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THE DESIGN OF LARGE FLEXIBLE SPACE STRUCTURES WITH INTRINSIC VIBRATION FILTERING CAPABILITY - STATUS AND DIRECTIONS

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ABSTRACT

This paper presents an overview of the research program underway at Southampton that is studying the design of large flexible space structures (LFSS) with intrinsic vibration rejection capabilities via exploitation of non-periodic structural geometries. An important objective of this research is to develop a rational design methodology for lightweight LFSS to meet the specifications of future space missions such as precision pointing, positioning, and vibration isolation. This paper outlines the progress made in the research program so far and the work that is currently underway. Directions for future research work in this area are also outlined.

INTRODUCTION

Future space missions such as the Horizon 2000+ program (ESA) and the Origins program (NASA) will involve the launch of a number of space-based observatories which seeks to enhance our understanding of the Universe by studying distant stars and the planetary systems orbiting them. The success of such missions hinges on whether the optical elements of the space telescope can be positioned accurately to within fractions of the viewing wavelength (of the order of 1-10 nanometer). This requirement is also critical for earth observation systems deployed for missions such as topography studies or reconnaissance.

Due to the impact of payload weight on mission cost, there has been considerable interest in employing light-weight large flexible space structures (LFSS) and interferometry techniques to meet the science goals of such missions. Space based interferometers consist of complex optical trains with numerous collecting devices and actively steered optics mounted on a light-weight LFSS subject to static and dynamic loads.

This class of LFSS tend to have highly resonant dynamics; the occurrence of hundreds of modes in the region of 0-200 Hz is not uncommon. During a mission, LFSS may be subjected to sudden changes in their thermal environment due to Earth eclipse or changes in spacecraft orientation. Such sudden changes in the thermal loads may induce dynamic structural responses. Other sources of vibrations include mechanical excitations from space machinery such as reaction wheel assemblies, centrifuges, rolling elements, etc. Due to their high modal density, such disturbances may result in vibration amplitudes in LFSS well into the micrometer range. Ultra-quiet light-weight structures are therefore required to maintain the stability of the precision optical systems.

This problem has motivated the development and validation of a design methodology for LFSS to meet stringent performance specifications such as high pointing accuracy, low weight and low controller energy requirements. These were some of the important goals of the NASA Controls-Structures-Interactions (CSI) technology program; see, for example, Maghami *et al.* (1993, 1994). In the Interferometer Technology Program (ITP), the Jet Propulsion Laboratory is using interferometry methods and vibration suppression techniques to take a quantum leap in space telescope resolution beyond the current Hubble Telescope. One of the key structural dynamic design objectives is to maintain mechanical stability of the optical telescope sub-systems to within 1 nanometer. Such challenging problems require innovative design approaches. Further, there also exists a need for new analysis and experimental methods for characterizing both low and high frequency dynamics of this new class of 'ultra-quiet' precision structures.

The objective of this paper is to present a brief overview of some of the research underway in this area, with particular emphasis on the program underway at Southampton. Most previous research in this field has been based on periodic structural configurations combined with active and passive vibration control techniques. In contrast, research at Southampton has focused on exploiting non-periodic structural geometries for designing LFSS with intrinsic vibration rejection capabilities. Note that vibration suppression is achieved here via energy reflection as opposed to dissipation. Figure 1 presents the overall approach of the methodology currently under development. The aim is to first isolate the vibration source at the point of attachment. The residual vibration levels are suppressed using an intrinsic vibration filtering structural geometry synergistically combined with

