Vibration Attenuation of the NASA Langley Evolutionary Structure Experiment Using H_∞ and Structured Singular Value (μ) Robust Multivariable Control Techniques

Final Report

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Abstract

This final report summarizes the research results under NASA Contract NAG-1-1254 from May, 1991 - April, 1995. The main contribution of this research are in the areas of

- Control of flexible structures.
- Model validation.
- Optimal control analysis and synthesis techniques.
- Use of shape memory alloys for structural damping.

1 Control of Flexible Structures

Stringent requirements on the pointing and shape accuracy of future space missions necessitate advances in the control of large structures. These structures will be extremely flexible, with little natural damping and structural modes densely packed throughout the frequency domain. Due to their size and complexity, ground testing of these structures in the earth's environment will lead to system models that are inaccurate for operation in a zero-g environment. Even with on-orbit identification of the structure, discrepancies between their mathematical models and the "real" structure will still exist. Therefore, control design methods must be developed to account for model inaccuracies or *uncertainties.*

1.1 Unmodeled Dynamics and Uncertain Natural Frequencies

Mathematical models of a flexible structure are often derived using finite element methods and refined based on experimental data. A characteristic of these models is that the low frequency modes of the structure are more accurately described than the higher modes. The performance requirements on these structures require accurate accounting for errors in the control design models, specifically unmodeled dynamics and variations or errors in the structural natural frequencies.

Under this contract a controller synthesis method for flexible structures was improved to achieve desired performance objectives and to be robust to uncertain modes and unmodeled higher frequency modes. This approach directly incorporates knowledge of modeling errors in the natural frequencies in the problem formulation. Frequency weighting functions are used to account for unmodeled dynamics in the structured singular value (μ) framework. Natural frequency uncertainty is first posed as parametric uncertainty in a state-space model of the structure. This is rewritten as a linear fractional transformation which fits directly into the μ framework for control analysis and design.

H_∞ and μcontrol design techniques were used to synthesize vibration attenuation controllers for the Phase Zero Evolutionary Structure. The Evolutionary Structure, constructed to emulate a future space platform, was located at NASA Langley Research Center. The main section of the truss was approximately 50 feet long to which were attached two vertical appendages. Mounted on the short appendage was a 16 ft. diameter reflector with a circular mirror attached to its center. A laser beam whose source was attached to the end of a vertical appendage was pointed at the mirror. The laser beam reflection from the mirror was detected by a spatially fixed optical detector array (target plant) mounted approximately 60 ft. above the structure.

A finite element model of this structure was developed by NASA Langley researchers. The model contained 86 modes corresponding to all of the CEM structural modes under 50 Hz. A 25 mode reduced order model of the structure, based on the 86 mode finite element model, was obtained through a controllability and observability analysis. These 25 modes correspond to the set of modes below 20 Hz that significantly contribute to the measured accelerations and LOS displacements. The first six lowest frequency modes are the pseudo rigid body modes (pendulum modes) which range from 0.14 Hz to 0.87 Hz, the seventh and eight modes are the first horizontal and vertical plane bending modes respectively.

Eight air actuators were used for control and the eight nearly collocated accelerometers were the measurements used for feedback. Variation between the experimentally derived transfer functions and the design model were accounted for in the control design process via unstructured uncertainty models. An additive uncertainty model was used to account for neglected structural modes in the design model. An actuator input uncertainty model was used to incorporate any errors between the experimental data and the $50th$ state-space model which occur within the control bandwidth.

The performance objective was to attenuate the sensed vibration at accelerometer locations 1 through 8. These sensors are nearly collocated with air actuators 1 through 8. The disturbances used to excited the structure entered at air thruster 1, 2, 6, and 7. The performance criteria is defined as minimizing the $||\cdot||_\infty$ norm of the transfer function. number of states in the control design.

The control problem formulation interconnection structure is shown in Figure 1. The goal of the control design is to minimize the low frequency vibration of the accelerometers due to input disturbances entering at air actuators 1, 2, 6 and 7. The controllers are tested by inputting a disturbance signal into the air thrusters for 9 seconds, terminating the disturbance signal and allowing the structure to vibrate in the open-loop configuration for one second, on implementing the controller which uses the air thrusters to attenuate the induced vibrations.

