the ability of propagating over tens of metres to detect a hidden defect. The dimensional assessment of a defect, on the other hand, requires reflection coefficients for two or more such modes. Multiple modes may be excited simultaneously by applying a short pulse to a structure's external surface. This situation is examined here for a circular, hollow and homogeneous, isotropic pipe having negligible damping and an open rectangular notch. A finite element model is employed in a region around a notch. It is coupled to a wave function expansion in the two adjacent, effectively, semi-infinite pipes. Representative longitudinal and flexural modes are investigated for different notch dimensions. A nonaxisymmetric notch, unlike an axisymmetric notch, introduces a plethora of cross modal couplings that lead to more singularities in a reflection coefficient's frequency dependence. There is, however, a common pattern to these distinctive singularities. It is conjectured that singularities corresponding to propagating modes may enable a notch to be detected and its dimensions determined.

<u>Session 4</u> Human Structure Interaction

10:30

Measuring Dynamic Force of a Jumping Person by Monitoring their Body Kinematics (919)

McDonald, M.G. and Zivanovic, S., *School of Engineering, University of Warwick, UK.*

Stadium structures could be exposed to significant dynamic forces generated by crowd activities during music or sport events. This loading is not well understood due to large variations in individual's activities and their capabilities to dynamically excite the structure. The dynamic forces created by individuals jumping could be indirectly determined by monitoring kinematics of the body. The body kinematics can be monitored by attaching reflective markers to anatomical landmarks and tracking the markers using a motion capture system. This technique has successfully been used in the past whilst monitoring multiple segments of the human body.

This paper aims to use the described motion tracking technique to determine the minimum number of monitoring points on the body required for successful measurement of the force and the best location of these points. Eight test subjects participated in experiments in the Gait Lab at the University of Warwick by jumping at controlled frequencies. The benchmark force generated during experiments was also measured using a force plate. It was found that monitoring a single body point can lead to a sufficiently accurate force reconstruction. This finding has potential to allow experimental determination of dynamic forces induced by crowd jumping at stadium events in future.

<u>Session 1</u> Nonlinear Vibrations I

10:50

Dynamic Instability in an Apparently Simple Experimental Structure (839)

Virgin, L.N., Wiebe, R., Spottswood, S.M. and Eason, T.G., *Department of Mechanical Engineering, Duke University, Durham, USA.*

Slender structures with softening force-deflection characteristics are liable to exhibit snapthrough buckling. This type of thoroughly nonlinear static behavior profoundly influences the situation in which the lateral loading is applied dynamically. In the case of harmonic loading the amplitude and frequency of the force are the key parameters influencing snapthrough. Although this is primarily a transient effect, the phenomenon of resonance may appear. Much of the previous research in this area is related to single-degree-of-freedom systems. The current presentation focuses attention on this type of behavior in very thin shallow arches from an experimental perspective, although a limited set of results from finite element analysis are included for verification purposes. For this kind of continuous system there is a surprisingly wide variety of possible behavior, e.g., the snap-through may occur in a symmetric or asymmetric type of mode, various higher-order periodic response, a sensitive dependence on initial conditions, all of which occur about and around potentially complicated equilibrium paths and corresponding natural frequencies. The key results are associated with establishing appropriate definitions of snap-through as well as delineating regions within parameter space where snap-through dynamics are likely to occur. The practical context for this work relates to the anticipation of sonic fatigue in thin curved panels typically used as structural components in aircraft structures.

<u>Session 2</u> Vibroacoustics I

10:50

Quantification of Airborne Noise Transmission in the Interior of an Ambulance (1037)

Magalhaes, M., Oliveira, R.C., Las Casas, E.B. and Santos, J., *Department of Structural Engineering (DEES), Federal University of Minas Gerais, Brazil.*

Although the ambulances are designed for the purpose of taking a patient to the hospital at the least amount of time, it is believed that no particular investigation has been made in order to analyse the noise level inside the ambulances in Brazil. It is well known that patients are stressed by the noise generated inside the cabin during ambulance transport. The focus of this paper is on the aspects of experimental tests for airborne sound transmission through ambulance panels and data for validation of predictive models found in the literature. An averaged reverberation time of 0.37 s was found for the ambulance cabin. The speech intelligibility was assessed measuring the Speech Intelligibility Index (STI) which was equal to 0.87, which is considered good for an adequate communication between paramedics and patients. The amount of airborne noise insulation provided by the left-hand side and rear façades was measured using the standardized level difference $D_{1m,\boldsymbol{nt}}$ which was equal to 23 dB(A) and 13 dB(A) respectively.

Session 3 Structural Health Monitoring

10:50

Comparative Study of Damage Detection in Steel Catenary Risers (906)

Rodríguez-Rocha, R., Hernández-Abraham, V.F., Pérez-Guerrero, F. and Burbano-Bolaños, R., *Sección de Estudios de Posgrado e Investigación - ESIA-UZ, Instituto Politécnico Nacional, Mexico.*

Risers are used to transport crude oil and may require management plans and programs of structural integrity to allow a proper functioning during its design life. Through Structural Health Monitoring (SHM) damage may be detected ahead, and be confirmed by non-destructive inspection assisted by remotely operated vehicles, with the information obtained used to prevent disasters such as environmental pollution, and human and economic losses.

This paper presents a comparative study of damage detection methods processing dynamic signals. Numerical study cases were defined for a Steel Catenary Riser (SCR) installed offshore with a depth of 1800 m. Two damage cases were studied decreasing stiffness values at specific locations of the structure. Dynamic analyses were performed using commercial software that incorporates nonlinear behaviour. Three numerical methods for damage detection were applied to damage location. Results demonstrate the effectiveness of the proposed methodology to detect damage in deep-water SCRs.

Session 4 Human Structure Interaction

10:50

Lattice Tower Dynamic Performance Under Human Induced Dynamic Loading (920)

Gaile, L. and Radinsh, I., *Department of Structural Engineering, Riga Technical University, Latvia.*

The structural design of light-weight lattice observation towers intended for general public use is mostly based on previous experience and mainly considers the wind loads. The most likely reason is a lack of understanding how these structures perform dynamically under human induced walking loads. The paper presents experimentally obtained geometrical and modal parameter ranges of typical light-weight lattice observation towers and the levels of their response to human walking loads. The paper investigates the sensitivity of tower to vibration caused by various walking harmonics and loading scenarios, the influence of visitors group size on the tower response and there are proposed a tentative limit to the maximum acceleration level of structure to ensure comfort for the tower visitors.

Session 1 Nonlinear Vibrations I

11:10

An Analytical Study of Non-Linear Behaviour of Coupled 2+2x0.5 DOF Electro-Magneto-Mechanical System by the Method of Multiple Scales (841)

Darula, R. and Sorokin, S., *Department of Mechanical and Manufacturing Engineering, Aalborg University, Denmark.*

An electro-magneto-mechanical system combines three physical domains - a mechanical structure, a magnetic field and an electric circuit. The interaction between these domains is analysed for a structure with two degrees of freedom (translational and rotational) and two electrical circuits. Each electrical circuit is described by a differential equation of the 1st order, which is considered to contribute to the coupled system by 0.5 DOF. The electrical and mechanical systems are coupled via a magnetic circuit, which is inherently non-linear, due to a non-linear nature of the electro-magnetic force. To study the non-linear behaviour of the coupled problem analytically, the classical multiple scale method is applied. The response at each mode in resonant as well as in sub-harmonic excitation conditions is analysed in the cases of internal resonance and internal parametric resonance.

Session 2 Vibroacoustics I

11:10

Modal Energy Analysis (943)

Totaro, N. and Guyader, J-L., *Laboratoire Vibrations Acoustique (LVA), INSA de Lyon, France.*

The Modal Energy Analysis presented in this paper is a method to predict energy exchanges between vibro-acoustic subsystems. As well-known methods like Statistical Energy Analysis (SEA) or Statistical modal Energy distribution analysis (SmEdA), the proposed method is based on equations of motion of two coupled oscillators. However, these equations are here solved in narrow band. The net exchanged power between the two coupled oscillators is then proportional to the total energies of oscillators using a pure tone modal coupling loss factor.

Extending it to the case of two continuous coupled subsystems (using dual modal formulation), it yields a system of linear equations linking modal injected power to modal energies of subsystems at a particular frequency. In that way, the non-resonant contribution of modes is intrinsically taken into account. In the present paper, the theoretical background of the proposed method will be explained and assumptions and domain of validity will be identified. Finally, numerical simulations on a plate/cavity and a cavity/plate/cavity test case will be addressed. A numerical example of a ribbed plate coupled to a cavity will be also presented

Notes

Session 3 Structural Health Monitoring

11:10

Helicopter Main Rotor Blade Modelling and Experimental Testing for Structural Health Monitoring (925)

Marques dos Santos, F.L., Peeters, B., Van der Auweraer, H. and Góes, L.C.S., *LMS International, University of Technology, Belgium.*

This work presents numerical and experimental results of a damage detection technique based on strain energy, with the application on a composite helicopter main rotor blade (MRB) from a PZL SW-3 helicopter. The blades from helicopter rotors are a very important structural element - they are very long beam-like structures that undergo different load conditions and aerodynamic forces at different parts of it. The damage detection method used in this study is based on the modal strain energy formulation of a beam. Initially, finite element method (FEM) simulations of a compositeMRB blade section were carried out to study the efficiency of the technique proposed and afterwards experimental parameters were extracted via an experimental modal analysis. Vibration modes and natural frequencies were identified by means of a least squares fit (PolyMAX). For this purpose, 55 uniaxial accelerometers were positioned along the blade in a way to measure the most significant vibration modes and an electrodynamic shaker was used to excite the system. Damage was introduced artificially on the blade by attaching a small mass to the MRB, changing its global properties this way. Experimental results for the damage detection technique are shown, and important remarks concerning sensitivity and robustness of the method are also discussed.

Session 4 Human Structure Interaction

11:10

A Novel Experimental Setup for the Identification of Human Actions on Laterally Oscillating Structures (1094)

Macdonald, J.H.G., Bocian, M., Burn, J.F. and Redmill, D., *Department of Civil Engineering and Department of Mechanical Engineering, University of Bristol, UK.*

Pedestrian lateral excitation of bridges has received considerable attention since the large vibrations of the Solférino Footbridge and the London Millennium Footbridge. Many loading models have been proposed, generally assuming frequency synchronisation of pedestrians to the bridge motion. However, some measurements from bridges and tests of pedestrians on oscillating surfaces seem to be inconsistent with this assumption. Rather they indicate self-excited forces at the bridge frequency, which is generally different from the walking frequency.

A simple model of human gait has been proposed, drawing on findings in the biomechanics field, which is consistent with the above observations. It predicts that pedestrians walking more slowly, such as in a denser crowd, generate larger self-excited forces. There is, however, a need to verify this predicted feature and validate or refine other details of the model.

To this end, this paper presents a new experimental campaign of the human-structure interaction. A custom-built instrumented treadmill with a generous walking area, equipped with a mechanism allowing for automatic adjustment of speed of the belt to that of the pedestrian, is placed on a hydraulic shaking table. A virtual reality representation of a vibrating bridge gives a realistic visual environment. Preliminary findings of the pedestrian response and the resulting dynamic forces on the structure are presented and related to the proposed pedestrian model and the response of bridges to crowd loading.

Session 1 Nonlinear Vibrations I

11:30

Friction Induced Vibration as Multi-Scale Dynamics (863)

Hoffmann, N., Wernitz, B. and Vitanov, N., *Vibration University Technology Centre, Imperial College London, UK.*

The present paper presents a study indicating limitations of the traditional single-scale modelling and analysis approach in friction induced oscillations. Vibration data extracted from a commercial vehicle friction brake during braking is subjected to a statistical increment analysis on different scales. It turns out that the increments of vibration signals under steady sliding are non-Gaussian and the degree of deviation from the Gaussian distribution depends on the scale under consideration. The results suggest that the seemingly simple random vibration during sliding is actually generated by mechanisms on different scales that leave their footprint in a complex multi-scale vibration signal.

Session 2 Vibroacoustics I

11:30

Comparison of Finite Element Formulations for Sound Transmission Modelling in the Outer Ear (1003)

Volandri, G., Carmignani, C., Di Puccio, F. and Forte, P., *Department of Civil and Industrial Engineering, Largo Lazzarino, Pisa.*

The work described in this paper is part of a broader research activity on the development of a virtual ear. The present study focuses on the tympanic membrane and auditory canal modelling, which are main components in sound transmission. The standard finite element method (FEM) and alternative methods (the spectral method and the generalized finite element method) suitable for modelling sound propagation at high frequencies were applied. Two domains (fluid and structural) for the auditory canal and the tympanic membrane, respectively, were considered in order to evaluate the coupling of different methods and to apply a fluid-structure interaction formulation. The analysis results on an anatomical finite element model, which include pressure distribution in the auditory canal and displacement distribution and frequency response of the tympanic membrane, confirm experimental and theoretical data reported in the literature. The spectral and generalized FE methods were implemented and applied to approximated three-dimensional models of the outer ear. The validation of such methods with standard FEM simulation at increasing mesh density shows their computational advantages in terms of reduced mesh density required for accurate results.

Notes

Session 3 Structural Health Monitoring

11:30

Ultrasonic Wave Dispersion Curves with Application to Crack Detection from Acoustic Emissions in Aircraft Structures (969)

Zarini, G., Elliott, S.J. and Waters, T.P., *Institute of Sound and Vibration Research, University of Southampton, UK.*

An established principle for detecting cracks in structures is to monitor high frequency acoustic emissions generated by micro-cracking. In the case of simple uniform plates the ultrasonic waves that propagate from a crack to a sensor are straightforward to infer from Rayleigh-Lamb theory. However, for built-up structures such as an aircraft wing the wave types responsible for propagating disturbances are potentially numerous, complicated and travel at differing velocities. In this paper a comparison between the dispersion curves obtained with various plate theories is presented and their applicability to plates of thickness commonly used in aircraft is discussed. Of equal importance is the prediction of free wave propagation in beam-like structures such as wing spars, the geometrical complexity of which may necessitate a numerical approach. The Semi-Analytical Finite Element (SAFE) method is applied here to predict the free wave propagation characteristics of an I-beam structure, which is adopted to resemble a wing spar. The resulting wave modes and dispersion curves are presented. The main aim of this paper is to identify which established analytical or numerical approaches are appropriate for modelling wave propagation in aircraft wing structures at few hundred kHz. This will facilitate future studies focussed on the number, placement and dynamic response of sensors.

Session 4 Human Structure Interaction

11:30

Quantitative Evaluation of the Rotational Motion Pattern in the Joints of the Lower Limb During the Unrestrained Human Gait (815)

Hayashi, Y., Tsujiuchi, N., Koizumi, T., Makino, Y., Tsuchiya, Y. and Inoue, Y., *Department of Mechanical Engineering, Faculty of Science and Engineering, Doshisha University, Japan.*

In human gait motion analysis, which is one useful method for efficient physical rehabilitation to define various quantitative evaluation indices, ground reaction force, joint angle and joint loads are measured during gait. For obtaining these data as the unrestrained gait measurement, a novel gait motion analysis system using mobile force plates and attitude sensors has been developed. On the other hand, a human keeps a high correlation among the motion of all his joints during gait. The analysis of the correlation in the recorded joint motion extracts a few simultaneously activating segmental coordination patterns, and the structure of the intersegmental coordination is attracting attention to an expected relationship with a control strategy. However, when the evaluation method using singular value decomposition has been applied to joint angles of the lower limb as representative kinematic parameters, joint moments related to the rotational motion of the joints has not yet been considered. In this paper, joint moments as kinetic parameters applied on the lower limb during gait are analysed under wide environmental conditions including slope and stairs by the wearable gait motion analysis system and the effectiveness to quantitatively evaluate the rotational motion pattern in the joints of the lower limb by using joint moments is validated.

Session 1 Nonlinear Vibrations I

11:50

Reduced Order System Model Nonlinear Response and Expansion for Full Field Results (860)

Harvie, J., Avitabile P. and Obando, S., *Structural Dynamics and Acoustic Systems Laboratory, University of Massachusetts, USA.*

Reduced order linear models interconnected with nonlinear connections can be used for the prediction of nonlinear response using piecewise linear solutions. These reduced order results are useful for response prediction but expansion to full space is needed for the prediction of stress and strain in the full system model to be of practical usefulness.

This paper presents some of the recent efforts predicting nonlinear response from highly reduced order models interconnected with discrete nonlinear connections to show the usefulness of these approaches. In addition, expansion techniques are also utilized to identify the system level response at the full set of finite element degrees of freedom. The expansion process uses a unique formulation of the linear component information to identify the system level response from the unassembled component information and provides a unique way to identify the system level full field response in the presence of nonlinear system response. These full field responses can be used in conjunction with the constitutive equations of the finite element model to identify dynamic stress/strain for non-linear responses.

Session 2 Vibroacoustics I

11:50

Aero-Acoustic Performance Analysis Method of Regenerative Blower (1010)

Kil, H.G., Lee, C., Ma, J.H. and Chung, K.H., *Department of Mechanical Engineering, University of Suwon, South Korea.*

Noise modelling and prediction of regenerative blowers are made by combining the performance analysis method and the noise models for discrete and broadband noise components in a computerized system of the FANDAS code. In the FANDAS code, the performances of regenerative blower such as flow capacity and pressure rise are computed by using momentum exchange theory. Based on the performance prediction results, the pressure fluctuation and its noise level at blade passing frequency due to rotating impellers are analysed by acoustic mode analysis, and the broadband noise is predicted by the correlation models for inflow turbulence, turbulence in impellers and exhaust jet mixing. The noise prediction results by the FANDAS code are compared and verified with the measurement on three different blowers within a few percentage of relative error.