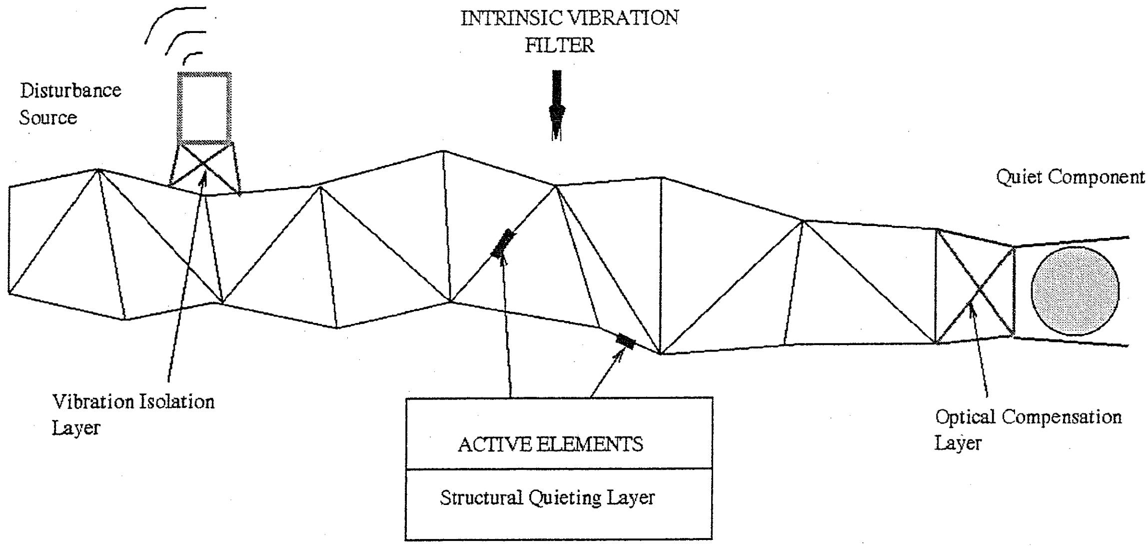

Figure 1: Integration of Intrinsic Vibration Filtering Non-periodic Space Structure with Active Control and Optics: A Modified Layered Control Approach (Neat *et al.*, 1997)

active control techniques to isolate those regions of the system where vibrations cannot be tolerated. Finally, the instrument is also isolated at the point of attachment.

The motivations for this approach are - (a) non-periodic structures tend to be less sensitive to design or manufacturing imperfections as compared to their periodic counterparts and (b) the synergy of the intrinsic vibration filtering capability with active control can be exploited to design high-performance LFSS with low controller energy requirements. The long term objective is to develop a rational design methodology for lightweight LFSS to meet the specifications of future space missions such as precision pointing, positioning, and vibration isolation. Further, it is intended to demonstrate the feasibility of advanced vibration suppression technology for future space-based interferometers on ground based test-beds. The specific application areas of interest include multi-sensor space infrared interferometers and synthetic aperture radars.

The design philosophy used in this research was proposed earlier in Keane (1994, 1995) for achieving passive vibration suppression of LFSS. The design methodology involves the use of stochastic design space search techniques to determine the exact pattern and magnitude of geometric disorder that will enable a LFSS to intrinsically filter/reflect vibrations across a broadband frequency bandwidth. Experimental validation of the design approach was reported in Keane and Bright (1996) for a two-dimensional space structure.

More recently, this research program has focused on four directions - (1) development of efficient approximation concepts (Nair *et al.*, 1998) and approximation model management frameworks (Nair, 2000) for improving the computational efficiency of the design process, (2) integration of robust active control strategies in the design procedure (Anthony, 2000), (3) development of efficient stochastic structural dynamic analysis methodologies (Nair and Keane, 2000a, 2000b, 2000c) for incorporating robustness considerations in the design formulation, and (4) an experimental program of investigation into the dynamics and control of non-periodic LFSS (Torbati *et al.*, 2000).

This paper presents a brief overview of the progress of the research program and the challenges that are yet to be overcome. The motivation for a multidisciplinary design methodology that takes into account concerns from the disciplines of structural statics, dynamics, thermal analysis, active control, and optics is presented. In the light of this, future research directions for optimal synthesis of non-periodic LFSS with enhanced vibration rejection capability are also discussed.

APPROXIMATION TECHNIQUES AND DESIGN OPTIMIZATION

In the present approach to LFSS design, the structural geometry parameters are considered as design variables. As noted earlier in Keane (1994), the inclusion of geometry design variables leads to a large-scale nonconvex design space and hence, evolutionary optimization techniques such as genetic algorithms (GAs) are required to ensure convergence to good designs. However, evolutionary optimization techniques tend to be profligate in terms of the number of function evaluations required to converge to an optimal solution. Hence, such a design methodology is computationally expensive, particularly when large-scale finite element models are used.

In Keane (1995), receptance analysis methods were coupled with GAs in the design procedure. More recent studies (Nair, 2000) used finite element (FE) methods for structural dynamic analysis. In order to ensure applicability to problems where high-fidelity FE models are required to accurately predict the dynamic characteristics, a computational optimization framework has been developed for arriving at good designs on a limited computational budget. The optimization framework involves the use of evolutionary optimization algorithms coupled with approximate dynamic reanalysis techniques to enhance the probability of converging to good designs on a limited computational budget. The following sections summarize recent research on approximation based dynamic reanalysis techniques and model management frameworks for design.