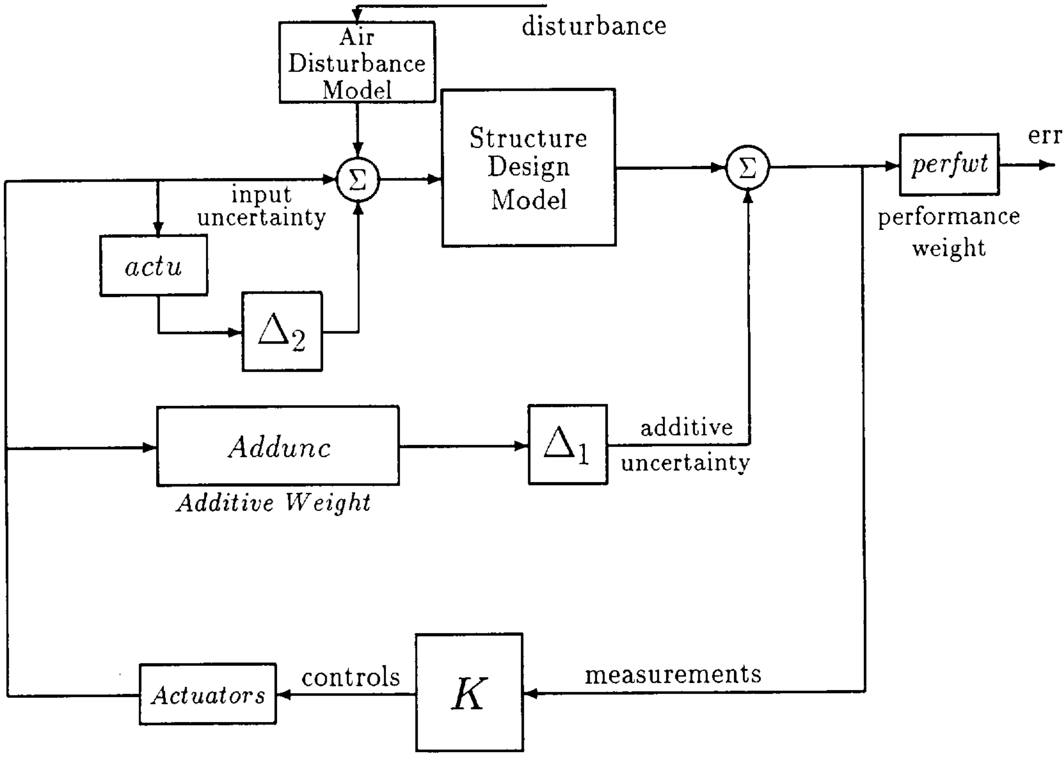

Figure 1: CEM Control Problem Formulation

Design	Model	Sensors	Actuators	Input Uncertainty	Additive Uncertainty	Performance Weight	Controller Order
1	`mod25r`	$1,2,7,8$	$1,2,7,8$	10%	addwt 1,2,7,8	10:1	28
2	`mod25r`	$1 \rightarrow 8$	$1 \rightarrow 8$	10%	addwt $1 \rightarrow 8$	10:1	36
3	`mod25r`	$1,2,7,8$	$1,2,7,8$	2%	addwt 1,2,7,8	10:1	30
4	`mod25r`	$1 \rightarrow 8$	$1 \rightarrow 8$	1%	addwt $1 \rightarrow 8$	10:1	40
6	`mod25r2`	$1 \rightarrow 8$	$1 \rightarrow 8$	1%	addwt $1 \rightarrow 8$	10:1, filters	50
7	`mod25r2`	$1 \rightarrow 8$	$1 \rightarrow 8$	10%	addwt $1 \rightarrow 8$	8:1, filters	50
8	`mod25r2`	$1 \rightarrow 8$	$1 \rightarrow 8$	$\frac{100(s+20)}{s+2000}$	addwt $1 \rightarrow 8$	8:1, filters	38
9	`mod25z`	$1 \rightarrow 8$	$1 \rightarrow 8$	10%	addwt $1 \rightarrow 8$	perfwt9	44