<u>Session 3</u> Structural Health Monitoring

11:50

Fault Diagnosis in Rotating Machine Using Composite Bispectrum (1036)

Elbhbah, K.A. and Sinha, J.K., *School of Mechanical, Aerospace, and Civil Engineering (MACE), The University of Manchester, UK.*

Conventional vibration-based condition monitoring (VCM) requires a number of vibration transducers at each bearing pedestal and vibration data analysis to identify fault(s), if any, in a machine. It is often observed that such diagnosis is also dependent on the experience of the person involved. Recently a method has been developed that uses just one vibration transducer on each bearing and then uses data fusion to construct a single composite spectrum and a bispectrum for the machine for the fault(s) diagnosis. The suggested method is expected to overcome the limitations imposed by conventional VCM techniques. This concept of using the composite bispectrum for the machines has now been extended to a number of simulated faults in an experimental rig at different rotating speeds to further validate the suggested approach.

<u>Session 4</u> Human Structure Interaction

11:50

Acceleration Response Spectrum of Long-Span Floor Under Human Walking Loads (979)

Chen, J., Yan, S. and Ye, T., *Department of Building Engineering, Tongji University, China.*

This paper investigates acceleration response spectrum of long-span floors under human walking load. Three hundred and twenty experimentally measured walking load curves have been applied to long-span floors with varying natural frequencies to calculate the 10-second root-mean-square (RMS) acceleration response spectrum, for which a simplified mathematical model has been proposed for. The effects of factors as higher modes of vibration, boundary conditions, floor spans, stride length and damping ratio on the spectrum have been studied and accordingly the modification measures for all these factors have been suggested. The proposed spectrum has been validated by comparing the predicted response with measured responses on an as-built long-span floor.

Session 1 **Vibroacoustics I**

12:10

Energy Flow Analysis of the Vibration of a Finite Plate Excited by an In-Plane Point Force (1035)

Kil, H.G., Lee, C., Choi, J.S., Hong S.Y. and Song, J.H., *Department of Mechanical Engineering, University of Suwon, South Korea.*

An energy flow analysis has been performed to analyse the vibration of a finite plate with an in-plane point force excitation. The analysis is based on energy governing equations for inplane waves (longitudinal and shear waves). Those equations are expressed with the time- and locally space-averaged energy density in the plate at high frequencies. To solve the equation for each type of wave, the input power due to the in-plane point force is estimated and decomposed to its contributions to propagation of longitudinal and shear waves. A verification of the study of the energy flow analysis is performed by comparing energy flow solutions for energy density and intensity in the plate with corresponding analytical solutions. The analytical solutions are evaluated using the wave decomposition of the in-plane vibration of the plates. Dependence of the power flow solutions on frequency and damping is discussed.

Notes

Session 1 Nonlinear Vibrations II

14:50

Some Insight into the Evidence of Detached Resonance Curves in the Frequency Response of Nonlinear Oscillators (876)

Gatti, G., Marchesiello, S. and Brennan, M.J., *Università della Calabria, Rende, Italy.*

Detached resonance curves, which lie inside or outside the main frequency response curve, have been theoretically predicted in multi degree-of-freedom nonlinear oscillators, when subject to harmonic excitation. The system parameters have been shown to critically affect their presence. This paper investigates the practical achievability of such features, when body geometry, weight and inertia effects are taken into account in a harmonically excited two degree-of-freedom mechanical system, consisting of coupled linear and nonlinear oscillators.

Based on a simplified nominal model of the system, the Harmonic Balance Method is used to derive approximate analytical solutions for the frequency response curves, and numerical validation is performed. To investigate the effects in a practical system, a multi-body model of the mechanical system is assembled with feasible mass distribution and dimensions. These effects on the system response are then investigated. A time domain approach for identifying the physical parameters of the nonlinear model of the system, which is based on subspace methods, is also adopted, by applying a random excitation.

Session 2 Vibroacoustics II

14:50

Development of Road Noise Estimation Technology Based on Character of Tire and Matrix Inversion Method (818)

Shin, T-J., Shin, K-S. and Lee, S-K., *Acousics Vibration Signal Processing Center (AVSP), Department of Mechanical Engineering, Inha University, Korea.*

Quantification of road noise is a challenging issue in vehicle NVH due to extremely complicated transfer paths of road noise as well as the difficulty in an experimental identification of input force from tire-road interaction. In this paper to estimate input force, measured acceleration during driving and inversed tire frequency response functions are used. Also, a vehicle transfer function between the ear point and axle was measured by acoustic excitation. The total system transfer function was calculated by inversion and multiplication of three frequency response functions. In the inversion procedure, a Tikhonov regularization method was used in order to reduce inversion error. From the proposed method, it was able to evaluate each contribution of tire to road noise.

Session 3 System Identification and Inverse Problems I

14:50

An Optimized Identification Method for Modular Models of Rubber Bushings (908)

Cosco, F.I., Gatti, G., Toso, A., Donders, S and Mundo, D., *G&G Design and Engineering Srl, Cosenza, Italy.*

Rubber bushings are important for automotive manufacturers, for ensuring the vehicle vibration comfort (in terms of vibrations and noise). Ideally the bushing design can be optimized based on virtual simulation models; after all, the more design decisions are taken in an early stage, the lower the design costs (as the physical prototype validation phase can be shortened) and the better the product quality (as earlier decision-making implies still a larger range of feasible design modifications based on the virtual simulations). For this purpose, including rubber bushing behaviour in multibody vehicle dynamic simulations is a crucial task, com-prising the solution of two sub-problems: the mathematical modelling to define a constitutive mathematical force-displacement relationship to reproduce the bushing behaviour, and the identification procedure to fit the selected model to the experimental data.

Modular modelling was recently presented as an efficient approach, resulting in a good trade-off between the complexity of the mechanical characteristics of bushing components, and the computational costs required to incorporate bushing component models with sufficient fidelity in the CAE simulation. On the other hand, the state-of-the-art identification procedures can be classified into two main groups: parameterization approaches, requiring an excessive amount of user interaction and expertise, and optimization approaches, which may require a high number of deterministic calculations and involves the risk to not converge to the optimal design.

This paper presents an innovative fast and robust identification tool that relies on efficiently combining a parameterization technique with a nonlinear fitting optimization algorithm. It is shown that the results fit very well experimental data reported in recent literature. Moreover, the method compares favourably to other recent prediction methods in terms of computational efficiency, yielding the same (or better) accuracy than prior art.

Notes

<u>Session 4</u> Earthquake Engineering I

14:50

Evaluating the Seismic Damage Index of LSF Systems Using FEA-ANN Approach (937)

Sadat Shokouhi, S.K., Dolatshah, A., Shafaei, S. and Atarodi, A., *Department of Civil Engineering, Islamic Azad University, Tehran, Iran.*

The Lightweight Steel Framing (LSF) system has been proposed as an economical system and earthquake resistant. Due to the lightness of LSF structures, the seismic performance of middle-rise buildings has been improved. Nowadays, various numerical-analytical methods have been proposed for seismic assessment of conventional structures. Providing a perfect seismic damage index is always regarded as one of the analytical passive points. In this research, a LSF building was selected as a case study for Finite Element (FE) modelling in which non-linear time-history analyses have been undertaken. Material properties were defined according to the performed experimental studies. A novel approach was presented for the seismic damage index of LSF systems using the simultaneous incorporation of the non-linear analysis results and the correction coefficient describing the seismic geotechnical effects. The presented seismic damage index indicates the seismic performance of the LSF structures well. Also, a two-layer perceptron Artificial Neural Network (ANN) was trained using the results of the FE model and a non-linear relationship was obtained to predict the seismic damage index. The proposed seismic damage index was finally validated using statistical analyses indicating that the proposed method does not show a significant difference as compared to the ANN results.

Session 1 Nonlinear Vibrations II

15:10

Trends in Tuning Nonlinear Absorbers: a Comparison (888)

Loccufier, M. and Aeyels, D., *SYSTeMS Research Group (SYSTeMS), Ghent University, Belgium.*

When it comes to reduce excessive vibrations in structures, tuned mass dampers, also called vibration absorbers are widely used. Their basic concept of a local addition of a spring-mass-damper-system to an existing structure is implemented in many different ways. This paper discusses absorbers with strongly nonlinear spring characteristics because of their ability to mitigate vibrations at different frequencies. The complex dynamics of nonlinear absorbers have extensively been studied by many authors yielding interesting insights. Translating those insights in robust design criteria for engineers is not straightforward due to the existence of an energy threshold, which abruptly separates regions of efficient vibration mitigation with regions of undesired response regimes. Understanding this energy threshold is crucial for proper tuning of the absorber. Here single degree of freedom main systems under impulsive load forcing are considered when connected to a single vibration absorber. Two realizations of nonlinear vibration absorbers on small scale plants are reported: a restoring force wire absorber and a path following absorber which are installed on the top of a building-like frame. Existing criteria are compared to own developed insights in the energy threshold for tuning purposes.

Session 2 Vibroacoustics II

15:10

Vibro-Acoustic Analysis of an Enclosure Bounded by a Flexible Panel: Effect of the Boundary Condition (883)

Wang, Y., Zhang, J., Liu, X., Le, V. and Sun, X., *College of Mechanical Engineering, Southeast University, China.*

The vibro-acoustic analysis of a panel-enclosure coupled system which consists of an enclosure with a clamped panel is investigated and compared with that of a simply supported one. The flexible wall on the enclosure is directly driven by the plane wave outside enclosure with different elevation angles, and the sound field in the enclosure is driven through the coupling with flexible wall. The response of coupled systems is obtained by the classical modal coupling method. In this analysis, the effect of incident angle of the plane wave which acts on the panel surface upon the response of two coupled systems are compared with each other. The results show that significant discrepancies between the two different boundary conditions are demonstrated in terms of several factors plot as frequency, including the noise reduction quantity, the panel vibration velocity distribution. It is found that panel modes which mode indices include even number are driven as the elevation angle of plane wave is increased.

Notes

Session 3 System Identification and Inverse Problems I

15:10

Operational Modal Analysis Using Joint Statistical Analysis of Multiple Records (938)

Cara, F.J., Alarcón, E. and Juan, J., *Laboratory of Statistics, Universidad Politécnica de Madrid, Spain.*

In Operational Modal Analysis (OMA) of a structure, the data acquisition process may be repeated many times. In these cases, the analyst has several similar records for the modal analysis of the structure that have been obtained at different time instants (multiple records). The solution obtained varies from one record to another, sometimes considerably. The differences are due to several reasons: statistical errors of estimation, changes in the external forces (unmeasured forces) that modify the output spectra, appearance of spurious modes, etc. Combining the results of the different individual analysis is not straightforward. To solve the problem, we propose to make the joint estimation of the parameters using all the records. This can be done in a very simple way using state space models and computing the estimates by maximum-likelihood. The method provides a single result for the modal parameters that combines optimally all the records.

Session 4 Earthquake Engineering I

15:10

Comparing the Results of Seismic Vulnerability of Steel Structures with and without the Integration of Low Cycle Fatigue Damage (790)

Saranik, M., Jézéquel, L. and Lenoir, D*., Laboratoire de Tribologie et Dynamique des Systèmes (LTDS), École Centrale de Lyon, France.*

This paper presents the results of seismic vulnerability assessment of a three-story steel frame with bolted connections. Accurate fragility curves are essential in the development of a general probabilistic performance-based engineering design. The fragility curves represent the probabilities that the structural damages, under various levels of seismic excitation, exceed specified damage states. In this study, a simplified method is applied to trace the fragility curves. A nonlinear time history analysis is adopted in evaluating the fragility curves for the considered structure. The nonlinear analyses are performed based on two hysteretic models. The first one is a fatigue damage based hysteretic model that allows considering the stiffness degradation produced by the cumulative damage. The second is a hysteretic model, without applying fatigue damage calculation, based on Richard-Abbott model. The performance of the building in terms of maximum inter-story drift ratio is studied at various seismic intensity levels. Finally, the fragility curves of the frame are obtained and compared for both model. Results demonstrate the importance of considering the stiffness degradation produced by fatigue damage. Results also indicate that the responses of the frame and the fragility curves are influenced by low cycle fatigue damage effects.

<u>Session 1</u> **Nonlinear Vibrations II**

15:30

Dynamic Characteristics and Sensitivities Analysis of a Power Turret Gear Train (872)

Xu, L. and Chen, N., *College of Mechanical Engineering, Southeast University, China.*

The dynamic transmission characteristics and the sensitivities of the three stage idler gear system of the new NC power turret are studied in the paper. Considering the strongly nonlinear factors such as the periodically time-varying mesh stiffness, the nonlinear tooth backlash, the lump-parameter model of the gear system is developed with one rotational and two translational freedoms of each gear. The eigenvalues and eigenvectors are derived and analyzed on the basis of the real modal theory. The sensitivities of natural frequencies to design parameters including supporting and meshing stiffnesses, gear masses, and moments of inertia by the direct differential method are also calculated. The results show the quantitative and qualitative impact of the parameters to the natural characteristics of the gear system. Furthermore, the periodic steady state solutions are obtained by the numerical approach based on the nonlinear model. These results are employed to gain insights into the primary controlling parameters, to forecast the severity of the dynamic response, and to assess the acceptability of the gear design.

<u>Session 2</u> **Vibroacoustics II**

15:30

Transition Among Veering, Crossing and Lock-In Through Variation of the System Parameters (910)

Giannini, O. and Sestieri, A., *Dipartimento di Ingegneria Meccanica e Aerospaziale, Università Roma La Sapienza, Italy.*

The phenomena of mode veering, crossing and lock-in are analyzed in this paper. Their occurrence is generally found, under different conditions, when there is a parameter varying in the system, which produces a change in its behavior. It often happens that, when the frequencies approach each other, they can cross, veer and eventually present a lock-in state. The problem is analytically investigated for a general weakly-coupled two-degrees of freedom systems and a simulation example of two coupled beams is presented. Moreover, numerical and experimental evidences of lock-in in brake squeal are recalled to show how in gyroscopic systems, when two coupled mechanical parts have the same eigenvalues (lock-in state) then the whole system may become unstable and at that frequency and noise is generated. How things change when the coupling is not weak is address, and is also discussed to highlight phenomena of particular interest.

Session 3 System Identification and Inverse Problems I

15:30

Structural Dynamics Identification of a Bolt and Nut Joint Using Modal Test Data (955)

Pishbin, M., Shokrollahi, S. and Hajiuon, B., *Department of Aerospace Engineering, Space Research Institute, Iran.*

Prediction of dynamic characteristics in actual structures using analytical methods is typically difficult and time consuming due to its structural complexity. One of the most effective solutions to this problem is experimental modal analysis method through which the number of degrees of freedom is decreased and consequently it becomes less time consuming and more efficient. Estimation of the modal parameters is a fundamental step in experimental modal analysis. This paper seeks to identify structural behavior of a bolt and nut joint via experimental modal analysis. Two methods of structural modal analysis were studied in the frequency domain and the results were compared with the direct method of the eigenvalue problem of the system. The structure is excited by using an impact hammer. Then, after extracting of data from frequency response functions by using the rational fraction method, modal parameters including natural frequencies, damping coefficients and mode shapes were experimentally estimated by curve fitting. The analytical structural model compatible with the experimental model was designed and solved using modal analysis by finite element method and modal parameters for first six modes were extracted. The frequency response functions are reproduced and the extracted modal parameters were compared together in order to secure the accuracy of the results. Finally the modal assurance criteria (MAC) are calculated for evaluating the test results and error of parameter estimations.

Session 4 Earthquake Engineering I

15:30

Natural and Man-Made Hazard Mitigation of Transportation Structures (995)

Harik, I.E., *Department of Civil Engineering, University of Kentucky, USA.*

Rapid assessment of a bridge structure's safety and functionality is a crucial procedure in restoring vital lifeline routes after a hazardous event. However, executing preparatory actions before a hazardous event occurs, and conducting feasible remedial actions during such an event, are also essential to bridge safety. This paper introduces a process for hazard mitigation of highway bridges through the example of an application of earthquake mitigation. Earthquake mitigation consists of three components: pre-earthquake, during earthquake, and post-earthquake mitigation. Pre-earthquake mitigation consists of a seismic evaluation of all applicable bridges and a prioritization of the seismic vulnerability of these bridges. Simultaneously, pre-earthquake mitigation requires the implementation of earthquake-response training programs for the necessary earthquake-response personnel. Due to the short duration and unpredictability of earthquakes, no form of during-earthquake mitigation is currently possible. Post-earthquake mitigation consists of the use of postearthquake investigation software that assigns a bridge safety-rating to effected bridges as the first stage of a two-stage approach to guide professional and non-professional personnel in making post-earthquake response decisions. The software is a bridge safety-rating program prepared for the state of Kentucky in the Southeastern United States in order to accelerate bridge investigations following an earthquake. The methodology and concepts presented herein can be extended to other types of hazard mitigation in other states and countries.

