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14. ABSTRACT
The primary objective of this research is to develop a multidisciplinary optimization methodology for the integrated design of a smart actuator consisting of: 1) an active material that functions as the main transducer, 2) a compliant mechanism that serves as a mechanical amplifier, and 3) drive electronics to provide the electrical power. These devices are characterized by the diverse nature of their components, although they are obviously highly coupled. In spite of the coupling, the design of the smart actuator is usually results in a suboptimal actuator. Therefore, the primary goal of the present research is to develop models for different components, study their interaction and design them in an integrated fashion. Energy is used as a common commodity to establish a base to study the interaction between the subsystems.
The development of an integrated design optimization methodology for smart actuators is divided into several subtasks. These subtasks are as follows:
1. The integrated design of the active material with the compliant mechanism.
   1.a Dynamic topology optimization of the compliant mechanism driven by a piezoelectric actuator.

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Optimization of Electronically Integrated Smart Actuators

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Introduction

The primary objective of this research is to develop a multidisciplinary optimization methodology for the integrated design of a smart actuator consisting of: 1) an active material that functions as the main transducer, 2) a compliant mechanism that servers as a mechanical amplifier, and 3) drive electronics to provide the electrical power. These devices are characterized by the diverse nature of their components, although they are obviously highly coupled. In spite of the coupling, the design of the smart actuator is usually carried out on the components separately. The decoupled design of the components usually results in a suboptimal actuator. Therefore, the primary goal of the present research is to develop models for different components, study their interaction and design them in an integrated fashion. Energy is used as a common commodity to establish a base to study the interaction between the subsystems.

Design optimization has emerged as an integration platform for the design of smart structures. Mathematical optimization techniques offer an organized and methodical way of formulating and solving the design problem. These automated design techniques allow designers to simultaneously consider many more design parameters and constraints than would be possible using traditional design procedures. Because they automatically consider large numbers of design alternatives, mathematical optimization methodologies can provide the designer with a better understanding of the tradeoffs involved in the design process and can help to illuminate non-obvious design trends. The increasing speed of computer hardware also allows designers to utilize more accurate simulation models, which may in turn reduce the number of iterations required during the hardware-testing phase.

The development of an integrated design optimization methodology for smart actuators is divided into several subtasks. These subtasks are as follows.

1. The integrated design of the active material with the compliant mechanism.

   1.a Dynamic topology optimization of the compliant mechanism driven by a piezoelectric actuator.

   1.b Theoretical energy analysis and optimization of a compliant mechanism driven by a stacked piezoelectric actuator.

   1.c Topology optimization of the compliant mechanism with distributed piezoelectric material.

2. Design optimization of a recurve actuator.

3. Integrated design optimization of a recurve actuator driven by a switching power converter.

1.a Dynamic Topology Optimization

A topology optimization method is developed to design a piezoelectric ceramic actuator together with a compliant mechanism coupling structure for dynamic applications. The objective is to maximize the mechanical efficiency with a constraint on the capacitance of the piezoceramic actuator. (This constraint is driven by electrical considerations.) Examples are presented to demonstrate the effect of considering dynamic behavior compared to static behavior, and the effect of sizing the piezoceramic actuator on the optimal topology and the capacitance of the actuator element. Comparison studies are also presented to illustrate the effect of damping, external spring stiffness, and driving frequency. The optimal topology of the compliant mechanism is shown to be dependent on the driving frequency, the external spring stiffness, and if the piezoelectric actuator element is considered as design or non-design in the optimization. At high driving frequencies, it was found that the dynamically optimized structure is very near resonance.

1.b Stack Actuator and Compliant Mechanism Combination

In this task the modeling and theoretical energy efficiency analysis of a stack actuator plus compliant mechanism and external load combination is undertaken. This analysis is used to establish theoretical upper bounds on the efficiency of the overall system.

One of the important metrics in the design of an active system is the energy efficiency. The energy efficiency is defined as the output energy divided by the input energy. The output energy is typically measured in terms of the work done by the forces acting on an external driven structure. The input energy is defined as the electrical energy delivered to the system. Even for an ideal system that ignores loses, the efficiency is less than one mainly because of the storage of the energy in the form of electrical energy in the actuator (because of the capacitive nature of the most electroactive active materials) and strain energy in the displacement amplifying structure (associated with elastic deformations). Compared to the energy efficiency of a drive electronics circuit, the efficiencies of the actuator and mechanical amplifier may be substantially smaller.

The system considered in this study consists of an electroactive stack actuator driven by an ideal input voltage source, a compliant mechanism (CM), and a mass-spring external load (Figure 1). The compliant mechanism to be considered is a frame structure represented by the ground structure. In order to design the compliant mechanism that will provide the mechanical amplification, cross sectional areas of the individual members of the ground structure between the input and output ports of the structure are designed. Before the optimization of the entire system to determine the design details of the compliant mechanism that will occupy portions of the selected ground domain configuration (with its specified boundary conditions), and the stack actuator details, we studied the bounds on theoretical system efficiency considering a generic compliant mechanism.

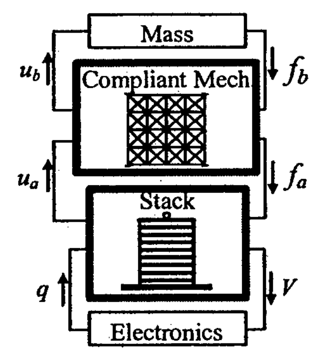

Figure 1: System with a compliant mechanism and stack actuator.