Table 1: Control Problem Formulation Uncertainty and Performance Weights

Table 1 contains the actuators, sensors, uncertainty weights and performance weights used in the control problem formulations to synthesize the controllers. μ-synthesis techniques based on $D - K$ iteration were used to design the controllers to achieve robust performance for the given problem formulation. The eight controller designed all had on the order of 80 states prior to being reduced. The large number of states is due to the order of the control design model, additive uncertainty weights and D-scaling used in the $D-K$ iteration process. The reduced order controllers for each design, the controller order reduction is done using balanced realization techniques, are listed in Table 1.

All eight of the controllers designed using the μ-synthesis techniques resulted in a stable closed-loop system and performed very well when implemented on the experimental structure. Control design 9 achieved the best performance of any controller previously tested. These results indicate that the μ-framework is ideally suited for the analysis and synthesis of controllers for flexible structures with numerous, lightly damped modes and multiple actuators and sensors.

Controller 1 was designed using only four of the eight air actuators available. It was implemented on the actual structure and performed as well as the previous best controller. Controller 2, used the same uncertainty and performance weights as control design 1, employed all eight actuators and sensors for control. The improvement in performance was limited, although only one set of disturbance excitations were used in the experiments. The most notable improvement with controller 2 was the attenuation of vibration at accelerometers 3 and 6. This is to be expected since accelerometers 3 and 6 are almost collocated with air actuators 3 and 6, which were used in control design 2 but not in control design 1.

The role the input multiplicative uncertainty level plays is evident when comparing the performance of controller 1 with that of controller 3. Controller 3 is designed the same as controller 1 except that the input multiplicative weight is selected to be 2% uncertainty compared with 10% uncertainty. The performance of controller 3 at all of the accelerometer locations is slightly improved. The increase in performance comes at the expense of increased actuator force, most notably from air thruster 1 and 8. Results from the implementation of controllers 1 and 3 indicate that the uncertainty models used in the problem formulations accurately represent the physical structure. The theoretical results for each design parallel the experimental data exactly.

Controller 4 uses the same problem formulation as control design 2 with the input multiplicative uncertainty weight chosen to be 1% as opposed to 10%. Similar results are obtained to controller 1 and 3. Controller 4 has increased the attenuate of low frequency vibration at the accelerometer locations at the expense of increased actuator control forces. It is interesting to note the high frequency content in the accelerometer 3 signal. The increased controller bandwidth in design 4 causes several high frequency modes to be excited.

The problem formulation used to synthesize controller 6 uses a higher order design model, different additive uncertainty models reduced in magnitude from designs 1 through 4 and first order filters on the performance weights. The performance of controller 6 is similar to controller 1, though controller 6 has significantly more high frequency content in the accelerometer signals. The additive uncertainty models used in design 6, allowed the controller to have a higher bandwidth leading to increased high frequency accelerometer signals. The higher bandwidth controller lead to poor robustness characteristics for controller 6. Similar problems were noted in control design 7. The input multiplicative uncertainty problem formulation was modified to 10% to account for the change in the additive uncertainty models. These results indicate that accounting for unmodeled dynamics via input multiplicative is not a good approach to the control design problem for lightly damped flexible structures. Based on intuition, one would expect that a very large multiplicative uncertainty weight would be required on the actuator in the neighborhood of an unmodeded flexible mode of the structure. A level of 10% multiplicative uncertainty would be inadequate to assure stability of the unmodeled flexible modes. Controller 7 appears to have destabilized a structural mode of the system around $7Hz$.

Control design 9 represents the controller with the highest level of performance. A high order model of the structure is used in the design process, with the goal to attenuate the structural mode at $7Hz$. The performance weight $perfwt$ is modified to reflect this goal and the additive uncertainty weight is modified accordingly. The controller attenuates the low frequency modes of the structure quickly with little high frequency content to the accelerometer signals. Unfortunately, due to the limited accuracy of the control design model above $4Hz$, the modeling errors between the design model and experimentally derived transfer function data, controller 9 is unable to attenuate the structural mode at $7Hz$. In spite of this shortcoming, controller 9 achieved the high level of performance of any controller implemented on the experimental Phase Zero structure.

achievable performance given the same problem formulation.