Approximate Dynamic Reanalysis

The equations of motion in the frequency domain of a linear structural system can be written in the form

$$[\mathbf{D}(\omega)]\ \{\mathbf{X}(\omega)\} = \{\mathbf{F}\}$$

where $\mathbf{D}(\omega) = ([\mathbf{K}] - \omega^2 [\mathbf{M}] + i [\mathbf{C}])$ is the dynamic stiffness matrix of the structure; $\{\mathbf{F}\}$ is the amplitude vector of the external harmonic forces; $\{\mathbf{X}(\omega)\}$ is the displacement response at the excitation frequency ω.

Consider the case when the dynamic stiffness matrix is perturbed by $\Delta\mathbf{D}$ during the optimization iterations. The objective of approximate reanalysis is to compute the perturbed response without recourse to solving the perturbed governing equations in their exact form. This may be carried out by approximating the perturbed eigenvalues and eigenvectors, which are then used to compute the frequency response of the modified structure. An alternative approach would be to directly approximate the perturbed frequency response.

A number of approximate dynamic reanalysis methods based on local series expansion can be found in the literature, see, for example, Adelman and Haftka (1992). However, such techniques are not useful when evolutionary optimization techniques are employed in the design process. This is primarily due to the fact that evolutionary algorithms tend to introduce radical design changes during the optimization iterations/generations, which lead to significant breakdown in the accuracy of local approximation techniques. In fact, the approximation errors in the dynamic response may become so high so as to be useless for the purposes of optimization.

This problem has motivated the development of a new class of approximation concepts which are valid for large changes in the design variables. Nair *et al.* (1998) presented the modal reduced basis approximation (MRBA) method for approximating the eigenvalues and eigenvectors of modified algebraic eigenvalue problems. This involved the use of the terms of the first-order Taylor series as basis vectors for Ritz analysis of the perturbed eigenvalue problem. It was shown that accurate approximations can be computed for moderate changes in the stiffness and mass matrices, particularly for low-rank perturbations.

Direct frequency response approximation (DFRA) methods for approximating the frequency response of modified structures were presented by Nair (2000). This involves the use of the terms of the Neumann series for the perturbed displacement response as basis vectors. Numerical studies were presented to demonstrate that DFRA methods give more accurate approximations as compared to the MRBA method. However, much remains to be done in this area, particularly for efficient dynamic reanalysis of structures with repeated eigenvalues.

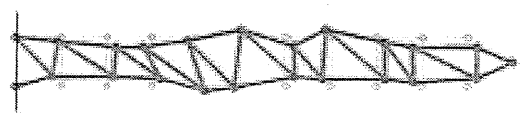

Figure 2: Geometry of Optimal Design

Model Management Frameworks in Optimization

The central idea behind the use of approximation methods in optimization is to reduce the computational cost involved in sampling large regions of the design parameter space. Model management frameworks (MMFs) are entrusted with the task of managing the interplay between the exact analysis and the approximation model as the optimization proceeds. The key idea here is to make use of computationally cheap approximate predictions in lieu of the exact analysis model during the optimization iterations. This is expected to enhance the probability of arriving at good designs on a limited computational budget.

A detailed description of the MMF used in the present research can be found in Nair (2000) and Nair and Keane (2000d). Some illustrative results are presented here for the optimal design of a two-dimensional beam network to achieve passive vibration suppression. The geometry of the optimal design is compared with the baseline periodic configuration in Figure 2. For this study the structure was subjected to transverse excitation near the cantilevered end and the aim was to suppress the total displacement response at the tip in the region of 100-200 Hz. The total displacement response at the tip for the optimized design is compared with the baseline response in Figure 3. It can be seen that significant vibration isolation of the order of 50dB is achieved over this frequency bandwidth. Figure 4 shows the convergence history of the objective function as a function of wall time for a conventional GA and the MMF. It can be seen that the MMF allows for the possibility of converging to better designs within a limited computational budget. Further developments, including parallelization of the MMF are the focus of ongoing research.