Session 1 Nonlinear Vibrations II

15:50

Large Vibration Amplitude of Circular Functionally Graded Plates Resting on Pasternak Foundations (855)

El Bikri Khalid, B., El Kaak Rachid, A. and Rhali, C.B., *Mohammed V University-Souissi, Morocco.*

In the present study, the problem of geometrically nonlinear free vibrations of functionally graded circular plates (FGCP) resting on Pasternak elastic foundation with immovable ends was studied. The material properties of the functionally graded composites examined were assumed to be graded in the thickness direction and estimated through the rule of mixture. The theoretical model is based on the classical Plate theory and the Von Kármán geometrical nonlinearity assumptions. Hamilton's principle is applied and a multimode approach is derived to calculate the fundamental nonlinear frequency parameters, which are found to be in a good agreement with the published results dealing with the problem of functionally graded plates. On the other hand, the influence of the foundation parameters on the nonlinear frequency to the linear frequency ratio of the FGCP has been studied. The effect of the linear and shearing foundations is to decrease the frequency ratio, where it increases with the effect of the nonlinear foundation stiffness.

Session 2 Vibroacoustics II

15:50

Numerical Study of a Submerged Hull with Internal Masses (1011)

Wu, H., Kessissoglou, N. and Mace, B., *School of Mechanical and Manufacturing Engineering, University of New South Wales, Australia.*

The onboard machinery of a marine vessel include the engines, generators, main motor, gearboxes and auxiliary equipment, and accounts for a large amount of the total mass of the vessel. In the medium to high frequency ranges, the hull of the vessel, being a flexible structure, has high modal density and short wavelengths and is more appropriately modelled using Statistical Energy Analysis (SEA). However, the onboard machinery are rigid body components with low modal density and well defined resonances, and are more suitably modelled using a deterministic approach such as finite element analysis (FEA). This work presents the dynamic responses of a simplified physical model of a submarine pressure hull, using both deterministic and statistical numerical models. A finite element / boundary element (FE/BE) model of a fluid loaded cylindrical shell with an internal floor-mass system is initially developed. A hybrid finite element / Statistical Energy Analysis (FE/SEA) model of the same structure is then developed. Two excitation cases are considered. In the first case, forces are applied externally to the cylindrical shell to simulate excitation from the propeller. In the second case, forces are applied to the internal mass to simulate excitation from the onboard machinery. For the two excitation cases, the vibrational energy levels of the shell are compared.

Notes

Session 3 Earthquake Engineering I

15:50

Vertical Seismic Vibration of Cantilever Constructions (843)

Esadze, S.Y., *Department of Civil and Industrial Engineering, Georgian Technical University, Georgia.*

The engineering analysis of the strong earthquake consequences clearly shows the significant influence of the seismic loads vertical component on earthquake damage effect. The said influence is particularly actual for the epicenter zones. In the Codes of many seismic active country, as well as in EuroCode 8, there is a requirement for calculation of certain construction elements taking into account vertical seismic load. Cantilever constructions are almost always subject to such requirements.

Taking into account that the bearing cantilever is an element of the entire construction system the submitted paper analyzes the following:

- cantilever as the element of the load-bearing wall construction system;
- cantilever as the element of the framework structure;
- cantilever as the element of solid structure.

As a result of the analysis the paper presents the design models of the aforementioned construction decisions and gives their computation algorithm; carries out numerical exercises and gives their comparison analysis and proper references.

Session 1 Modal Analysis and Structural Modification

16:40

Explanation and Application of the SAFE Diagram (1093)

Neri, P., Bertini, L. Monelli, B.D., Santus, C. and Guglielmo, A., *Civil and Engineering Department, University of Pisa, Italy.*

Vibration of industrial application bladed wheels is reason of noise and structural dynamic loads. Compressor and turbine bladed wheels interact with the fluid distributed by the stator vanes. The blades are excited by these fluctuating forces and their vibration can be reason of fatigue failures, especially when resonance conditions are excited. Obviously, avoid resonances is a strategic requirement in bladed wheels design. The Campbell diagram approach just excludes the matching between the natural mode frequency and the excitation frequency. However, bladed wheels show many natural frequencies that are very near each other, so it is difficult to avoid any resonance matching. The Singh's Advanced Frequency Evaluation (SAFE) diagram approach introduces also the shape matching instead of just the frequency matching. Many frequency matching can be identified as non-critical and then tolerated. The present paper explains the SAFE diagram and introduces an analytical expression to identify the critical shape interactions. The matching map is introduced, showing the shape of the mode that fully interact with each excitation harmonic order. Full resonances are distinguished from partial resonances that are not identified on the SAFE diagram. Finally, an application is reported on a family of bladed wheels, identifying the optimal geometry configuration to avoid any critical resonance.

Session 2 Vibroacoustics III

16:40

Calculating the Forced Response of Cylinders Using the Wave and Finite Element Method (766)

Renno, J.M. and Mace, B.R., *Institute of Sound and Vibration Research, University of Southampton, UK.*

The dynamic response of cylinders can be obtained analytically in very few (and simple) cases. For complicated (thick or anisotropic) cylinders, researchers often resort to the finite element (FE) method which can be computationally expensive at higher frequencies. In this paper, the response of cylinders is obtained using the wave and finite element (WFE) technique. The FE model of a small rectangular segment of the cylinder can be post-processed using periodic structure theory to yield its wave characteristics. Thus, cylinders with arbitrary complexity can be considered since the full power of FE methods can be utilised to obtain the FE model of the small segment. Then, the response of the cylinder is posed as an inverse Fourier transform. However, since there are an integer number of wavelengths around the circumference of a cylinder, one of the integrals in the inverse Fourier transform reduces to a simple summation, whereas the other is resolved analytically using contour integration and the residue theorem. The result is a computationally efficient technique for obtaining the response of cylinders to arbitrarily distributed loads.

Session 3 System Identification and Inverse Problems II

16:40

Parameter Identification of Multistorey Frame Structure from Uncertain Dynamic Data (829)

Chakraverty, S. and Behera, D., *Department of Mathematics, National Institute of Technology Rourkela, India.*

In general, identification of structural parameters may be categorized as inverse vibration problem. Usual method of identification uses the values of the parameters initially given to the structure by an engineer. It then modifies the original parameter values as per the observed values from test by an iteration process. The parameters involved in the said problems are traditionally considered as crisp. But, rather than crisp value we may have only the uncertain or incomplete information about the parameters being a result of errors in observations etc. These uncertainties may be modelled through probabilistic, interval or fuzzy theory. Unfortunately, probabilistic methods may not able to deliver reliable results with required precision without sufficient data. Hence interval and fuzzy theory are becoming powerful tools for handling the uncertainties in recent decades. This paper investigates the identification procedure of the uncertain column stiffness of multistorey frame structures by using prior known estimates of the uncertain parameters and uncertain dynamic data. Uncertainties are modeled through triangular convex normalized fuzzy sets. Bounds of the uncertain parameters are obtained by using a proposed fuzzy based iteration algorithm. Example problems are solved to demonstrate the reliability and accuracy of the identification process.

Session 4 Earthquake Engineering II

16:40

Finite Element Modeling of Reinforced Concrete Beam Column Joint (765)

Shaikh, M.G. and Sakhiuddin, S.S., *Government College of Engineering Aurangabad, India.*

The performance of beam-column joints have long been recognized as a significant factor that affects the overall behavior of reinforced concrete (RC) framed structures subjected to large lateral loads. The reversal of forces in beam-column joints during earthquakes may cause distress and often failure, when not designed and detailed properly. In the present study, finite element modeling of four types of exterior beam-column joint specimens is done by using ANSYS10.0.The first specimen conforms to the guide lines of IS 13920: 1993 for seismic resistant design. Second one is detailed with additional diagonal cross bracing bars at joints and beam reinforcements. Third with cross bars in beam region of 6mm instead of cross bars in joint. A fourth specimen has cross bars of 8mm instead of 6mm in the beam region. The specimens are subjected to similar reverse cyclic loading to simulate earthquake loading in structures. The experimental results found out by K.R. Bindhu and K.P. Jayaare [1] is compared with the studies carried out by these finite element models. The comparison shows better performance of the joint when it is provided with cross bars of 8mm in beam region.

<u>Session 1</u> Modal Analysis and Structural Modification

17:00

Operational Modal Analysis of Passenger Cars: Effect of the Correlation Between Front and Rear Inputs (909)

Soria, L., De Filippis, G., Palmieri, D., Mangialardi, L., Peeters, B. and Van der Auweraer, H., *Dipartimento di Meccanica, Matematica e Management, Politecnico di Bari, Italy.*

Operational Modal Analysis (OMA) allows the structural identification of systems in working conditions, moving from output data only. External forces remain not measured. Basically some fundamental assumptions have to be satisfied: (i) the not known loads acting on the system need to have the form of white noise sequences, (ii) in the case of multi-point excitation the external inputs are required to be strictly uncorrelated. In the field of vehicle dynamics, OMA can be utilized to assess the performance of different suspension systems equipping the same type of vehicle. The output data recorded at the different sensor locations during vehicle road tests are affected by a certain correlation among the road forces acting on the wheels, mainly that loading the front and the rear axle, even if inputs on wheels belonging to the left and the right side could be also in some way correlated. In this paper, the effect of the existing correlation between the road inputs, acting on the front and the rear axles of a numerically simulated passenger car, on the estimates of modal parameters is investigated. The estimates are obtained by using a standard curve fitting technique, as the LMS PolyMAX for Operational Modal Analysis, on the time data evaluated in several virtual sensor locations.

<u>Session 2</u> Vibroacoustics III

17:00

Waves in a Three-Dimensional Model of the Cochlea (836)

Ni, G., Elliott, S.J. and Mace, B.R., *Institute of Sound and Vibration Research, University of Southampton, UK.*

The conventional travelling wave theory of the cochlea assumes that only a single “slow” wave, which determines the overall response in the cochlea, can propagate. Various different mechanisms, such as longitudinal coupling in the fluid or the basilar membrane, BM, may give rise to other types of wave. In this paper the wave finite element method is used to predict all possible waves in a three-dimensional model of the passive cochlea using an orthotropic plate model for the BM, in terms of wave mode shape and wavenumber as a function of position along the cochlea. Mode conversion in waves can then be explored by decomposing results from a full finite element model. It is found that only one wave, the slow wave, is dominant basal to the characteristic place and then a higher order fluid mode starts to make a significant contribution to the overall response when system damping is small.

Session 3 System Identification and Inverse Problems II

17:00

Identification of Vibration Path in a Gasoline Direct-Injection Engine Using Two Input-One Output Model (819)

Choi, S-I., Chang, J-U., Lee, S.K. and Lee, S-M., *Acoustics Vibration Signal Processing Center (AVSP), Department of Mechanical Engineering, Inha University, South Korea.*

The paper describes the method of separating the effect of two vibration inputs on the total vibration output from an engine block of a car. The authors use the partial and pure coherence functions, which are derived from the power spectral functions of the input and output vibrations, to distinguish the effects of the high-pressure pump from those of the engine itself. The experimental measurements and spectral analysis show that the effects of the pump dominate in a wide frequency range, though the engine and the pump have nearly the same effects at around 1000 Hz.

Session 4 Earthquake Engineering II

17:00

The Analysis of Methods of Generating Accelerograms for Calculation of Buildings (966)

Vakhrina, G.N., Smirnov, V.I. and Zakrailov, Z.Z., *Earthquake Engineering Research Center (TsNIISK), Central Research Institute of Building Constructions, Russia.*

In the report the method of modeling artificial accelerograms earthquakes for concrete sites of buildings is presented. Accelerograms are calculated by means of the stochastic method developed for a dot seismic rupture. In calculations extent of the seismic rupture and local soil conditions was considered. The basic approach at the account of extent of the rupture is representation of a plane of rupture in the centre in the form of set of the subruptures of the smaller sizes.

For each earthquake average spectra of fluctuations (accelerations and velocities). average spectra of reaction and average duration of strong movements (as duration of the fluctuations exceeding on amplitude level of 50 % of peak values) have been generated 25 synthetic accelerograms on which average values of the maximum accelerations were estimated. the maximum speeds.

Notes

Session 1 Modal Analysis and Structural Modification

17:20

Damping in Jointed Friction Plates with Partially Overlapping Interfaces (1019)

Hirai, T., Kuratani, F., Kazushi Koide, K. and Kido, I., *Department of Mechanical Engineering, University of Fukui, Japan.*

In this paper, we investigate the damping characteristics for the fundamental and the higher modes in jointed plate structures with partially overlapping interfaces. First, the damping characteristics are experimentally evaluated. Second, the effect of the mode shape on the damping characteristics is examined. Third, the characteristics of energy dissipation due to friction at the interface, which determine the damping characteristics in jointed plates, are analysed. Consequently, we propose a procedure for estimating the energy dissipation at the interface using finite element (FE) analysis. The structure considered in this paper consists of three steel plates bolted together in which a long plate is sandwiched between two short plates. Comparison of the modal damping ratios estimated from the dissipated energy and those measured in modal testing confirms the validity of the proposed estimation procedure. The FE analysis and the experimental results show that the damping characteristics vary depending on the mode, especially for the difference between the symmetric and antisymmetric mode shapes. This is supported by the characteristics of the energy dissipation obtained in the contact analysis of the proposed estimation procedure.

Session II Vibroacoustics III

17:20

The Reflection of SV-Waves in a Poroelastic Half-Space Saturated with Viscous Fluid (976)

Al Rjoub, Y.S., *Civil Engineering Department, Jordan University of Science and Technology, Jordan*.

In this paper, the effect of finite skeleton permeability of soils on the surface strains, rocking strains, and energy partitions during the reflection of SV-waves in a poroelastic half-space saturated with viscous fluid is presented. The motion of the medium of the half-space is described using Biot's theory of wave propagation in fluid-saturated porous media. Numerical results presented in this paper show that the skeleton permeability of soils has a negligible effect on the rocking strains with respect to vertical displacement. The effect of permeability on the surface strains and rocking strains with respect to horizontal displacement becomes noticeable as the value of porosity increases and the value of Poisson's ratio decreases. In general, the skeleton permeability of soils decreases the energy carried by the slow P-wave and increases the energy carried by the SV-wave.

Session 3 System Identification and Inverse Problems II

17:20

Identification of Mechanical Systems with Local Nonlinearities Through Discrete-Time Volterra Series and Kautz Functions (864)

Shiki, S.B., Noël, J-P., Kerschen, G., Lopes Jnr, V. and da Silva, S., *UNESP - Universidade Estadual Paulista, Faculdade de Engenharia de Ilha Solteira, Brazil.*

Mathematical modelling of mechanical structures is an important research area in structural dynamics. The goal is to obtain a model that accurately predicts the dynamics of the system. However, the nonlinear effects caused by large displacements and boundary conditions like gaps, backlash, joints, as well as large displacements are not as well understood as the linear counterpart. This paper identifies a non-parametric discrete-time Volterra model of a benchmark nonlinear structure consisting of a cantilever beam connected to a thin beam at its free end. The time-domain data of the modal test are used to identify the Volterra kernels.

To facilitate the identification process, the kernels are expanded with orthogonal Kautz functions to decrease the number of parameters to be identified. The nonlinear parameters are also estimated by the updating of a finite element model with local nonlinearity involving the optimization of residue of the numerical and experimental kernels. The capability of the representation of the nonlinear phenomena is investigated through numerical simulations. The paper concludes by indicating the advantages and drawbacks of the Volterra series for modelling the behavior of nonlinear structures with suggestions to overcome the disadvantages found during the tests.

Session 4 Earthquake Engineering II

Evaluating the Seismic Effects on Lifting Equipment (913)

Solazzi, L., *Dipertimento di Ingegneria Meccanica e Industriale, Università degli Studi di Brescia, Italy.*

The purpose of this paper is to assess the dynamic behaviour of various lifting equipment (different types of cranes, elevating work platform, etc.) subjected to seismic actions, evaluating how these actions can both generate failures and affect the structural behaviour of the machine. The work is developed starting from the design of the different machines of interest (according to some classical standards and specific performance like working load, lifting speed, working area, etc.), determining their geometry. Subsequently are applied the characteristic load spectra to the structures, related to the magnitude of earthquake; the final step consist in the structural analysis of the machines, computing their maximum stresses, displacements and natural frequencies, using different finite element codes. The results show that the first natural frequencies of the structures are very low and consequently the effects of the seismic action, in general, are not dangerous. Otherwise it is important to underline that the maximum stress induced by the earthquake is detectable in different position in the lifting equipment respect to maximum stress position in the normal loading operations, therefore seismic analyses are indispensable for study these parts of machines.

Notes

Session 1 Modal Analysis and Structural Modification

17:40

Finite Element Model Updating of a Bolted Joint Using Modal Test Data (956)

Hajiuon, B., Shokrollahi, S. and Pishbin, M., *Department of Aerospace Engineering, Space Research Institute, Iran.*

One of the most applicable experimental analysis methods is modal testing, which can extract structural dynamics parameters of a mechanical system such as natural frequencies, mode shapes and modal damping. In this paper the procedure of finite element model updating of a bolted joint of an aerospace structure is done. For this purpose, at first, a numerical model of the problem is created and analyzed in a finite element software and then an experimental model is created and modal test is done. Experimental model is divided into 21 node so for comparing two models, the numerical model is reduced and then by convergence of these models, an exact model of structure is produced. Correlation between numerical and experimental model is investigated by using MAC criterion. The finite element model is updated by direct methods using reduced mass and stiffness matrices. Also the effects of some basic parameters of structure on finite element model data are investigated.