1.1.1 Summary

H_∞ and structured singular value (μ) based control design methods were used to analyze and synthesize control laws for the NASA Langley Controls-Structures Interaction (CSI) "Evolutionary Model." This structure had numerous lightly damped, coupled flexible modes, collocated and noncollocated sensors and actuators and stringent performance specifications which lead to a difficult control problem. The control design problem was further complicated by the model errors noted between the model used for control design and experimentally derived transfer function data. These model inaccuracies or *uncertainties* are accounted for in the control design process via unstructured uncertainty models in addition to the performance specifications on the attenuation of structural vibration due to external disturbances. Eight controllers were synthesized for a variety of input multiplicative uncertainty, additive uncertainty and performance weights.

The controllers exhibited excellent correlation between the theoretically predicted and experimentally achieved results especially associated with the low frequency modes of the structure. This was expected due to the error between the design model and experimental at frequencies above $4Hz$. The μ-synthesis techniques resulted in controllers which traded off between robustness and performance given the specific problem formulation and achieved outstanding performance when implemented on the structure. It was seen that unstructured uncertainty models of the modeling error were more than adequate in the control problem formulation. It should be noted that the methods developed during this results on including unmodeled dynamics and natural frequency errors into the μ framework are now standard and are used often by control engineers for active vibration suppression of flexible structures.

1.2 Performance vs. Robustness Tradeoff

Robust control design methods optimize control laws based on knowledge of how model error enters into the problem description. Since controller optimization is based on mathematical system descriptions, accurate accounting and characterization of variations between "real" flexible structures and their mathematical models is essential.

During this contract a detailed study of the role modeling uncertainty plays in the design of controllers for flexible structures was performed. It was shown that improper selection of nominal and uncertainty models may lead to unstable or poor performing controllers on the actual system. In contrast, if the uncertainty descriptions are overly conservative, performance of the closed-loop system may be severely limited. Therefore, tight uncertainty bounds are required to synthesize robust controllers which achieve high performance when implemented on the actual system. More importantly, it was shown that the location and/or type of the uncertainty in the control problem was as important as its magnitude.

Controllers were designed for the Phase Zero Evolutionary Structure using a nominal model with varying levels and location of uncertainty. Experimental results indicated that the control designs were much more sensitive to actuator modeling errors than sensor measurement errors. Improved modeling of the actuators lead to increased closed-loop performance. It was also shown that similar performance, both theoretically and experimentally, was obtained for a surprisingly wide range of uncertain levels in the design model. This suggests that while it is important to have reasonable uncertainty models, it may not always be necessary to pin down precise magnitude levels of the uncertainty description. This work has lead me to focus on developing integrated system modeling, identification and control methods for flexible structures.

1.3 Contributions to Control of Flexible Structures

The contributions of this research to the control of flexible structures include the development of a systematic approach to the design of multivariable controllers for flexible structures and quantification of the direct tradeoff between performance and robustness in multivariable control designs. Engineers at the Jet Propulsion Laboratory, NASA, TRW, Honeywell and McDonnell Douglas have used these results with great success in the analysis and design of controllers for flexible structures. In addition, companies are applying these ideas to commercial products. For example, the Philips Corporation in The Netherlands is using these techniques to design controllers for compact disc players. Caterpillar is using these approaches to synthesize slope-finish controllers for back hoe excavators. Japanese companies are using μ methods for end point control of lightweight robotic arms. In addition, these same techniques are being used to design active suspension systems for automobiles in the US, Japan, England, The Netherlands and Germany.

2 Model Invalidation

The successful application of robust control design tools for uncertain systems is contingent upon selection of accurate nominal models and non-conservative uncertainty and noise models. To be able to predict loss of stability under feedback, models which include norm bounded unmodeled dynamics in addition to additive noise are needed. However, it is well known in the control literature that the classical system identification techniques do not lend themselves to identification of models which are suited for robust control design. This is due to classical identification techniques attributing all uncertainty to additive noise at the output.