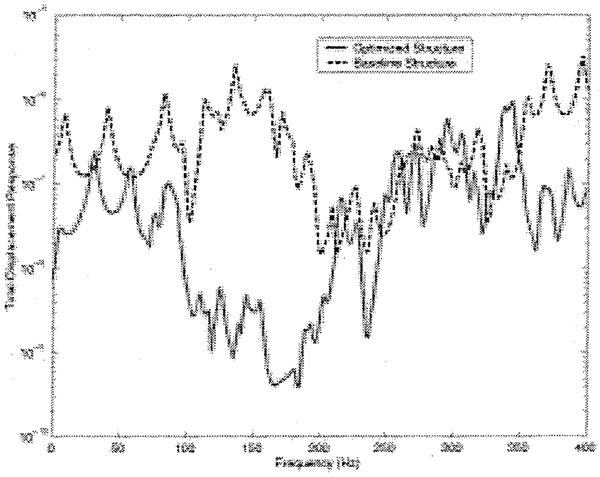

Figure 3: Comparison of Total Displacement Response of the Baseline and the Optimized Structure.

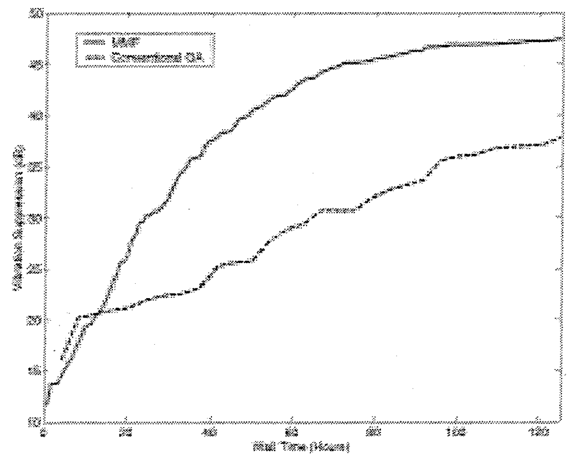

Figure 4: Comparison of Convergence History of the MMF with a Conventional GA

MULTIDISCIPLINARY DESIGN OF LFSS

Note that by virtue of the physics, the performance analysis of LFSS requires a multidisciplinary approach involving structural statics, dynamics, control, thermal analysis and optics. Hence a multidisciplinary approach to design hardly needs any advocacy for its existence. The Jet Propulsion Laboratory developed the Integrated Modeling of Optical Systems (IMOS) software for integrated controls-structures-optics modeling of interferometers (Milman and Levine, 1997). The motivation for this activity arose from the need for an integrated modeling environment necessary for end-to-end disturbance analysis of space-borne interferometers.

In practice, it is desirable to integrate active vibration control techniques with any non-periodic geometries in order to enhance the passive vibration filtering characteristics of a system. This enables the possibility of meeting the stringent vibration suppression requirements of LFSS. A conventional practice common in LFSS design was to design the structure first to meet static strength objectives, and then to design a controller to damp the excessive vibrations. However, it was realized in the 80s that such a sequential strategy leads to sub-optimal designs with attendant weight penalties. Integrated controls-structures design methodologies were proposed to achieve a rational tradeoff between the performance and structural weight. Such a methodology was theoretically as well as experimentally shown to exploit the synergy between structural dynamics and control; see, for example, Maghami *et al.* (1993, 1994).

Anthony (2000) conducted detailed numerical studies on integrating feed-forward control schemes with non-periodic structural geometries. The effect of optimal actuator placement on the robustness and performance of the integrated vibration suppression scheme was also examined in detail. It was shown that the vibration suppression performance of non-periodic structures tends to be robust to parametric uncertainties. Further, the integration of active control with non-periodic geometries was shown to significantly improve the overall vibration suppression performance.

Future research work on non-periodic structural design will need to focus on a multidisciplinary approach in order to accommodate constraints arising from static strength and optics in the design. Such an approach would allow a rational tradeoff between the various disciplinary considerations.

STOCHASTIC STRUCTURAL DYNAMICS

Inevitably, due to manufacturing defects, faults occurring in service, or unexpected loading conditions arising from environmental changes the dynamics of LFSS can significantly deviate from theoretical predictions. This is particularly true for periodic LFSS with high modal density and many weakly coupled substructures (Benediksen, 1987) which are highly susceptible to vibration localization. This may lead to excessive vibration levels, which in turn could potentially trigger failure due to high cycle fatigue. Hence, it is important from a practical viewpoint to accommodate parametric and environmental uncertainty in the design of LFSS.