Session 2 Vibroacoustics III

17:40

Wave Based Method for Free Vibration Analysis of Ring-Stiffened Cylindrical Shells with Bulkheads (809)

Wei, J., Chen, M. and Xie, K., *School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology, China.*

Wave based method (WBM) which can be recognized as a combination of a semi-analytical and semi-numerical method is presented to analyze free vibration characteristics of cylindrical shells with T-shaped ring-stiffeners and bulkheads for arbitrary boundary conditions. According to the structure type and the positions of the discontinuities, the model is divided into different substructures whose vibration field is expanded by wave functions which are exactly analytical solutions to the governing equations of the motions of corresponding structure type. The T-shaped section stiffeners are treated as discrete members and each stiffener is divided into three elements. The first element is the web of the stiffener which is considered to be an annular circular plate, the other two elements are considered to be two shell elements with free edges attached to the lower end of the web and compose the flange of the stiffener. Natural frequencies and vibration mode shapes of the cylindrical shell are calculated and the results are compared with those from a finite element model which shows good agreement. Effects of the number and distribution of bulkheads on free vibration characteristics of cylindrical shell have been investigated. Results show that the cylindrical hull can be considered being divided into separate cabins vibrating with their own natural frequencies with constraints by the bulkheads imposed at the end of the cabin.

Session 3 Earthquake Engineering II

Effect of Irregularity on the Fundamental Period of Setback Buildings (820)

Agrawal, V.M. and Sarkar, P., *Department of Civil Engineering National Institute of Technology Rourkela, India.*

This paper presents a design code perspective of 'setback' building category. Almost all the major international design codes recommend dynamic analysis for design of setback buildings with scaled up base shear corresponding to the fundamental period as per the code specified empirical formula. However, the empirical equations of fundamental period given in these codes are a function of building height only, which is ambiguous for a setback building. It has been seen from the analysis that the fundamental period of a setback building changes when the configuration of the building changes, even if the overall height remains same. Based on modal analysis of 17 three-dimensional setback building frames with varying irregularity, this study critically reviews the existing method of quantifying vertical geometric irregularity and discusses the effect of irregularity on the fundamental period of setback buildings.

Notes

Plenary Sessions

09:00

The Influence of Boundary Conditions and Internal Constraints on the Performance of Noise Control Treatments: Foams to Metamaterials

Bolton, J.S., *Purdue University, USA.*

Theories governing coupled wave propagation in noise control materials are now well-developed. As a result, it is, in principle, possible to design optimal noise control materials, whether sound absorption or barrier performance is the goal. However, it is now understood that details of the external and internal boundary conditions applied to poroelastic materials such as foams have a dramatic impact on the wave propagation within them, and as a result, their performance. It is important to understand these effects if the best performance is to be obtained under particular circumstances and if the opportunity to achieve enhanced performance in particular frequency ranges owing to these sensitivities is to be realized. Here, these effects will be described and demonstrated. First, the impact of front and rear surface boundary conditions on the performance of layers of foams will be demonstrated and the possibility of enhanced low frequency performance will be discussed. Next, the impact of material inhomogeneity will be discussed as will the effects of segmenting poroelastic materials into finite-sized, constrained pieces, hence creating a dissipative metamaterial. It will be shown, for example, that internal constraints can greatly enhance barrier performance, but that a weight penalty is inevitably incurred. Finally, a connection will be drawn with recently developed cellular metamaterials comprising finite-sized panels mounted within a rectangular, elastic frame, whose performance similarly depends on finite length-scales and internal constraints. It will be shown, in particular, that the mass of a homogeneous elastic panel can be redistributed to create such a realistic metamaterial whose low frequency barrier performance is well in excess of that of the original homogeneous panel.

13:40

Response Control of Tall Buildings using Tuned Liquid Dampers

Bhattacharyya, S.K., *Central Building Research Institute, Roorkee, India.*

The present trend of the creation of tall buildings and the usage of light weight high strength materials, though have created economy, reduction in space requirement etc., structurally these have become susceptible to the lateral loading due to wind or earthquake. Several attempts are made to control the response of tall systems by introducing control mechanisms in the form of active, passive or hybrid system. Usage of liquid storage tanks in tall building system in the form of a passive control device proves effective. Several works have been carried out in the past to understand the efficacy of such system, which popularly is known as Tuned liquid dampers. The present paper deals with the development of a numerical code to demonstrate the efficacy of such tuned liquid dampers considering fluid structure interactions.

<u>Session 1</u> Nonlinear Vibrations III

10:30

Nonlinear Vibrations of a Stroke-Saturated Inertial Actuator (972)

Wilmshurst, L.I., Ghandchi-Tehrani, M. and Elliott, S.J., *Institute of Sound and Vibration Research, University of Southampton, UK.*

Proof-mass actuators are typically used to supply an external control force to a structure, for the purpose of vibration suppression. These devices comprise a proof-mass suspended in a magnetic field that is accelerated in order to provide a reaction force on the actuator casing and the structure itself. If the actuator stroke length is reached or exceeded, the proof-mass will hit the end stops, resulting in a nonlinear phenomenon known as stroke saturation. In this paper, a theoretical and experimental investigation into the actuator's dynamical behaviour is undertaken. First, the blocked inertial force of the actuator in response to an input voltage was measured experimentally using a variety of excitation amplitudes and frequencies. An analysis was conducted in the time- and frequency-domains, and the first-order force-voltage FRF of the actuator was ascertained for each excitation amplitude. The information provided by the analysis was then used to estimate the parameters for a linear piecewise stiffness model of the actuator, in order to simulate the time-domain response. Finally, a comparison of the simulated and measured signals is conducted to establish the accuracy of the model.

<u>Session 2</u> Vibration Control

10:30

Analysis and Optimisation of Tuned Mass Dampers for Impulsive Excitation (1002)

Salvi, J., Rizzi, E., Rustighi, E. and Ferguson N.S., *Dipartimento di Ingegneria, Università di Bergamo, Italy.*

Tuned Mass Damper (TMD) devices have been widely studied and optimised in the framework of persistent dynamic loadings, such as harmonic and white noise excitations, in order to reduce as much as possible the steady-state response of an assigned primary structure. In this sense, the present paper arises as a complementary study on the topic, since here shock input is assumed as dynamic loading, so as to investigate the effectiveness of TMDs in reducing the transient structural response. In particular, an impulsive loading has been considered, acting as a base displacement, which is a situation that may occur in real applications. First, a comprehensive dynamic analysis of the system comprising of a primary structure and an attached passive TMD is carried out in the time domain. Focus is placed on the relationships between the load input and the system properties, in order to explore the dynamic behaviour of such system and to identify the main response trends, mostly as a function of the free TMD parameters, namely mass, frequency and TMD damping ratios. Subsequently, a hybrid TMD has been considered, by adding a feedback controller to the previously optimised passive TMD, so as to improve the performance of such a device, especially in reducing the peak response of the primary structure. The contents of the present work have the final aim of identifying the potential level of effectiveness of the TMD devices and to supply important guidelines towards their optimal design in reducing the structural response also to shock excitations. This should display significant relevance in different practical applications, including in the field of earthquake engineering.

Session 3 Civil Engineering Structures

10:30

Equivalent Static Wind Loads for Structures with Non-Proportional Damping (828)

Blaise, N., Canor, T. and Denoël, V., *Department of Architecture, Geology, Environment and Constructions, University of Liege, Belgium.*

In current practice, wind structural design is often carried out using the concept of equivalent static wind loads. The main characteristic of such loadings is to reproduce, with static analyses, the same extreme structural responses as those resulting from a formal buffeting analysis. This paper proposes a method for the computation of equivalent static wind loads for structures with slight non-proportional damping in a modal framework. Because of the smallness of the out-of diagonal terms, this method is based on recent developments related to asymptotic expansion of the modal transfer matrix of such structures. As a main benefit, the static loading is described as a perturbation of the equivalent loading that would be obtained for the uncoupled system. The main contribution of this paper is to formalize the expression of the correction terms resulting from the non-proportionality of damping. The method is presented with a detailed illustrative example.

Session 4 Numerical Techniques

10:30

PGD-VTCR: a Reduced Order Model Technique to Solve Mid-Frequency Broad Band Problems on Complex Structures (825)

Riou, H., Barbarulo, A., Kovalevsky, L. and Ladeveze, P., *LMT-Cachan, PRES UniverSud Paris, France.*

The calculation of the vibrational responses of systems on frequency bands appears to be more and more important in engineering simulation. This is particularly true in medium frequency regimes, where these responses have a strong sensitivity to the frequency. To find this, standard techniques may involve many frequency fixed computations. In this work, we propose a novel technique that does not need the resolution of vibration problems at many different frequencies. It combines the use of the Variational Theory of Complex Rays (VTCR), a mid frequency dedicated numerical strategy, and the Proper Generalized Decomposition (PGD), a reduced order model technique. The VTCR uses exact solutions of the governing equation (propagative and evanescent waves) to find approximated solutions of the vibrational problem. The PGD expands the VTCR approximation over the frequency band thanks to a separated representation of the unknowns. Examples of such a strategy on complex structures will illustrate the efficiency of the proposed approach.

<u>Session 1</u> Nonlinear Vibrations III

10:50

On the Performance of a Nonlinear Vibration Isolator Consisting of Axially Loaded Curved Beams (1034)

Abolfathi, A., Waters, T.P. and Brennan, M.J., *Department of Mechanical and Aerospace Engineering, University of Strathclyde, UK.*

A desirable characteristic for nonlinear vibration isolators is a high static stiffness and a low dynamic stiffness. A curved beam is a possible candidate for this role provided that the amplitude of vibration about the static equilibrium position is sufficiently small. However, for large amplitude oscillations, the nonlinear dynamics may have a detrimental effect. This paper considers the force transmissibility of a single degree-of-freedom system where the stiffness element is a curved, axially loaded beam. The transmitted force is calculated by numerical time domain integration of the equations of motion. The exact force-deflection relation for the beam is used for the spring. By comparison, a frequency domain solution is sought using the Harmonic Balance (HB) method in which the system is modelled as a Duffing oscillator. It is shown that the HB and time domain solutions are in close agreement for small amplitudes of excitation and both predict advantageous performance of the nonlinear isolator compared with its equivalent linear counterpart. However, significant discrepancies occur between the two solutions for large excitation since the beam can no longer be approximated by a linear and a cubic stiffness. It is also strongly asymmetric – soft in compression but stiff in extreme extension– which gives rise to an impulse in the transmitted force in each fundamental period. This numerical problem is alleviated by inserting a linear spring in series with the beam isolator with a modest compromise in isolation performance at the excitation frequency.

<u>Session 2</u> Vibration Control

10:50

Optimisation of a Tuned Liquid Column Damper for Building Structures (1328)

McCrum, D.P., Kenny, A. and Broderick, B.M., *School of Planning, Architecture and Civil Engineering, Queen's University Belfast, UK.*

The effectiveness of a tuned liquid column damper (TLCD) to reduce the lateral displacement response of a building structure during seismic excitation is investigated. The TLCD uses the inertia of a moving column of liquid in a U-tube to reduce the lateral displacement response of the structure. Damping of the response is as a result of the headloss of the liquid column as it passes through an orifice inside the column. The optimisation of the mass ratio, length ratio, tuning ratio and the orifice damping coefficient of the TLCD are numerically investigated for a range of structural types. A series of real-time hybrid tests (RTHT) will be performed on the TLCD (physical substructure) whilst the remainder of the structure will be numerically modelled (numerical substructure).

Notes

Session 3 **Civil Engineering Structures**

10:50

New Empirical Formula for the Determination of the Fundamental Period of Vibration of Multi-Storey RC Buildings (831)

Elgohary, H.A. and Assas, M.M., *Structural Engineering Department, Faculty of Engineering, Mansoura University, Egypt.*

The period of vibration is an important parameter in the seismic design of buildings as this parameter governs the effect of earthquakes. The fundamental period of vibration defines the spectral acceleration and thus the base shear force to which the building should be designed. Many design codes provide simple empirical relationships relating the fundamental period of vibration of a building to its height. These relationships conservatively estimate the period and consequently the resulted base shear force will be conservatively predicted.

In the present paper, a review study to evaluate the empirical formulae for the fundamental period of multistory RC frame buildings of some current Codes and formulae reported in recent researches has been carried out. The results of these formulae have been compared with the results obtained using finite element analysis (eigenvalue analysis). Comparison shows that the codes' formulae underestimate the fundamental period with a large deviation from finite element results due to the ignorance of major parameters influencing the period in the codes formulae.

A parametric study has been performed using finite element analysis to study the effect of the parameters influencing the fundamental period. On the bases of the parametric study a new empirical relationship between the building fundamental period and its main characteristics (height, width, total weight, beams' stiffness and columns' stiffness) has been obtained. The results obtained using the recommended formula show good agreement with the finite element results.

Session 4 **Numerical Techniques**

10:50

System Model Modes Developed from Expansion of Uncoupled Component Dynamic Data (856)

Obando, S., Avitabile, P., Harvie, J. and Nonis, C., *Structural Dynamics and Acoustic Systems Laboratory, University of Massachusetts Lowell, USA.*

System models are often developed from component models either as modal components or as reduced order models. The resulting system model data is only available at the reduced order space unless some expansion is performed. Of course this can be achieved using system model mapping matrices but then requires the development of the full space system model which defeats the purpose of the component synthesis approach. However, the individual uncoupled component mapping matrices can be utilized to expand to the full space of the system model providing the modes of the components span the space of the full system model. This paper shows the results of using component modes from the unconnected components as projection matrices to identify the system level full field response. Multiple analytical cases are presented to show how the selection of component modes affects the expansion results. The results show accurate system model expansion using a sufficient set of component modes that span the space of the system model.

Session 1 Nonlinear Vibrations III

11:10

Nonlinear Vibrations of Base Excited Shallow Arches: Effects of Hinge Friction (902)

Fey, R.H.B., Van Hoof, J.A.J.M., Shukla, A. and Nijmeijer, H., *Department of Mechanical Engineering, Eindhoven University of Technology, The Netherlands.*

The influence of hinge friction on the nonlinear vibrations of a transversally, base excited shallow arch is examined. Two semi-analytical models are derived by applying an assumedmodes approach based on sinusoidal modes and Craig-Bampton modes respectively. Hinge friction induces the presence of equilibrium sets rather than distinct static equilibria. In the steady-state analysis of the semi-analytical models, amplitude-frequency diagrams are presented. These plots are obtained by solving two-point boundary value problems (using timestepping) in combination with a path-following technique. Local stability and bifurcation analysis of periodic solutions is carried out using Floquet theory for systems of Filippov-type. Nonlinear harmonic resonances, superharmonic resonances, period doubling bifurcations, and symmetry-breaking bifurcations are observed. Especially for low excitation amplitudes, the responses dramatically change due to hinge friction, since these responses are dominated by hinge stick. Near resonances and in case of high amplitude excitation, the frictional hinge will only slip and the influence of hinge friction is significantly reduced. When hinge friction is relevant, the Craig-Bampton model is expected to predict responses most accurately.

Session 2 Vibration Control

11:10

Design Method of Multiple Dynamic Absorbers for Suppressing Chatter in End-Milling Operation (999)

Nakano, Y. and Takahara, H., *Department of Mechanical Sciences and Engineering, Tokyo Institute of Technology, Japan.*

In the present study, experimental and analytical investigations are performed to study the design method of multiple dynamic absorbers for effectively suppressing chatter generated in the end milling operations. The triple and sixfold absorbers are attached to a rotating collet holder. Using a machining center, up-cut milling tests are performed to study the effect of the absorbers on chatter experimentally. The critical axial depth of cut at the onset of chatter with and without the absorbers is compared. A dynamic milling model with the absorbers is modelled as a lumped mass system with orthogonal degrees of freedom in the feed and normal directions. Stability of the milling process is investigated by performing a complex eigenvalue analysis. It is confirmed experimentally that an improvement in the chatter-free axial depth of cut can be obtained using the sixfold dynamic absorbers. The analytical results reveal the optimal natural frequency and damping ratio of the absorbers in order to increase the chatter free axial depth of cut. Furthermore, it is shown that the number of the absorbers has an influence on the suppression effect on chatter

Session 3 Civil Engineering Structures

11:10

Improving the Blast Performance of Base-Isolated Structures Using Pneumatic Dampers Via Genetic Algorithm (897)

Sadat Shokouhi, S.K., Dolatshah, A., Shafaei, S. and Atarodi, A., *Department of Civil Engineering, Islamic Azad University, Iran.*

In this study, the improved blast performance of the base-isolated (BI) structures that use hybrid Lead-Rubber Bearings (LRBs) and pneumatic dampers has been evaluated via the genetic algorithm. Since the layout of LRBs is employed for controlling the shock waves, the blast performance of these base isolation systems against explosion waves needs to be investigated. To do this, the accelerograph record of a standard blast load was applied to the finite element model of a BI structure and different structure responses were analyzed. The results of the non-linear blast load time-history analysis such as maximum story drift were used as a basis for the comparison of results. It was revealed that the application of base isolation systems in the structures subjected to blasting singly causes an increase in the story drift demonstrating serious hazards for the structural performance. Thus, the pneumatic dampers were employed for a better performance of the BI structure at certain points where their optimal locations were identified by genetic algorithm.

Session 4 Numerical Techniques

11:10

Advanced Linear Dynamic Capabilities and Modeling Abstractions in Abaqus (898)

Belyi, M., Bajer, A., Belsky, V., Boni, B., Chin, C., Ianculescu, C., Larionov, A., Kim, M. and Wood, M., *Dassault Systems SIMULIA, USA*.

This paper presents a snapshot of the current linear dynamics capabilities in Abaqus. Parallel performance of Abaqus linear dynamic procedures is illustrated with examples of large scale simulations. Inclusion of nonlinear and unsymmetric effects in linear dynamic simulations is illustrated with an example of the frequency response analysis for a model of a full car with rolling tires.