Under this contract a method for model *invalidation* was developed which builds on classical system identification and robust control methods. This method exploits the properties of the structured singular value to determine if a set of data is consistent with a proposed nominal model given *a priori* bounds on the system perturbations and the noise entering the system. The model is *invalid* if the model set is inconsistent with all experimental data taken. A plant model set, which is not invalidated, is used to redesign the closed-loop control to improve the robustness and performance properties of the control design.

These model invalidation results were successfully applied model invalidation to increase the closed-loop performance of a two-mass, three-spring experiment at the University of Minnesota. The performance objective in the experiment was to minimize the vibration of the masses in the presence of exogenous disturbances. One controller was designed based on a nominal plant model and estimates of the modeling error in the system. A second controller was designed using the model invalidation technique to refine the models of uncertainty. Both controllers were implemented on the physical system. The controller designed using information from model invalidation tests achieved significantly better closed-loop performance than the controller designed based on estimates of the modeling error.

We are in the process of working with NASA Langley engineers on developing generic tools for robust identification for control that bridge the gap between structural dynamicists and control engineers. A common framework will be developed for system identification, model validation and robust control. A graphical user interface (GUI), based on this framework, would be concurrently developed and would make use of existing software for identification, validation and control. The GUI would provide an interface, for example, to system identification procedures to easily fit various types of models in both the time and frequency domain. Models developed using this software would naturally interact with software for the robust model validation and control synthesis software. The features of the GUI for this type of project would mainly focus on pull-down menus and dialog boxes. The pull-down menu is a common feature of many software packages and most operating systems to list available options. Dialog boxes allow information to be given along side user input mechanisms. Similarly we would have GUI options for model validation and robust control. the key idea is that there is no "ideal" method for doing identification, validation or control that works well on every system. Our idea is to provide the user with a variety of different methods which can all be easily tried. The control engineer or end-user can then try out different ideas and see how successful they are. This approach also eliminates too heavy a reliance on one specific method that may not perform well on spacecraft.

3 Optimal Control Analysis and Synthesis Techniques

The objective of closed-loop control is to feed back sensor measurements to controller to generate actuator signals that change the closed-loop dynamics of the system. This type of control is based on "output" feedback. A specialized control problem called "full information control" receives perfect measurements of the plant model states and input disturbances affecting the system. Optimal solutions to full information control problems are important guides to achieve robustness and performance objectives for output feedback controllers. In addition to its theoretical interest, these controllers provide a lower bound for an output feedback controller of the same order.

We have extended the theory by developing algorithms to solve the optimally constant scaling, $\mathcal{H}_\infty$ full information control design in the presence of complex and real time-varying parametric uncertainty. Complex uncertainty often represents unmodeled dynamics and real uncertainty represents errors in system parameters or coefficients of a plant model. The scale $\mathcal{H}_\infty$ control problem is directly related to μ synthesis with constant scalings. We have shown that constant scaling $\mathcal{H}_\infty$ full information, controller synthesis with complex and real parametric uncertainty can be formulated as a single linear matrix inequality. Since linear matrix inequalities are convex, convex optimization methods can be used to solve the problem, resulting in a globally optimal controller.

This technique has been to the design a missile autopilot and a vibration suppression controller for his experimental flexible structure at the University of Minnesota. Work is currently underway to extend these results to the case of dynamic scalings. Results on this topic will have an impact on achievable levels of robust performance for output feedback controllers.

4 Use of Shape Memory Alloys for Passive/Active Damping

Studies to date on space structure have shown that passive damping and feedback control are required to achieve desired performance for the next generation of deep space antennas. One potential method of adding passive damping to a structure is the use of a coupling or static member made of a shape memory alloy (SMA). For SMAs, the time delay of strain with respect to stress results in the dissipation of energy. This is caused in part by the micromechanical motion of structural imperfections in the material. However, the damping mechanism, unique to SMAs, is the mechanism by which the amount of product phase is changed by the application of stress, i.e. the stress induced martensitic transformation or pseudoelasticity.