Robust design methodology is an enabling technology to meet these requirements. This methodology assumes the existence of a mathematical model that is capable of predicting the response of a LFSS in the presence of uncertainty. Probabilistic or Interval descriptions of uncertainty in the excitation and structural parameters are assumed to be available. A challenging task in stochastic structural dynamics involves accurately propagating the uncertainty in the physical parameters to that of the dynamic response. The challenge arises from the fact that the dynamic response is a highly nonlinear function of the system parameters.

Commonly used approaches in the literature (Manohar and Ibrahim, 1999) involve the use of perturbation schemes to compute the first and second-order statistical moments of the response. However, the accuracy of these methods degrades rapidly when the coefficient of variation of the uncertain parameters are large. Anthony (2000) applied experimental design techniques for ensuring that the optimization process converges to designs that are robust to parametric uncertainties. However, such techniques tend to be computationally intensive when optimization is carried out using high fidelity computational models. Even so, such studies clearly indicate the potential benefits of incorporating robustness considerations in the optimization formulation.

Recent research at Southampton has focused on the development of more accurate and computationally efficient numerical schemes, referred to as Stochastic Reduced Basis Methods (SRBMs). Nair and Keane (2000c) developed a stochastic reduced basis method for approximate solution of algebraic random eigenvalue problems. Significant improvements over the first-order perturbation scheme were demonstrated for a network of stochastic Euler-Bernoulli beams with random Youngs modulus and mass density. It was shown that highly accurate results can be obtained for the statistics of the eigenvalues and frequency response, particularly for structures with low to moderate modal density. The choice of basis vectors for ensuring accurate results for structures with high modal density remains an area of open research.

For directly computing the frequency response statistics of stochastic structural systems, an approach based on using the terms of the Neumann expansion scheme as stochastic basis vectors was proposed by Nair and Keane (2000a, 2000b). Further theoretical analysis of SRBMs, including *a posteriori* error estimation is the focus of a forthcoming paper (Nair and Keane, 2001). This theoretical analysis shows that there are intimate connections between preconditioned iterative solvers for linear systems and SRBMs. However, much theoretical and numerical work remains to be done before SRBMs can be routinely applied to analysis of complex stochastic systems.

Experimental studies conducted during the NASA CSI technology program showed that the performance and stability of controlled LFSS are highly dependent upon the knowledge of its structural characteristics, particularly for structures with very low damping. Further there is a dearth of test data for microdyamics of complex structures, which leads to difficulties in validating mathematical models of such phenomena. Another major challenge in experimental studies on LFSS arises from the fact that the structural joints are preloaded in ground tests due to gravity and thus ground based tests may indicate linear response. In contrast, joint gaps may arise in micro-gravity environments, which lead to a chaotic response in space, i.e., the dynamic response is random and bounded when subjected to a deterministic load. Developing nonlinear stochastic models of such phenomena remains a challenging area for future research.

MANUFACTURE AND ASSEMBLY

The highly non-periodic structures that lie at the center of much of the work described here are clearly not simple to manufacture or assemble. Considerable effort has recently been focused on producing a construction scheme that overcomes these difficulties as far as possible, Torbati *et al.* (2000). In this scheme small solid spheres are used as the joining elements between the (circular) beams that the LFSS is constructed from. These spheres may be manufactured using numerically controlled machines with holes reamed into them at precise angles and with precise depths. Then when the beam elements of known lengths are inserted and bonded into them the geometry of the overall boom is assured. For small to medium size structures this approach allows each boom to be pre-assembled before launch and then the overall LFSS to be constructed in space from the resulting larger units. Clearly, for very large structures all of the assembly stages would need to be carried out in space. In these circumstances the self-aligning nature of the design being adopted is vital to the ultimate performance of the system. Currently, tests are underway on 4.5m long structures constructed from aluminium alloy – the final designs will be based on CFRP beams using titanium joints.

CONCLUDING REMARKS

This brief overview has highlighted some of the research currently underway at Southampton for designing space structures with intrinsic vibration filtering capability. It has shown that the use of approximation models in design can significantly reduce the computational burden of optimization using high fidelity dynamic analysis models. The motivation for a multidisciplinary approach, which takes into account the concerns of static strength, vibration isolation and optics is also discussed. An overview of the research underway on stochastic structural dynamics and its ramifications for the design process has also been presented. For a detailed discussion of ongoing experimental investigations into the dynamics and control of non-periodic structural systems at Southampton, the reader is referred to Torbati *et al.* (2000).

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