Session 1 Nonlinear Vibrations III

11:30

Coulomb Friction-Induced Damping Estimation at the Crack Interface for Cantilever-Type Specimen (1091)

Rehman, A.U., Rongong, J.A., Worden, K. and Mughal, H.U., *Department of Mechanical Engineering, University of Sheffield, UK.*

This study is a continuance of the preceding work by the author on the investigation of the dynamic behaviour of the breathing crack in the cantilever–type structures. Such structures are widely employed in the engineering applications including a blade attached to rotor in the turbomachinery bladed system. The level of damping arising from a breathing crack interface alters the tip deflection of the blade and hence difference in the time of arrival of each blade is ascertained in the blade tip timing (BTT) technique. Therefore, an accurate estimation of the coulomb friction-induced damping is required for the effective damage detection utilising BTT. In this work, damping arising from a breathing crack inside a dog–bone specimen (a representative model for cantilever–type structures) is quantified numerically and experimentally. Modes of vibration considered are bending and torsion modes which represent a crack operating in different combinations of Mode-I (opening), II (sliding) and III (tearing) behaviour. The dog–bone specimen is experimentally tested for varying excitation levels (ELs) and the damping levels obtained are then compared with the numerical results, where the dog–bone specimen model is subjected to the impulse excitation.

Session 2 Vibration Control

11:30

Linear Friction Damper Consisted of Tilt Lever Supported with Leaf Spring and Cylindrical Block (901)

Yamaguchi, H., Furukawa, Y. and Yoshida, H., *Department of Mechanical Systems, Engineering National Defense Academy, Japan.*

For passive vibration isolation systems, an ordinary friction damper of constant frictional force has performance limitations. That is, the isolation performance declines and the displacement remains apart from the equilibrium position after the disturbance has disappeared, when the friction force is large. These drawbacks are avoided when the friction force varies depending on the relative displacement. In order to achieve this characteristic in a simple way, this paper proposes a friction damper that consists of a cylindrical block and a tilt lever supported with a leaf spring. When the cylindrical block moves and pushes the tilt lever, the normal force exerted by the leaf spring at the contact position increases. Thus, the friction force varies in proportion to the relative displacement between the tilt lever and the cylindrical block. The expected characteristic is verified by the numerical simulation and the experimental results. The numerical simulation also investigates the effects of the geometrical parameters as the design guideline.

Session 3 Civil Engineering Structures

11:30

Dynamic Analysis for Ball Mill Foundation (1290)

Han, Y.C. and Guevara, F., *Fluor Canada Ltd, Vancouver, Canada.*

The dynamic analysis of ball mill foundation is a typical problem of soil-structure interaction, and the sub-structure method is used to estimate the structural vibration. In this study a practical case of ball mill foundation is investigated to illustrate the approach and the dynamic behaviour of structure. The concrete mat foundation and piers are modelled by FEM model, and the stiffness and damping of soil (rock) are generated by a computer program. Then the stiffness and damping input to the FEM model as the base boundary condition. A series of dynamic experiments had been done in the field to validate the values of radiation damping which can be generated from the program. Different design options are compared to obtain the better solution. The large mill foundation is an irregular structure and located in a severe seismic zone. The response spectrum analysis is used to determine the earthquake forces and seismic response.

Session 4 Numerical Techniques

11:30

An Assessment Tool for Quantifying Cumulative Effect of Modeling Errors for Smart Hybrid Simulation (936)

Avramova, N., Pong, W. and Chen, C., *School of Engineering, College of Science and Engineering, San Francisco State University, USA.*

Laboratory experiments play a critical role in earthquake engineering research. Hybrid simulation provides a viable technique to assess structural performance through component tests. One challenge exists for current practice of hybrid simulation when a complex structure has more critical components than that could be accommodated in laboratories. A smart hybrid simulation (*SHS*) technique has recently been developed which integrates the substructure technique with model updating. During the experiment, the measured responses of the experimental substructures are used to refine the numerical models of similar parts within analytical substructures to improve their accuracy. *SHS* thus has great potential to extend hybrid simulation practice to complex structures further beyond existing laboratory capacity. It however also raises concern on how the potential modelling errors in analytical substructures will affect the accuracy of *SHS* results and how to quantify its cumulative effect. This paper presents an effective tool to quantify the effect of modelling error which enables future reliability assessment of *SHS* results when actual structural response is not available for immediate comparison.

<u>Session 1</u> Nonlinear Vibrations III

11:50

Efficient Predictions of the Steady State Response of a Beam Interacting with Viscoelastic Materials (1023)

Bhattiprolu, U., Bajaj, A. and Davies, P., *Ray. W. Herrick Laboratories, School of Mechanical Engineering, Purdue University, USA.*

It is challenging to develop static and dynamic models of structures interacting with nonlinear and viscoelastic materials; yet there are many real world examples of structures that incorporate such materials. Furthermore, it is computationally expensive to predict the steady state response of these structures to static and harmonic loads, even when using the simpler models in the literature. The example of a pinned-pinned beam interacting with polyurethane foam that reacts in both tension and compression is focused on. The steady state solution is expressed as the sum of an arbitrary number of modes and Galerkin's method is used to derive modal amplitude equations. For polynomial-type nonlinearities, it is possible to speed up computation time by using a convolution method to evaluate integral terms in the model. Also, incremental harmonic balance is used to make the frequency response predictions more efficient. By using these computationally efficient solution approaches, it is possible to explore a much wider variety of loading conditions and also quickly determine the number of modes required for convergence. Using this solution method, the influence of various parameters e.g., loading configuration, excitation amplitude, linear and nonlinear stiffness, on the response of the beam is studied.

<u>Session 2</u> Vibration Control

11:50

The Vertical Seismic Isolator by Using A Link-Crank Mechanism (1004)

Koizumi, T., Tsujiuchi, N., Hattori, T. and Yasuda, M., *Doshisha University, Department of Mechanical Engineering, Japan.*

In recent years, various seismic isolators have been developed to prevent earthquake damage to valuable art. Many seismic isolators only enable horizontal motion because horizontal vibration is the usual cause of falling objects. However, development of a seismic isolator designed for vertical vibration is necessary, since great vertical vibration earthquakes, such as the 2004 Niigata Prefecture Chuetsu Earthquake, have occurred. Vertical seismic isolators have been developed in the past, but some of their characteristics, such as the large size of the static deflection of the spring and the increased height of the seismic isolator, are undesirable. In this study, we developed a vertical seismic isolator that can support loads using a horizontal spring without requiring a vertical spring. Thus, our vertical seismic isolator has a major stroke and lower installation height. We verified this vertical seismic isolator's performance through shaking tests and mathematical calculation. The calculation verified the seismic isolation because the average reduction rate of acceleration in six seismic waves was 0.32. Sinusoidal waves of 2, 3, and 4 Hz were inputted to the base plate of the seismic isolator and, as a result of the response of the top plate, the effect of seismic isolation was verified in the experimental model because the average reduction rate of acceleration was 0.57. In addition, we uncovered some problems for this vertical seismic isolator's practical use.

<u>Session 3</u> **Civil Engineering Structures**

11:50

Development of Fragility Curves for Cylindrical Concrete Water Tanks (807)

Behnamfar, F. and Yazdabad, M., *Department of Civil Engineering, Isfahan University of Technology, Iran.*

Concrete cylindrical storage tanks are the usual structures in water supply systems. Due to importance of continuity of operation of the aforementioned structures after earthquakes, it is necessary to estimate seismic vulnerability and fragility of water tanks to prepare emergency plan and make governmental decisions. The purpose of this study is development of analytical seismic fragility curves for open top concrete cylindrical storage tanks. To develop these curves, both free vibration and time history analysis are carried out on concrete tank models with three different aspect ratios (*H/D*). The fragility curves are based on two critical failure modes: crack propagation in wall and bending moment capacity exceedance. An analytical method is used to obtaining the fragility curves. Moreover nine far field records of earthquakes are employed for dynamic analyses of models. Models are assumed to be anchored to the rigid ground. As a result of this study, it is concluded that aspect ratio (*H/D*) acts as uncertainty characters for seismic vulnerability of storage tanks and by increasing aspect ratio, damage of tank during earthquake is more probable.

<u>Session 4</u> **Numerical Techniques**

11:50

Magnetostriction-Induced Dynamics of Laminated Structures (1046)

Javorski, M., Čepon, G., Slavič, J. and Boltežar, M., *Laboratory for Dynamics of Machines and Structures, Faculty of Mechanical Engineering, University of Ljubljana, Slovenia.*

This research provides a new methodology for identification and calculation of the dynamic behaviour of laminated structures, resulting from magnetostriction. The topic relates to electrical steel components of electrical devices (e.g., the transformer cores, stators, and rotors of specific electric motors) and a similar test structure was prepared in form of a clamped stack of electrical steel laminations.

Firstly, the excitation mechanism via magnetostriction was experimentally identified and analysed in the frequency domain. Significant frequency components were extracted and a function approximation was made. On this basis, a magnetostriction model for use in finite element analysis (FEA) was prepared.

Secondly, a finite element model of the structure was made with the emphasis on the assembly technique, the resulting frictional contact between laminations and material orthotropy. The numerical model was validated against the results of an experimental modal analysis.

Finally, a set-up for analysis of magnetostriction-induced vibrations was built and operating deflection shapes method was used to measure the response. The magnetic field of the set-up was analysed using FEA, providing input data for the magnetostriction model. The latter was integrated into the structural numerical model. Vibrations of the structure, resulting from magnetostriction, were calculated and compared to the experimental data.

<u>Session 1</u> Nonlinear Vibrations II

12:10

The Effect of Cubic Damping on a Base Excited Isolator: an Experimental Study for Harmonic Excitation (934)

Pananananda, N., Ferguson, N.S. and Waters, T.P., *Institute of Sound and Vibration Research, University of Southampton, UK.*

An experimental study has been conducted to validate theoretical solutions for the response of a base excited single degree-of-freedom isolation system possessing pure cubic damping. The cubic damping characteristic was implemented using an electromagnetic shaker with a simple non-linear velocity feedback control. The rig and practical implementation of the active damping are described. The base excitation was harmonic at a set of discrete frequencies with constant displacement amplitude. Consistent with theoretical predictions, the isolation performance at high excitation frequencies is shown to be worse than either the undamped or linear viscously damped isolation system with the displacement transmissibility tending to unity. This is contrary to the case of force excitation reported in the literature where cubic damping offers improved performance. The physical causes of the distinct behaviours and the consequences for isolator design are discussed.

<u>Session 2</u> Vibration Control

12:10

Proposing a New Elastomeric-Sliding Isolator System (816)

Behnamfar, F. and Mozaheb, S.A., *Department of Civil Engineering, Isfahan University of Technology, Iran.*

A new isolator system with cheap production and simple installation is presented. It includes a rubber core and the surrounding steel rings in free contact with each other. The system's vertical stiffness is provided by the steel rings and the lateral bilinear behaviour by a combination of friction and the elastomeric core mechanisms. The steel rings are thicker at their outer edge. While the friction coefficient of steel on steel is large, the system works in friction with tuning of steel rings' share from vertical load by inserting a topmost rubber ring. The lateral slip of steel rings provides an effective hysteresis behaviour. The rubber pushes the rings from inside under vertical load thus producing a lateral pressure. This results in transfer of an adjustable part of vertical load to steel rings. The transferred vertical load provides the frictional resistance necessary for preventing the system from moving under small lateral forces. Under severe earthquakes the rings slip and energy is dissipated. After earthquake, the rubber core causes the rings return to their initial state. In this study, results of the analysis and tests performed on the system are compared with the lead rubber bearing system (NZ system).

Session 3 Civil Engineering Structures

12:10

Offshore Structural Assessment by Dynamic Approach (1609) Presentation only.

Jia, J., *Aker Solutions, Bergen, Norway.*

This presentation will present both the state of art as well as the state of practice of the dynamic analysis and relevant design on the offshore infrastructures. Case study on recent significant offshore accidents (I am responsible for forensic investigations and remediation measure) due to the in-appropriate design with regard to dynamics and vibration will also be discussed.

Session 4 Numerical Techniques

12:10

Nonlinear Component Mode Synthesis Using Modal Derivatives (1550WIP)

Tiso, P. and Wenneker, F., *Delft University of Technology, Faculty of Mechanical, Maritime and Materials Engineering, The Netherlands.*

We present an extension of the Craig-Bampton substructuring technique to handle cases where components of the assembly feature geometrical nonlinearities. The fixed interface modes are extended with modal derivatives to capture the large deflections only for the required components.

Session 1 Active Vibration Control and Smart Structures I

14:50

A New Vibration Suppression System for Semi-Active Control of a Two-Storey Building (891)

Lazar, I.F., Wagg, D.J. and Neild, S.A., *Department of Mechanical Engineering, University of Bristol, UK.*

This paper proposes the use of a novel type of control system suitable for the vibration control of civil engineering structures subjected to base excitation. The control system investigated is based on the inerter, a device that was initially developed for high-performance suspensions of Formula 1 racing cars. The principal advantage of the inerter is that a very good vibration isolation level can be achieved with low levels of added mass. This feature makes it an attractive alternative to traditional tuned mass dampers (TMD). The inerter system is modelled inside a two storey building and is located on braces between adjacent storeys. Numerical results show that an excellent level of vibration reduction is achieved, offering significant improvement over TMDs. Two TMD and two inerter-based systems are investigated and their performance compared. The key parameters of the control systems are varied to study their performance under a range of operating conditions.

Session 2 Soil-Structures Vibrations

14:50

Measurement of Wave Attenuation in Buried Plastic Water Distribution Pipes (939)

Brennan, M.J., Almeida, F.C.L., Joseph, P.F., Whitfield, S. and Dray, S., *Department of Mechanical Engineering, State University of Sao Paulo (FEIS – UNESP), Brazil.*

Leaks in pipes are a common issue encountered in the water industry. Acoustic methods are generally successful to find and locate leaks in metallic pipes. However, they are less effective when applied to plastic pipes. This is because leak-noise signals are heavily attenuated due to high damping in the pipe-wall and sound radiation into the soil. As result, the leak noise does not travel a long distance. To determine how far leak noise may travel in a pipe at any frequency, the attenuation of the wave responsible for leak noise propagation should be known. In this paper a new method to estimate the attenuation of this wave is described. The method is then applied to some measurements made on a bespoke pipe-test rig in the UK, and the results are compared with theoretical predictions.

Session 3 Reusable Hypersonic Platform I

14:50

A Review of Fatigue Failures with Aircraft Engine Nacelle Components (887)

Millar, D.M.A. and Ferguson, N.S., *Bombardier Aerospace Belfast, Northern Ireland, UK.*

The paper discusses some of the fatigue problems observed in-service with components on aircraft engine nacelles. Acoustic fatigue (or sonic fatigue) has been an issue with nacelle components given the proximity of the structure to the high intensity noise generated by the fan on modern high bypass ratio gas turbine aircraft engines.

Reference is made to test measurements – both full scale engine testing and sub-element component testing. Theoretical result predictions using finite element models are summarised and compared with the test measurements. The dynamic stiffness method is also used to predict the fundamental frequency and strain response and shows good agreement with test data.

Session 4 Analytical Modelling

14:50

Influence of Displacement-Dependent Suspension Damping on Transient Response of Earth-Moving Machinery Cab (865)

Sun, X-J., Zhang, J., Sun, B-B., Lu, X. and Wang, Y., *School of Mechanical Engineering, Southeast University, China.*

Earth-moving machinery drivers are often exposed to whole body vibrations and shock due to terrain irregularities and moving devices. For the increasing demand of operator comfort, the application of hydraulic mounts for cab's vibration reduction is of concern. In this paper, effects of the displacement-dependent damping presented by the hydraulic mount on dynamic responses of a frame-cab system under the transient displacement excitation are investigated. As a result that the cab mass center is positioned relatively high above the supporting surface but hardly in the center of the supported mounts, cab shake is prone to generate. Therefore, a three degree-of-freedom (DOF) model is established, considering the cab vibration along the vertical, roll and pitch axes. The acceleration response of the cab mass center and the rattle space response are compared between with and without the displacement-dependent damping. Also, the effects of the parameter that decides the nonlinear damping characteristic on the responses are studied. Simulation results show that suspended cab system with nonlinear hydraulic mounts present better performance than the system with linear cab mounts and has benefit to alleviate the effect of shake on the cab's operators. Although it produces higher acceleration peaks, the nonlinear hydraulic mount quickly dampens the subsequent responses. The study also shows that the parameter related to the displacement-dependent damping has more significant effect on the acceleration response than on the relative displacement response.

Session 1 Active Vibration Control and Smart Structures I

15:10

Design and Adaptive Model-Based Feedforward Control of an Electromagnetic Tuned Vibration Absorber with Shunt Electronics (990)

Mace, B.R. and McDaid, A.J., *Department of Mechanical Engineering, The University of Auckland, New Zealand.*

Tuned vibration absorbers are effective devices for vibration control in the presence of tonal or broadband excitation. However, when the properties of the host structure or absorber change or, for tonal excitation, the excitation frequency varies they become detuned and their performance can degrade to an unacceptable level. It is therefore desirable, in any real application, that a TVA must be able to automatically adapt to variations in system operating parameters. In this paper an electromagnetic device with an adaptive electrical shunt impedance is described. The application focusses on tonal excitation. The shunt is implemented synthetically to allow the parameters and hence natural frequency of the TVA to be altered on demand. A proposed model-based feedforward controller updates the TVA parameters to ensure the natural frequency of the TVA tracks the excitation frequency. In the steady state the system therefore always operates with an antiresonance at the excitation frequency, maintaining optimal performance throughout a large range of excitation frequencies. Finally, additional adaptation is included to introduce robustness to model errors. Simulations and experimental results show that the adaptive controller demonstrates better performance than the equivalent non-adaptive system as well as an H_∞ optimally tuned system.