To determine the damping characteristics of SMAs, we fabricated an experiment consisting of a cantilever beam with a tip mass, constrained at the ends by SMA wires. The base of the cantilever is excited sinusoidally. The SMA wires are pre-strained to lie within the pseudoelastic hysteresis loop. This forces the SMA wires around inner hysteresis loops as the beam vibrates. Three models of the SMA pseudoelastic hysteresis were considered and compared with experimental results. Experimentally results indicate that SMA increased by a factor of 6 the equivalent viscous damping of the first natural frequency of the beam.

It was noted that the theoretical models of the SMA pseudoelastic hysteresis loop provided a poor estimate of the increase in damping and shift in the structural natural frequencies. Therefore, we have developed new theoretical models of the behavior within the pseudoelastic hysteresis loop of SMA. Based on experimental results, the behavior of the inner hysteresis loop plays an important role in the damping level and shift in natural frequencies of the structure. These results suggest the possibility of the existence of two trigger lines, one for loading and one for unloading, within the hysteresis loop, and a relationship between the trigger line angle and a maximum dissipation principle.

We are currently performing dynamics tests of the SMA to better characterize their dynamics behavior at large strain rates. These results will be used to refine the inner hysteresis loop models that have been developed. Based on experimental results to date, we have designed a passive SMA structural member for an experimental flexible structure in the Aerospace Engineering Dynamics and Controls Laboratory at the University of Minnesota. The SMA member was attached to the structure and its vibrational response compared with the theoretical response of the structure with the model of the SMA material hysteresis and the unaugmented structure. A factor of 5 increase in damping values of low frequency modes, below 6 Hz, was observed with the addition of the SMA member which correlated exactly with the predicted theoretical results. Based on this work, simplified dynamic models of the SMA wires were developed for control design and active controllers for vibration suppression were designed. The additional passive damping due to the SMA member led to an increase in the vibration attenuation of the closed-loop system by a factor of two. We are currently investigating the use of SMAs as both passive and active control members. The design of active SMA actuators is an exciting area of research we are currently involved in.

5 Publications Support by this Contract

The following papers have resulted from this research: NAG 1-1254

1. G.J. Balas, R. Lind and A.K. Packard, "‘Optimally scaled H_∞ full information control with real uncertainty: Theory and application," *AIAA Journal of Guidance, Dynamics and Control*, to appear.
2. P. Thomson, G.J. Balas, and P.H. Leo, "The effects of shape memory alloy pseudoelastic hysteresis models on structural systems," *Journal of Intelligent Material Systems and Structures*, to appear.
3. P. Thomson, G.J. Balas, and P.H. Leo, "The use of shape memory alloys for passive structural damping," *Journal of Smart Materials and Structures*, vol. 4, pp. 36-42, 1995.
4. A. Kumar and G.J. Balas, "A scaling approach to model validation in the μ-framework," *1995 American Control Conference*, pp. 693-697, June 1995.
5. R. Lind, G.J. Balas, and A.K. Packard, "Optimal scaled H_∞ FI synthesis with real parametric uncertainty," *1995 American Control Conference*, pp. 3463-3467, June 1995 (resulted in Journal Publication 1).
6. A. Kumar and G.J. Balas, "An approach to model validation in the μ-framework," *1994 American Control Conference*, Baltimore, MD, pp. 3021-3026, June, 1994.
7. R. Lind, G.J. Balas, and A. Packard, "Evaluating $D-K$ iteration for control design," *1994 American Control Conference*, Baltimore, MD, pp. 2792-2797, June, 1994.
8. P. Thomson, G.J. Balas, and P.H. Leo, "Pseudoelastic hysteresis of shape memory wires for passive structural damping: Theory and experiments," *Passive Damping at Smart Structures and Materials '94 Conference*, Int. Society for Optical Engineering, pp. 188-199, Feb. 1994.
9. K. Lim and G.J. Balas, "Line-of-sight control of the CSI evolutionary model: μ control," *American Control Conference,* Chicago, pp. 1996-2000, June, 1992.