Session 2 Soil-Structures Vibrations

15:10

A 3D Time Domain BEM Approach Accounting for Internal Soil Attenuation (1538WIP)

Maestre, J., Romero, A. and Galvín, P., *Escuela Técnica Superior de Ingeniería. Universidad de Sevilla, Spain.*

This paper deals with a work-in-progress about an efficient development of a 3D time domain BEM approach based on the half space fundamental solution. Internal soil attenuation is implicitly considered by means of the Barkan's model. All fundamental solution singularities are identified. Different techniques are proposed to avoid unstable solution behaviour. BEM approach is numerically validated by comparison with analytical half space solution.

<u>Session 3</u> Reusable Hypersonic Platform I

15:10

Coupled Reduced Order Model-Based Structural-Thermal Prediction of Hypersonic Panel Response (890)

Mignolet, M.P., Matney, A.K., Spottswood, S.M., Culler, A.J. and McNamara, J.J., *Schools for the Engineering of Matter, Transport, and Energy (SEMTE), Arizona State University, USA.*

This paper addresses some aspects of the development of a fully coupled thermal-structural reduced order modeling of planned hypersonic vehicles, most notably the construction of the thermal and structural bases. A general framework for this construction is presented and demonstrated on a representative panel considered in prior investigations. The thermal reduced order model is first developed using basis functions derived from appropriate conduction eigenvalue problems. This basis is validated using published data of which it is found to provide an accurate representation. The coupling of this thermal model with a recently developed nonlinear structural reduced order model of the same panel is next considered. This coupling requires first the enrichment of the structural basis to model the elastic deformations that may be produced consistently with the thermal reduced order model. This step is detailed for the present panel and then the temperature dependent coefficients of the structural model are determined. The validation of the combined structural-thermal reduced order model is carried out by comparison with full finite element results (Nastran here) corresponding to pure mechanical loads, pure thermal loads, and combined mechanical-thermal excitations. Such comparisons are performed here on static solutions with temperature increases up to 2700R and pressures up to 3 psi for which the maximum displacements are of the order of 3 thicknesses. The reduced order model predicted results agree well with the full order finite element predictions in all of these various cases.

<u>Session 4</u> Analytical Modelling

15:10

The Frequency Analysis of Double-End Tuning Fork Quartz Resonators (968)

Chang, C-O., Chien, W-T.C., Huang, B-S., Shieh, F-H., Chou, C-S. and Chang, P-C., *Institute of Applied Mechanics, National Taiwan University, Taiwan.*

The resonant frequencies of a double-end fixed tuning fork quartz resonator, which is composed of two parallel beams with their ends fixed to the proof masses and the two ends of the proof masses are clamped, are analyzed. The structure is made of Z-cut quartz wafers, which are anisotropic in elastic stiffness, dielectric and piezoelectric constants. Without the proof masses, the two parallel beams are independent in vibration. With the proof mass included more additional modes, such as anti-phase modes, are created. In anti-phase bending mode the two parallel beams vibrate in opposite directions, the advantage of this mode is that the center of mass is unchanged during motion so that the system has higher signal-to-noise ratio, and it can be used as oscillators in electronic or mechanical devices. It is easy to model the deformation of the two slender beams, but difficult to model that of the proof masses, due to this there is no analytical solution of frequencies in the literature. The deformation model of the proof mass is proposed so that the mode shapes and natural frequencies can be solved exactly based of the equations of motion derived from the Hamilton's principle. The theoretically-obtained natural frequency is compared with the experimental one and that obtained by the finite element method.

<u>Session 1</u> Active Vibration Control and Smart Structures I

15:30

Active Control of Seats to Reduce Helicopter Aircrew Exposure to Vibration (804)

Wickramasinghe, V., Chen Y., Sasiadek, J. and Nitzsche, F., *Aerospace Portfolio National Research Council, Canada.*

Although the helicopter has become a versatile mode of aerial transportation, high vibration levels can lead to poor ride quality for its passengers and the aircrew. Undesired vibration transmitted through the helicopter seats have been known to cause fatigue and discomfort to the aircrew in the short-term as well as neck strain and back pain injuries due to long-term exposure. This research study investigated the use of novel active control methodologies integrated as an adaptive helicopter seat mount to mitigate the aircrew exposure to high vibration levels.

The novel adaptive seat mount approach was designed using two stacked piezoelectric actuators incorporated as active struts to generate forces to counteract harmonic vibration. A real-time controller implemented using a feed-forward algorithm based on adaptive notches counteracted the forced vibration peaks while a robust feedback control algorithm suppressed the resonance modes of the seat structure. The effectiveness of the adaptive seat mount system was demonstrated through extensive closed-loop control tests on a full-scale helicopter seat using representative helicopter floor vibration profiles generated using a mechanical shaker platform. The test results concluded that the proposed adaptive seat mount approach based on active control technology is a viable solution for the helicopter seat vibration control application.

<u>Session 2</u> Soil-Structures Vibrations

15:30

Accurate Location of Explosive Misfires Using a Single Channel Detector (1548WIP)

Liddell, K., *Institute of Sound and Vibration Research, University of Southampton, UK.*

Drill and blast techniques are employed in tunnel construction around the world. A means of confirming that every charge has fired would increase worker safety and productivity. A range of experiments were conducted to determine the spatial accuracy of predicted location estimates derived from measurement s of individual blast-induced impulses using a single accelerometer. Cross correlations of pre-blast signature-impulse time-series signals were made with those from a range of candidate impulses that were made progressively closer in proximity to the original signature impulse. Additional trials were conducted using more representative blast-induced impulse signals in situ at a mine. Spatial mapping of the correlation coefficients obtained from bench tests showed resolutions of <2cm from the signature origin. In more open test environments resolutions of <10cm can be achieved. Experiments in a mine environment using detonator-induced impulses showed that spatial resolutions could be seen around 20-30cm. Further tests to establish the viability of this technique at a production scale are planned.

Session 3 Reusable Hypersonic Platform I

15:30

Allowing for Non-Proportionality in Multiaxial Spectral Fatigue Analysis (914)

Sweitzer, K.A. and Sherratt, F., *Booz Allen Hamilton, USA.*

Spectral methods of life estimation, using Power Spectral Densities (PSD) are in regular use in the case of uniaxial fatigue. They are often linked to Finite Element Analysis (FEA). Recently their use has been extended to the field of multiaxial fatigue, again commonly linked with FEA. This paper examines some of the techniques, particularly ones linked to the non-proportionality which is inherent in such loading. The aim is to identify strategic issues in choosing a design method.

Fundamental reasons for the difficulties caused by non-proportionality lie in the complexities of the crack initiation process caused by fatigue, even when the loading history is simple and uniaxial. This has been, and still is, the subject of intensive research, Abuzaid, et al. [1] being a typical modern reference. The details of material behavior needed to apply such considerations to the design of complete structures require computations too demanding for regular use, though. Instead, a variety of simplified models, such as strain-life analysis and fracture mechanics, are employed. Loading histories used by modern methods also impose simplifications. Probabilistic data reduction techniques like rainflow counting and frequency domain analysis based on power spectral densities (PSDs) are in regular use.

But, methods for calculating appropriate “equivalent” stress parameters like principal stress planes are not yet fully accepted. This paper reviews recent work in this field and then proposes new methods suitable for rapid fatigue design in the frequency domain.

Session 4 Analytical Modelling

15:30

Three-Dimensional Elasticity Solutions for Free Vibrations of Thick Rectangular Plates with Various Boundary Conditions (821)

Zhang, Y., Du, J., Yang, T., Zhan, X. and Liu, Z., *College of Power and Energy Engineering, Harbin Engineering University, China.*

Plate structure is widely used in many engineering branches, such as marine, aerospace, vehicle and building engineering. A deep understanding on its vibration characteristics is of critical importance for the relevant design and vibration control engineers. Most of the current studies are based on the classical plate theory or other high-order approximation theories for the plate structure with relatively thin thickness. However, few efforts have been devoted to the vibration problem using three-dimensional elasticity theory, in which the plate is very thick. In this paper, a three-dimensional improved Fourier series method is proposed to model the three vibrating displacement fields in the thick rectangular plate with various boundary conditions. All the unknown coefficients are then determined from the minimization of system Lagrangian constructed completely from the 3-D elasticity theory. Finally, numerical examples are given to validate the current method through the comparison with those results from other approach and/or Finite Element Analysis (FEA) by using NASTRAN. The results show that the natural frequencies and mode shapes of thick plate can be easily and accurately obtained no matter the boundary condition is symmetric or not.

<u>Session 1</u> Active Vibration Control and Smart Structures I

15:50

Seat Design and Control of Passenger Vibrations in a Quarter Car Model (771)

Singru, P. and Anilkumar, A., *Department of Mechanical Engineering, Birla Institute of Technology and Science, India.*

This paper is based on a theoretical study for seat modeling and control of passenger vibrations. The first objective of this work is to develop a seated passenger model considering hysteretic structural damping of the seat. Jump discontinuities, generally seen in equations of the duffing type are studied and a limiting values of loss factor, β is calculated. The equations of motion of the coupled passenger-car model are developed and linearized for control. The second objective is to develop an efficient controller to minimize vibrations transmitted through the modeled seat. An h_{∞}controller for minimizing passenger deflection and thereby acceleration, is designed and simulated. It is expected that the seated passenger model developed here will have relevance in practical situations like semi-active suspension and vehicle seat designing.

<u>Session 2</u> Reusable Hypersonic Platform I

15:50

Reduced Order Modeling for the Static and Dynamic Geometric Nonlinear Responses of a Complex Multi-Bay Structure (946)

Mignolet, M.P., Perez, R., Wang, X.Q. and Matney, A.K., *SEMTE, Faculties of Mechanical and Aerospace Engineering, Arizona State University, USA.*

This paper focuses on the continued development and deepened validation of nonlinear reduced order models of structures experiencing large deformations. Of particular interest here is a complex structure with rich dynamics: a previously introduced 9-bay panel with stiffeners and longerons modeled by finite elements using approximately 96,000 degrees-of-freedom. Building on a general methodology successfully validated in recent years on simpler beam and plate structures, a reduced order model of the panel motions is developed step-by-step. This 85-mode model is shown by comparison with full finite element (Nastran) results to lead to accurate predictions of both static and dynamic responses of the panel. Coupling of this reduced order model with piston-theory aerodynamics is also achieved to demonstrate the capability of these reduced order models to support multidisciplinary analyses.

<u>Session 1</u> Experimental Methods

16:40

Gear Transmission Error Measurement Accuracy Using Low-Cost Digital Encoders (942)

Palermo, A., Britte, L., Janssens, K., Mundo, D. and Desmet, W., *Dipartimento di Ingegneria Meccanica, Energetica e Gestionale, Università della Calabria, Italy.*

Gear Transmission Error (TE) is widely recognized as the main internal source of vibration in power transmissions. It quantifies the deviations from a perfectly kinematic motion transmission which in a real case are introduced by deflections, misalignments and manufacturing errors. The TE can then be directly linked to durability, noise and diagnostics assessment. Given the relevance of this physical quantity and since gears usually attain very high stiffness, experimental techniques have been developed for measuring it with a tight constraint on measurement accuracy. Measurement procedures using encoders with a very high number of divisions (above 18000), paired with dedicated acquisition systems is the common way of achieving the required accuracy. Few methods have been proposed which use low-cost digital encoders and multi-purpose acquisition systems. The accuracy of such techniques was discussed empirically for a few case studies. In the proposed paper, the authors determine numerically how errors in encoder spacing and in acquisition clock affect gear dynamic TE measurement for an experimental case study. It is concluded that it is unnecessary to seek for increased sampling time accuracy for the speed range of interest as encoder accuracy dominates the measuring chain.

<u>Session 2</u> Fluid-Structure Interaction

16:40

Dynamics of a Nonlinear Liquid Sloshing Inside a Tank (874)

Haitao, Z., Sun, B-B., Jian, C. and Jiandong, C., *School of Mechanical Engineering, Southeast University, China.*

Sloshing is a phenomenon which is caused by the movement of the container. If the excitation frequency is close to the natural frequency of the container, the sloshing can be violent, the structure of the container would damage under the heavy shock load on the wall, and the hydrodynamic forces and moments acting on the wall would change the dynamic behavior of the container and its host systems in return. Hence, sloshing will have much impact on the safety and stability of the system. It is important to study the dynamic characteristics of the sloshing in moving containers.

In the past a few years, research of sloshing has been made by using analytic, numerical and experimental methods (e.g., Abramson [1], Faltinsen [2], Ibrahim [5]). Because of the rapid development of electronic computers, it seems that numerical simulation has become a mainstream method (e.g., Wu, etc[4], Pirker.S, etc[6]). FLUENT, which is an excellent CFD (Computational Fluid Dynamics) software, can be used to simulate many complicated fluid dynamical processes with high precision, so it has been widely applied in CFD problems.

In this paper, liquid sloshing problems with free surface in moving containers are studied, the CFD models of liquid sloshing are built and calculated, taking consideration of many factors such as tank shapes, mesh dividing and convergence, which affect the calculating results. The movements of containers are simulated by using dynamic mesh technique, and UDF (User Defined Function) is programmed to get the hydrodynamic forces and moments. Natural frequencies of sloshing in tanks with different shapes or different filling-rates are studied, and the nonlinear impact of excitation on frequencies and amplitudes of sloshing forces are analyzed. The results will provide theoretical basis for the optimal design and proper operation of tanks, and lay the foundation for the more research of dynamic coupling of sloshing in tanks and its host systems.

<u>Session 3</u> Reusable Hypersonic Platform II

16:40

Understanding how Kurtosis is Transferred from Input Acceleration to Stress Response and its Influence on Fatigue Life (1006)

Kihm, F., Rizzi, S.A., Ferguson, N.S. and Halfpenny, A., *HBM-nCode Products Division, Rotherham, UK.*

High cycle fatigue of metals typically occurs through long term exposure to time varying loads which, although modest in amplitude, give rise to microscopic cracks that can ultimately propagate to failure. The fatigue life of a component is primarily dependent on the stress amplitude response at critical failure locations. For most vibration tests, it is common to assume a Gaussian distribution of both the input acceleration and stress response. In real life, however, it is common to experience non-Gaussian acceleration input, and this can cause the response to be non-Gaussian. Examples of non-Gaussian loads include road irregularities such as potholes in the automotive world or turbulent boundary layer pressure fluctuations for the aerospace sector or more generally wind, wave or high amplitude acoustic loads.

The paper first reviews some of the methods used to generate non-Gaussian excitation signals with a given power spectral density and kurtosis. The kurtosis of the response is examined once the signal is passed through a linear time invariant system. Finally an algorithm is presented that determines the output kurtosis based upon the input kurtosis, the input power spectral density and the frequency response function of the system. The algorithm is validated using numerical simulations. Direct applications of these results include improved fatigue life estimations and a method to accelerate shaker tests by generating high kurtosis, non-Gaussian drive signals.

<u>Session 1</u> Experimental Methods

17:00

Monitoring the Dynamics of an Operating Helicopter Rotor using 3D Digital Stereophotogrammetry (950)

Niezrecki, C., Baqersad, J., Lundstrom, T. and Avitabile, P., *Structural Dynamics and Acoustic Systems Laboratory, University of Massachusetts Lowell, USA.*

The measurement of vibration data on rotating structures (e.g. helicopters rotors or wind turbines) during operation has historically been a challenge. Conventional sensors are difficult to implement (due to wiring and power requirements) and can induce mass loading effects. Moreover, cabling and data transmission through slip rings or wireless devices can introduce noise into the measured data. In this paper, stereophotogrammetry is investigated as an alternative to conventional sensors for measuring the vibration of a rotating helicopter rotor. Dynamic point tracking is used to measure displacements at numerous points distributed along a 10.1-meter diameter rotor blade of a Robinson R44 helicopter. A pair of high speed cameras was installed on a long camera bar that was calibrated by using an array of coded targets placed on the ground. The displacement of 22 optical targets mounted to the blades was measured while the helicopter rotor was spinning with the helicopter on the ground and hovering. Operational modal analysis of the measured data was performed revealing the dominant contribution of the structural modes to the operating deflection shapes. The helicopter rotor motion was dominated by harmonics of the blade passage frequency, however some non-harmonic operating deflection shapes were also observed. This paper provides a description of the experiment performed along with lessons learned while performing the test. This study reveals that stereophotogrammetry has significant potential as a robust non-contacting measurement technique for monitoring dynamic behavior of rotating helicopter rotors or wind turbine blades.

<u>Session 2</u> Fluid-Structure Interaction

17:00

Free Vibration Analysis of a Fixed-Free Rectangular Tank Partially Surrounded with Water (982)

Jeong, K-H., Kim, J-W. and Kim, J-I., *Reactor Mechanical Engineering Division, Korea Atomic Energy Research Institute, Republic of Korea.*

A theoretical method to calculate the natural frequencies of a fixed–free rectangular tank partially surrounded with water is proposed. Orthogonal polynomials satisfying the boundary conditions of the tank are used as admissible functions in the Rayleigh–Ritz method. The fluid displacement potential functions satisfying the Laplace equation and water boundary conditions are derived, and the compatibility requirement along the contacting interfaces between the tank and water is applied for the finite Fourier transform. An eigenvalue problem is derived so that the natural frequencies of the wet rectangular tank can be extracted. The predictions from the proposed analytical method show good agreement with the finite element analysis results.

Session 3 Reusable Hypersonic Platform II

17:00

Vibrational Fatigue and Structural Dynamics at Harmonic and Random Loads (1045)

Česnik, M., Slavič, J. and Boltežar, M., *Laboratory for Dynamics of Machines and Structures, Faculty of Mechanical Engineering, University of Ljubljana, Slovenia.*

The presented study experimentally and theoretically researches the vibrational fatigue of the aluminum-alloy specimen at harmonic and random loads. The relation between vibrational fatigue for deterministic and random vibration loads is demonstrated with presented experiments and standard frequency-based counting methods. Firstly, a new fatigue testing methodology is proposed to obtain the material fatigue parameters with harmonic basevibration excitation. With the developed methodology it is possible to monitor in real-time the principal stress amplitude at the specimen as well as to track the natural frequency shift and the increase of the structural damping of the specimen due to the accumulated fatigue damage. Secondly, with a validated numerical model of the specimen the mechanical stress transmissibility of the structure was obtained for the case of the random-vibration base excitation. Finally, by respecting the mechanical stress response along with experimentally obtained material fatigue parameters the vibration fatigue life was estimated for the case of the random vibration load. The numerical fatigue life is compared to the experimental one, obtained with the electro-dynamic shaker. The influence of the damping loss factor on the calculated fatigue life is indicated and discussed. The presented research shows new possibilities and critical aspects in the area of accurate high-cycle vibration fatigue life-estimation of dynamic structures.

<u>Session 1</u> Experimental Methods

17:20

Ultrasonic Motor using First and Second Bending Modes (770)

M'Boungui, G., Jimoh, A.A., Loveday, P.W. and Long, C.S., *Department of Electrical Engineering, Tshwane University of Technology, South Africa.*

This paper presents the design of a novel resonator for use in a piezoelectric linear ultrasonic motor. The work is motivated by a motor previously developed by the authors that showed to be capable of achieving a force of 50 mN and a velocity of 14 mm/s, which they found unsatisfactory. To that end, among an existing variety of working principles for Piezoelectric Ultrasonic Motors, the principle of giving the material points of the stator in contact with the rotor a "∞" trajectory and thus propelling the rotor was utilized.

Our concept is based on Euler-Bernoulli beam theory which shows that the natural frequency ratio of the first and second bending modes for a beam, fixed at both ends, is approximately 3 and we employ a gradient-based optimization algorithm to assist in the design of the structure.

<u>Session 2</u> Fluid-Structure Interaction

17:20

Review and Upgrade of a Bulk Flow Model for the Analysis of Honeycomb Gas Seals Based on New High Pressure Experimental Data (991)

Saba, D., Forte, P. and Vannini, G., *Dipartimento di Ingegneria Civile e Industriale (DICI), Università di Pisa, Italy.*

The design of the gas seals used in centrifugal compressors and axial turbines requires to consider not only their aptitude to reduce leakage, but also their contribution to the overall dynamics of the machine. Honeycomb and hole pattern annular seals are often employed in compressors for the end balance piston seal or as the central balance piston seal in a back-to-back arrangement. In contrast to labyrinth seals, they show a beneficial damping effect. In order to obtain an effective tool for predicting the leakage and the dynamic response of honeycomb seals, a bulk flow model has been devised in the past and, implemented in numerical codes, it is presently used in the design process. This kind of codes, however, require simplifying assumptions: in particular, one reference code available to the authors adopts the hypothesis of isothermal process. However, as the required level of confidence in seal design is increasing due to the fact turbomachinery design is more challenging, an experimental validation and possibly some refinement are needed. In this work, the bulk flow model was reviewed and the sensitivity to different hypotheses was explored. New experimental data from a high pressure test rig were compared with the results of simulations.

Session 3 Reusable Hypersonic Platform II

17:20

Combined Environment Validation of Hypersonic Structures (1055) Presentation only.

Swanson, A., *Air Force Research Laboratory, USA.*

This presentation will review the capabilities of the AFRL Structures Test Facility and describe some recent research into thermal, mechanical, and acoustic loads testing of structures for hypersonic vehicles. The United States Air Force's continuing interest in air vehicles that fly ever higher and faster leads to the need for improved validation methods and facilities for evaluating the effects of high temperatures on structural response. Since the early 1990s, AFRL has been developing combined environment test capabilities to validate the performance of structural concepts for a wide variety of high-speed vehicles. Large scale thermal, mechanical, thermoacoustic, and thermal-mechanical capabilities have been developed and will be described. Some of the pitfalls, success stories, and opportunities will also be discussed. Of special interest are the difficulties measuring structural response in harsh environments and the methods employed to obtain good data.

Session 1 Experimental Methods

17:40

Recent Enhancements to the NASA Langley Structural Acoustics Loads and Transmission (SALT) Facility (803)

Rizzi, S.A., Cabell, R.H. and Allen, A.R., *NASA Langley Research Center, Structural Acoustics Branch, USA.*

The Structural Acoustics Loads and Transmission (SALT) facility at the NASA Langley Research Center is comprised of an anechoic room and a reverberant room, and may act as a transmission loss suite when test articles are mounted in a window connecting the two rooms. In the latter configuration, the reverberant room acts as the noise source side and the anechoic room as the receiver side. The noise generation system used for qualification testing in the reverberant room was previously shown to achieve a maximum overall sound pressure level of 141 dB. This is considered to be marginally adequate for generating sound pressure levels typically required for launch vehicle payload qualification testing. Recent enhancements to the noise generation system increased the maximum overall sound pressure level to 154 dB, through the use of two airstream modulators coupled to 35 Hz and 160 Hz horns. This paper documents the acoustic performance of the enhanced noise generation system for a variety of relevant test spectra. Additionally, it demonstrates the capability of the SALT facility to conduct transmission loss and absorption testing in accordance with ASTM and ISO standards, respectively. A few examples of test capabilities are shown and include transmission loss testing of simple unstiffened and built up structures and measurement of the diffuse field absorption coefficient of a fibrous acoustic blanket.

Session 2 Fluid-Structure Interaction

17:40

Aeroelastic Stability of a Symmetric Multi-Body Sectional Model (1014)

Lepidi, M. and Piccardo, G., *DICCA Dipartimento di Ingegneria Civile, Chimica ed Ambientale, Università degli Studi di Genova, Italy.*

The aeroelastic stability of a multi-body system is studied through a four-degree-of-freedom model, which describes the linearized section dynamics of particular suspended bridges with doubly-symmetric cross-section, subject to a lateral stationary wind flow. A multi-parameter perturbation solution, applied on the classic modal problem in internal resonance conditions, allows a consistent reduction of the model dimensions. The bifurcation scenario described by a local stability analysis in the resonance region is featured by two stability boundaries, strongly interacting in the parameter space. The analysis of the critical wind velocity provides satisfying engineering results, pointing out how resonant light cables or dissipative cable-deck couplings may have beneficial effects in preventing the aeroelastic instability.

Session 3 **Reusable Hypersonic Platform II**

17:40

A Structural Perspective on the Challenges Associated with Analyzing a Reusable Hypersonic Platform (892)

Spottswood, S.M., Eason, T.G. and Chona, R., *U.S. Air Force Research Laboratory (AFRL), USA.*

The AFRL is researching methods for structural-scale simulation to address deficiencies in the analysis of extreme-environment structures that have historically stymied the aerospace community. The root of these deficiencies is the inability to accurately quantify the interactions between the high-speed flow environment and the vehicle structure through modeling and experimentation. Hypersonic vehicles require structures to withstand complex non-proportional loading leading to path-dependant responses with interacting failure modes forcing the analyst to consider margins over a trajectory instead of assumed worst-case points. Specifically, these structures will experience high transient surface temperatures and gradients from flow compression/viscous dissipation, broadband pressure fluctuations due to boundary layer turbulence, deformation induced pressures, and long-duration exposure to these environments [1,2]. Challenges include coupling between the aero-thermal environment and the structural deflections; consideration of local effects inherent in hypersonic flows; the computational cost of large models; material degradation and nonlinearity; spatial variation of material and structural properties; uncertainty in loads, material properties, and boundary conditions. Further compounding these challenges is the inability to account for interacting failure modes such as high-cycle fatigue due to aeroacoustic and mechanical vibrations, low-cycle fatigue due to thermal-mechanical loading, and material degradation or oxidation due to the extreme thermal environment [3]. To address these challenges, the Structural Sciences Center (SSC) at the Air Force Research Laboratory, has embarked on a campaign to uncover the knowledge gaps associated with defining the structural margins for a reusable Mach 5-7 air breathing class hypersonic vehicle. The current focus of this campaign includes: (1) reviewing the structural challenges encountered in past high-speed structures programs, (2) assessing the current state-of-the-art in design and analysis methods; and (3) identifying critical knowledge gaps in current methods. Each of these areas will be discussed and presented, with the goal of energizing the aerospace community to participate in helping to define and develop an appropriate series of relevant benchmark challenge to address key critical knowledge gaps.

Notes

Plenary Sessions

09.00

An Overview of Virtual Acoustic Simulation of Aircraft Flyover Noise

Rizzi, S.A., *NASA Langley NASA Langley Research Center, USA.*

Methods for testing human subject response to aircraft flyover noise have greatly advanced in recent years as a result of advances in simulation technology. Capabilities have been developed which now allow subjects to be immersed both visually and aurally in a three-dimensional, exterior virtual environment. While suitable for displaying recorded aircraft noise, the true potential is found when synthesizing aircraft flyover noise because it allows the flexibility and freedom to study sounds from aircraft not yet flown. A virtual acoustic simulation method is described which is built upon prediction-based source noise synthesis, engineering-based propagation modeling, and empirically-based receiver modeling. This source-path-receiver paradigm allows complete control over all aspects of flyover auralization. With this capability, it is now possible to assess human response to flyover noise by systematically evaluating source noise reductions within the context of a system level simulation. Examples of auralized flyover noise and movie clips representative of an immersive aircraft flyover environment are made in the presentation.

13:40

Broadband Vibration-Based Energy Harvesting: Model Reduction and Frequency Up-Conversion

Wickenheiser, A.M., *The George Washington University, USA.*

In many scenarios where vibration energy harvesting can be utilized – particularly those involving bio-motions or environmental disturbances – energy sources are broadband and non-stationary. On the other hand, design procedures have been predominantly developed for harmonic or white noise excitation, specifically for single degree of freedom approximations of the transducer. In this study, a general approach for design optimization of cantilevered, piezoelectric energy harvesters in the presence of band-limited, white-noise excitation is outlined. Human motions such as walking, running, and riding in a car are considered; these complex waveforms are distilled into a small set of dominant features with regard to their impact on the power output of the device. These features are used to inform the modal truncation of the transducer model such that only the modes that contribute significantly to the energy harvested are retained. These reduced-order models are then used in a design optimization process for each vibration energy source.

The results of this optimization indicate that it is impossible to design an efficient linear transducer for low frequency sources, such as walking, without resorting to heavy masses or large dimensions. Therefore, a non-linearity is introduced in the form of frequency up-conversion; this technique uses a magnetic tip mass inside a ferrous enclosure to create a sequence of potential wells. The transition of the tip mass between the wells induces a pluck followed by a free response, similar to an impact. The dynamics of the base motion and the free response are then decoupled by (1) predicting how often the plucks occur and what their initial deflections are and (2) calculating the subsequent free response to each pluck. Simulations show that the nonlinear response converges to the impact-based approximation at low frequencies (compared to the fundamental natural frequency), whereas it converges to the linearization of the system in the vicinity of the fundamental natural frequency. Hence, the impact-based approach shows utility for modeling low-frequency energy harvesting using frequency up-conversion. This is demonstrated by applying several low-frequency measured acceleration waveforms that are dominated by impacts in case studies.

Notes

Session 1 Active Vibration Control and Smart Structures II

10:30

Tuneable Vibration Absorber for Multi Modal Control of Lightly Damped Structures (1025)

Zilletti, M. and Gardonio, P., *Dipartimento di Ingegneria Elettrica Gestionale e Meccanica (DIEGM), Università di Udine, Italy.*

This paper presents the design of an experimental multi modal vibration absorber for controlling the transverse vibration of a lightly damped panel. Traditionally, when multiple modes of a structure need to be controlled many absorbers are scattered on the structure, each tuned to control a specific structural mode. However the use of multiple units increases the added weight to the structure and requires complex tuning process, which therefore raise the cost of the control treatment.

In this paper an integrated vibration absorber able to incorporate in one unit the effect of two traditional single axis absorbers is proposed. The absorber consists of a beam with a cylindrical inertial mass mounted at the centre. The connection between the mass and the beam is realised through flexible fins that allow rotational vibrations of the mass around the beam but do not allow relative displacement. When the two ends of the beam are attached to a structure, the flexural vibration of the beam-mass system produces a transverse control force on the structure while the rotational vibration of the inertial mass generates a control moment.

These two actions can be used to control the response of two resonant modes of a structure by tuning the two resonances of the device to match those of the modes under control. The flexural resonance of the beam-mass system is tuned by varying the axial tension of the beam using a piezoelectric stack transducer while the rotational resonance of the device is regulated by varying the tension on capacitors whose plates are mounting on the beam and on the rotating mass respectively.

Session 2 Uncertain Dynamical Systems

10:30

Compressional Wave Features Propagating in a Two Dimensional Domain with Randomly Imperfect Material Density (817)

Náprstek, J. and Fischer, C., *Institute of Theoretical and Applied Mechanics, v.v.i., Academy of Sciences of the Czech Republic, Czech Republic.*

The paper deals with radial compressional wave propagation in 2D continuum, the density of which is a continuous random function of (x; y) coordinates. This concept refers materials with microscopic non-homogeneity. Many papers appeared dealing with similar problem in a semi-infinite bar (1D) using spectral decomposition or Fokker-Planck equation analysis. Harmonic excitation acts in the origin. Material density is considered as a sum of a constant mean value and Gaussian, homogeneous and ergodic fluctuations in the plane (x; y). The correlation function is approximated as exponential being dependent on the distance of two points only. Derived spectral density in polar coordinates reads then in irrational and Bessel functions. The governing integro-dierential system for unknown stochastic parameters of waves propagating from the origin is then investigated. There has been shown a steep drop of the response deterministic part in radial direction with the increasing distance from the point of excitation due to stochastic character of material properties. In the same time a simultaneous increase of the response uncertainty rate (stochastic part) has been detected. These processes don’t represent any mechanical energy loss, but only changes of its form. An upper limit of the excitation frequency (critical frequency) depending on the mean correlation length of material imperfections has been identified. Similar effects can be observed in the FEM analysis, where a certain permissible upper boundary of the excitation frequency corresponds with the size and type of the element.

Notes

Session 1 Active Vibration Control and Smart Structures II

10:50

Velocity Feedback Loops with Composite Hexagonal and Circular Piezoelectric Patch Actuators (1031)

Gardonio, P., *Dipartimento di Ingegneria Elettrica Gestionale e Meccanica (DIEGM), Università di Udine, Italy.*

This paper investigates the feasibility and control performance of a single channel velocity feedback loop located at the centre of a rectangular panel. The feedback control system is made by either a composite hexagonal or a circular piezoelectric patch with an accelerometer sensor at its centre. The hexagonal patch is formed by six triangular piezoelectric leafs, each with the principal axis aligned along the lateral edge of the hexagon and the radial direction. Thus the hexagonal piezoelectric patch can be regarded as a composite transducer that produces a net transverse force at its centre, which is balanced by transverse forces at the six vertices of the hexagon, and bending moments along the six edges of the hexagon. The circular patch is made of an homogeneous piezoelectric material with principal axis oriented in tangential and radial directions so that a uniform distribution of bending moments oriented in radial direction is produced along the perimeter of the patch together with a point transverse force at the centre position, which is balanced by a uniform transverse force along the perimeter of the patch. When a velocity feedback loop is implemented, these sensor–actuator configurations show improved stability properties in comparison with the standard configuration that uses a square piezoelectric patch actuator. Also, the two feedback loops produce a transverse sky–hook active damping action localised at the centre of the panel, which effectively absorbs flexural energy and thus reduces the broad-band flexural response and sound radiation of the panel at low audio frequencies.

Session 2 Uncertain Dynamical Systems

10:50

Evaluation of Statistical Overlap and Frequency Spacing of Two Randomised Dynamic Systems (1042)

Yang, J. and Kessissoglou, N., *School of Mechanical and Manufacturing Engineering, The University of New South Wales, Australia.*

This work examines the statistical overlap and frequency spacing of structures with uncertainties. Two dynamic systems are examined corresponding to a simply supported plate in flexural motion and a multi-degree of freedom system comprised of mass-spring oscillators coupled in series. For the plate, structural uncertainty was generated by mass perturbations. The mass-spring chain was randomised in two ways. In the first case, every individual mass was modified using a log-normal distribution. In the second case, small mass-spring systems were added at random locations to the main masses. The natural frequencies and frequency statistics are derived for each system. The probability distributions of the modal spacings are presented.

Session 1 Active Vibration Control and Smart Structures II

11:10

Development and Validation of a Finite Element Structure Semi-Active Tuned Liquid Damper System Model (1300)

Soliman, M., Tait, M.J. and El Damatty, A.A., *Department of Civil, Structural and Architectural Engineering, AMEC Americas Limited, Canada.*

Similar to a tuned mass damper (TMD) device, a tuned liquid damper (TLD) device can reduce resonant vibrations of a structure by modifying its frequency response function. In the structure-TLD system, the secondary mass is liquid and the damping forces primarily result from the motion of liquid through an energy dissipating device such as damping screens. The primary difference from a TMD is the amplitude dependent nature of a TLD. It would be beneficial to provide TLDs with variable damping that can be adjusted through a certain mechanism to achieve an optimal control performance over a wide range of loading conditions in a semi-active mode of control. To the best of the authors' knowledge, no previous study has considered structural control of tall buildings using semi-active TLDs. In this paper, a control strategy based on a gain scheduling scheme is utilized by controlling the inclination angle of the damping screen(s) and consequently the screen loss coefficient value(s). The gain scheduling control strategy is employed on a three dimensional single-story structure equipped with a semi-active TLD in order to maintain the optimal damping value ($\zeta TLD{-}opt$) based on a prescribed look-up table.

Session 2 Uncertain Dynamical Systems

11:10

Impact Dynamics of Cylindrical Shells (1043)

Caresta, M., Langley, R.S. and Woodhouse, J., *University of Cambridge, Engineering Department, UK.*

This work presents an asymptotic approach to predict the response of cylindrical structures to an impact in the time domain. The theory is based on the calculation of an asymptotic impulse response function by knowledge of the modal density. The approach presented predicts a mean response on an ensemble of random structures with structural uncertainties. Both numerical and experimental results are presented. The theory has been successfully applied to thin and thick cylinders; in the latter case a modal density has been developed that differs from the classical case available for thin cylinders.

Notes

<u>Session 1</u> Active Vibration Control and Smart Structures II

11:30

Unknown Disturbance Estimation and Compensation Using PI Observer for Active Control of Smart Beams (788)

Zhang, S.Q., Li, H.N. and Schmidt, R., *Institute of General Mechanics (IAM), RWTH Aachen University, Germany & School of Mechanical Engineering, Northwestern Polytechnical University, China.*

Thin-walled structures with integrated piezoelectric materials are effective in vibration suppression with a suitable control strategy. This paper develops a disturbance rejection (DR) control for vibration suppression and implements the control scheme into the finite element (FE) model that is derived based on first-order shear deformation (FOSD) hypothesis. A proportional-integral (PI) observer is employed to estimate the unknown disturbances using the measured signals, which are then fed back into the controller as known inputs. The vibrations suppressed by the present proposed control strategy are compared to those by linearquadratic regulator (LQR) control, which implies that the DR control with slowly varying disturbances estimated by PI observer has a better effect on active vibration control.

<u>Session 2</u> Uncertain Dynamical Systems

11:30

Distribution of Vibrations of a Double-Leaf Plate with Random Inhomogeneities (899)

Chung, H., *School of Computing and Mathematical Sciences, Auckland University of Technology, New Zealand.*

This paper shows how to compute vibrations of a double-leaf plate with random inhomogeneities in its components, two plates and reinforcement beams. The modelling method is based on the variational principle for elastic plates and beams. In addition to the deformation of individual components, the model includes contributions from junctions between components, e.g., how rigidly a beam is attached to a plate, and slightly twisted beams. The junction rigidity is included as potential energy in addition to the strain and the kinetic energies of the components. The random inhomogeneities are simulated as continuous smooth random functions of locations in the structure. A random function is realized using a predetermined probability density function and an autocorrelation function over the dimension of the component. The vibration is computed for each set of random functions, and statistical properties of the simulations are analysed. The random stiffness and the junctions affect the behaviour of the structure in a wide frequency range and a lower frequency range, respectively. The spectrum of surface vibration level shows changes in resonance frequencies depending on the random functions. Further relationship between the vibrations and the distributions of the random functions will be presented.

Session 1 Active Vibration Control and Smart Structures II

11:50

Development of Control System for Dynamic Absorber using Neural Oscillator and Position Controller (832)

Senda, T., Hongu, J., Iba, D., Nakamura, M. and Moriwaki, I., *Department of Mechanical and System Engineering, Kyoto Institute of Technology, Japan.*

This paper describes development of a new control system for active dynamic absorbers using a neural oscillator and position controller. When major earthquakes happen, it is necessary to shut down the traditional control systems designed by linear control theories. Typically as dynamic absorbers have stroke limitations of the mass due to the installation site, it is difficult for the linear systems to respond flexibly to changes of the stiffness as a result of destruction and deformation by earthquakes. On the other hand, a neural oscillator, which is a nonlinear oscillator, has been studied over the last few decades in the field of biology. The oscillator can be synchronized with an external sinusoidal input whose frequency is within a frequency band determined by the natural frequency of oscillator. In an effort to alleviate the problems associated with the stroke limitation and flexibility, the authors have recently proposed a new control system which is capable of confining the movable region of the mass and following the change of stiffness of the structure. The proposed control system consists of a mathematical model of the neural oscillator so-called Matsuoka oscillator and a position control system with a PD controller. However the proposed system is still coarse, and we are trying to further improve the system. In this paper, we deal with a new estimation method for the vibration energy in a structure. The proposed system requires information about vibrational energy at a specified natural frequency of the structure for determination of the travel distance of the auxiliary mass of dynamic absorber. We devise a new way using the neural oscillator, which has a function as a filter, and verify the method by numerical simulation.

Session 2 Uncertain Dynamical Systems

11:50

An Efficient Krylov Model Reduction Approach for the Direct Evaluation of Analytical Frequency Average of Transfer Functions in the Low-, Mid-, And High-Frequency Ranges (927)

Lecomte, C., *Southampton Statistical Sciences Research Institute (S3RI) and Institute of Sound and Vibration Research, University of Southampton, UK.*

Analytical expressions for the Gaussian frequency average and frequency variance of transfer functions, of linear dynamic systems are available from the author's previous work [1]. Since these expressions are valid and can be evaluated at any frequency, independently of the system complexity and modal density, and since they also give the frequency average of the energy, they provide a natural framework in which to study the transition from low- to high-frequency ranges. In principle, the analytical expressions would require the knowledge of the modal characteristics of the dynamic system of interest. The fact that modal information is not needed to evaluate the frequency average of transfer functions is highlighted. Rather, the average can be evaluated up to desired precision by using an analytical Krylov model reduction approach. The efficiency of this approach is demonstrated on systems of different

dimensions and modal densities. It is further demonstrated that system characteristics that are important at different frequency ranges can be integrated into a single reduced model and that low- to high-frequency ranges analysis can be run with a single model.

Notes

Session 1 **Active Vibration Control and Smart Structures II**

12:10

Sensor Layout Design Procedure for Active Control of Floor Panel Vibration with Modal Filtering Technique (924)

Shiomi, K., Igarashi, A., Yamada, H., Kachi, T., Kondo, M. and Takada, T., *Department of Civil and Earth Resources Engineering, Kyoto University, Japan.*

Application of the modal filtering technique to active control of floor vibration under impact excitation is expected to be effective and advantageous in reducing the floor impact sound associated with floor vibration. It is often the case that floor panels of actual practice in buildings do not obey the assumption of proportional damping and consequently have the dynamic characteristics of complex modes. The complex modal shapes render the modal filtering technique ineffective and pose considerable difficulty in its application to active control systems. In this study, a sensor layout design procedure for active control systems to avoid this problem is developed. Based on the discussion on the effects of the sensor locations to the performance of the modal filtering and active control, principles of preferable sensor layouts to obtain modal response component separation and control with the greatest performance are established and proposed as a design procedure. Verification tests using a floor panel unit and an active control system are conducted to investigate the performance of the modal filtering based on the sensor location determined by the proposed procedure, and the test result shows that effective reduction of the vibration level is successfully achieved.

Session 2 **Uncertain Dynamical Systems**

12:10

First Investigations on Bounded Eigenvalues for Spectral Finite Elements Models (1536WIP)

De Rosa, S., Franco, F., D'Alessandro, V. and Petrone, G., *PASTA-Lab, Department of Industrial Engineering – Aerospace Section, University of Naples, Italy.*

It is briefly presented an on-going activity on the dynamic characterisation of aluminium foam sandwich plates. The bounds of the eigenvalues representing the wave travelling in an infinite plate are given for a given interval of stiffness and mass in the foam part of the model. The resulting dispersion curves are thus associated to the given variations.

Session 1 Energy Harvesting

14:50

On the Simultaneous use of a Resonator as an Energy Harvester and a Vibration Absorber (853)

Brennan, M.J., Melo, G.P. and Lopes Jnr, V., *Departamento de Engenharia Mecanica, Universidade Estadual Paulista, Brazil.*

A mass-spring-damper system is at the core of both a vibration absorber and a harvester of energy from ambient vibrations. If such a device is attached to a structure that has a high impedance, then it will have very little effect on the vibrations of the structure, but it can be used to convert mechanical vibrations into electrical energy (act as an energy harvester). However, if the same device is attached to a structure that has a relatively low impedance, then the device may attenuate the vibrations as it may act as both a vibration absorber and an energy harvester simultaneously. In this paper such a device is discussed. Two situations are considered; the first is when the structure is excited with broad band excitation and the second is when the structure is excited by a single frequency. The optimum parameters of the device for both energy harvesting and vibration attenuation are discussed for these two cases.

Session 2 Stochastic Dynamics and Random Vibrations

14:50

Dynamic Response and Reliability Analysis for a Turret (875)

Liu, C., Chen, N., Sun, B-B., Zhang, J., Lu, X. and Liu, X., *School of Mechanical Engineering, Southeast University, China.*

Turret is a critical functional component for CNC lathe，it clamps a few cutting tools and programmlly takes one of the tools reached a designed indexing position to machine a work piece, so it participates in the machining process directly. As a tools holder the turret dynamic response determines the operating condition of the machining process and so has important effect on the machined work piece quality. Based on the transfer matrix method of multibody system (MS-TMM), the dynamic simulation system for a turret is established which includes the transfer equations, the characteristic equations, etc.. The dynamic response under the machining condition random load spectrum is obtained. Utilizing the Monte-Carlo test, the theoretical model of dynamic response distribution of the turret is proposed. According to the dynamic response under the machining condition random load, an operating condition information-based reliability prediction method is proposed, and the instantaneous reliability of a turret installed in the reliability test platform is estimated. The research provides a basis for the analysis of turret performance degradation and design for reliability enhancement test.

Session 3 **Railway Noise and Vibration**

14:50

The Effect of Temperature Variability when Monitoring a Railway Bridge (947)

Casciati, S., Faravelli, L. and Bortoluzzi, D., *Department DICA, University of Catania at Siracusa, Italy.*

In this paper the effect of temperature variation on the structural response of a railway bridge is analysed. In particular the main goal consists of clearing the measurements from the temperature effects. The approach pursued in this work is to use the field data to calibrate a numerical model which sees the temperature time history as an external excitation. A different set of measurements is then used to validate the model. It should be emphasized that the train crossing effects are taken into account in a separated manner from the environmental ones. The structure under study is the ÖBB Brucke Großhaslau railway bridge, in Austria.

Session 1 Energy Harvesting

15:10

Energy Harvesting using Semi-Active Nonlinear Control (933)

Ghandchi Tehrani, M., Elliott, S.J., Di Monaco, F. and Bonisoli, E., *Institute of Sound and Vibration Research, University of Southampton, UK.*

This paper presents the application of semi-active control for power harvesting using an electro-mechanical energy harvester. Two semi-active control strategies are proposed in the form of a time-periodic damper and a nonlinear cubic damper. For the periodic time-varying damper the average harvested power and the throw are obtained based on the Fourier series. The semi-active periodic time-varying damper is optimised to maximise the harvested power. The performance of the optimum semi-active periodic damper is compared with the optimum passive and semi-active on-off model at a particular frequency. It is demonstrated that the periodic time-varying damper can significantly increase the harvested power at all frequencies of interest. For the nonlinear damper, the harvested power and the throw are derived using the concept of the describing function. The results are compared with the linear damper. It is demonstrated that the nonlinear damper can significantly increase the absorbed power despite having much lower displacement compared to the linear damper. This makes the semi-active nonlinear damper very attractive for mechanical energy harvesters.

Session 2 Stochastic Dynamics and Random Vibrations

15:10

Nonlinear Stochastic Dynamical Post-Buckling Analysis of Uncertain Cylindrical Shells (922)

Capiez-Lernout, E., Soize, C. and Mignolet, M-P., *Laboratoire Modélisation et Simulation Multi-Echelle, Université Paris-Est, France.*

This paper presents the nonlinear dynamical post-buckling analysis of an uncertain cylindrical shell. The proposed approach is adapted to the dynamical analysis of geometrically nonlinear structures subjected to a stochastic ground-based motion in the presence of both system parameter uncertainties and model uncertainties. The structure is modeled by a large finite element model using 3D elasticity theory. The ground-based motion is represented by a Gaussian centered non-stationary second-order stochastic process. Then, a reducedorder basis is constructed using the POD (Proper Orthogonal Decomposition) analysis of a nonlinear static reference response combined with selected linear eigenmodes of vibrations. The mean reduced-order nonlinear computational model is then explicitly constructed. A positive-definite operator involving the nonlinear stiffness of the structure is defined, allowing the nonparametric probabilistic approach to be used for constructing the uncertain nonlinear reduced-order computational model. The dispersion parameter controlling the level of stiffness uncertainty is a scalar which has been previously identified experimentally in a nonlinear static context. Finally, the instantaneous spectral density power of the dynamical response is analyzed in order to quantify the influence of both geometrical nonlinearities and random uncertainties on the stochastic dynamical response.

Notes

Session 3 Railway Noise and Vibration

15:10

Train-Induced Building Vibration due to High-Speed Train Passage (1026)

Maestre, J., Romero, A. and Galvín, P., *Escuela Técnica Superior de Ingenierí, Universidad de Sevilla, Spain.*

This paper analyses train induced vibration in buildings. Emission, transmission and immission mechanisms are considered rigorously. Track-ground-building interaction have been studied, concluding that maximum vibration levels are achieved in the floors of the structure. Theoretical building induced vibration due to an impulsive load applied at the track have been analysed. The results show an amplification of the structure response around the natural frequencies of the building. Also, an attenuation in the medium-high range frequency is found. Finally, the effects produced by the high speed trains have been investigated. The conclusions show that vibration levels could exceed the limits set by the standards. In these cases, corrective actions are required. Effectiveness of isolated track systems is evaluated.

Session 1 Energy Harvesting

15:30

Feasibility Study on Energy Harvesting using Stochastic Resonance (1009)

Nakano, K., Cartmell, M.P., Hu, H. and Zheng, R., *Institute of Industrial Science, The University of Tokyo, Japan.*

Stochastic resonance is a physical phenomenon where large vibration occurs when a weak sinusoidal force is applied to a bi-stable system. It is expected that a larger vibrational response can be produced than for a typical resonance. Then the authors utilize this system as an energy harvester, which converts energy from vibration. The energy balance between the converted energy and the energy consumed to produce the necessary weak sinusoidal force is analyzed through numerical simulations. It is shown the proposed harvester can convert more energy than a system using a typical linear system resonance.

Session 2 Stochastic Dynamics and Random Vibrations

15:30

Uncertainty Propagation in Complex Modes Based Component Mode Synthesis (1541WIP)

Cortes, L., Ferguson, N.S. and Bhaskar, A., *Institute of Sound and Vibration Research, University of Southampton, UK.*

Monte Carlo analyses are usually performed in order to characterize the uncertainty in system structural dynamic responses. In this context, Component Mode Synthesis may be used to speed up the Monte Carlo computation time. When non-proportional damping is present in the system being modelled, it is necessary to introduce complex modes in the formulation to correctly account for the damping. This work presents a method for uncertainty propagation in complex modes based Component Mode Synthesis models for systems with uncertain damping.

Session 3 **Railway Noise and Vibration**

15:30

Interaction between a Flexible Wheel-Set and Corrugated Rails (814)

Belotserkovskiy, P.M., *Department of Higher Mathematics, Moscow State University of Communications (M I I T), Russia.*

In presence of short pitch rail corrugations, a wheel moving at high speed induces vibrations whose frequency is greater than the frequency of the second symmetric bend mode of a wheel-set. Thus, the wheel-set cannot be regarded as a rigid body. Therefore, it is modeled by means of five lumped masses connected to a weightless flexible uniform axle. The masses correspond to the boxes, the wheels and the wheel-set axle. The primary suspension springs isolate the boxes from the bogie frame. However, the primary suspension dampers influence the box vibrations. This influence is considered.

High frequency vibrations induce short flexural waves in rails. This means that shear de-formations in the rail cross-section are important and so the rails are modeled as the Timo-shenko beams. Comparison between the Timoshenko beam model and the Euler-Bernoulli beam model is made. Due to a certain wheel radius the wheel centre trajectory differs from the rail vertical profile. This mainly results in appearance of higher order harmonics in the wheel centre trajectory and in the wheel-rail contact force.

The periodically varying curvature of the rail vertical profile causes periodic variation in the wheel-rail contact stiffness whose period equals the corrugation length. The above force is determined by means of a Fourier series which represents an infinite row of harmonics. These harmonics influence each other due to the rail periodic support. Both periodic rail support and uniform rail support are compared. Comparison between two track models show that the peri-odicity of the rail support should be taken into account when the interaction between the wheel and the corrugated rail is studied.

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