A linear two-port model of a generic compliant mechanism represented in the following form was used,

$$\begin{Bmatrix} u_a \\ u_b \end{Bmatrix} = -\begin{bmatrix} F_{11} & F_{12} \\ F_{21} & F_{22} \end{bmatrix} \cdot \begin{Bmatrix} f_a \\ f_b \end{Bmatrix}$$

where the F_{ij}'s are functions of driving frequency that characterize the transfer relations between forces and displacements at the input and output ports of the system. With this definition, one can further define an energy conversion efficiency of the compliant mechanism in the form,

$$\gamma^2 = \frac{F_{12}^2}{F_{11}F_{22}}$$

without taking into account the piezoelectric actuator or the external mass spring structure driven by the system.

Next, the relationship between the compliant mechanism energy transfer efficiency, γ, and the energy conversion efficiency of the whole system, η, is derived in closed form. The energy conversion efficiency of the piezoelectric and compliant mechanism combination is defined as the ratio of output mechanical energy,

$$\mathrm{E}_m = \frac{1}{2} u_b f_b$$

where u_b and f_b are the displacement and force of the compliant mechanism output, to the input electric energy is given by,

$$\mathrm{E}_e = \frac{1}{2} qV$$

where V is the voltage and q is the charge feeding into the drive electronics.

After algebraic manipulations, an expression for the maximum achievable system efficiency, η^*, as a function of the electromechanical coupling coefficient, k^2, of the active material and the compliant mechanism efficiency, γ^2, and given in the form,

$$\eta^* = \frac{k^2}{\left(1+\sqrt{1-k^2}\right)^2} \frac{\gamma^2}{\left(1+\sqrt{1-\gamma^2}\right)^2}$$

The resulting theoretical maximum efficiency curves are shown in Figure 2 for three different coupling coefficient values. Clearly, the overall efficiency of the system is limited by the efficiency of the active material, measured by k^2. Even if the compliant mechanism is 100% efficient, the representative number for k^2 shown on the figure limit the overall efficiency to be less than 30%.

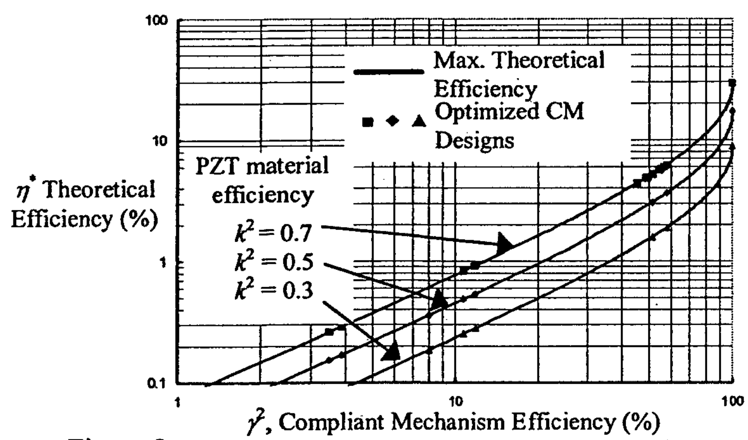

Figure 2. Maximum theoretical efficiency of a system with a compliant mechanism and stack actuator.

Optimized compliant mechanisms with bending elements are considered to demonstrate the computed efficiencies for specific designs. The analysis of the compliant mechanism is conducted using a finite element model and a mathematical optimization engine was used for design. The design variables are related to the design of the frame members of the compliant mechanism. The performance function is either the energy conversion efficiency or the weighted combination of the efficiency and geometric advantage so that a tradeoff between the system efficiency and the displacement amplification is obtained.

When only efficiency is used as the performance function compliant mechanisms with 100% efficiency, which corresponds to frame members that connect the stack actuator directly to the mass with completely flexible connections to the boundaries, are obtained. For such mechanism, the geometric advantage is one. When the combined efficiency and geometric advantage is used as the performance measure, then series of designs, whose efficiencies were on the curves shown in Figure 2 were obtained. The locations of the points were functions of the external spring stiffness and weighing coefficients of the geometric gain, as well as the coupling coefficients.

2. Recurve Actuator Optimization

In this task we develop a design optimization methodology for a recurve actuator. (Note that in a sense the recurve is an active material distributed throughout a compliant mechanism.) Design variables included the dimensions of the recurve elements (length, width, number of layers, layer thickness) and the number of parallel and series recurve elements making up the actuator. In each case, the actuator was designed to achieve a minimum acceptable free displacement and a minimum blocked force. The actuator size was restricted so that it would fit inside a prescribed volume, and the thickness of the PZT layers was restricted to ensure that the piezoelectric material would not lose its poling characteristics when subjected to a large electric field.

Two families of optimized recurve actuator designs were obtained. The first family consists of designs that were optimized for minimum weight, and the second family consists of designs that were optimized for maximum energy conversion efficiency. The energy conversion efficiency is defined as the ratio of the output mechanical energy to the input electric energy. Within each family, parametric studies were performed to determine how the optimal actuator design is affected by (1) the stiffness of the driven structure and (2) the maximum voltage delivered by the electronics.

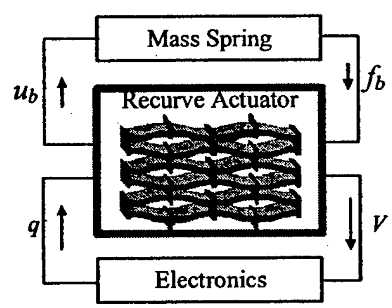

Figure 4: System with a Recurve

For small values of structural stiffnesses (1000-10,000 *N/m*), optimizing for minimum weight yields designs similar to those obtained by optimizing for maximum energy efficiency. In both cases, the blocked force constraint is active. For large values of the structural stiffness (100,000-500,000 *N/m*), however, significant differences arise. Compared to the minimum weight designs, the maximum efficiency designs are 25% to 50% heavier, but over 500% more efficient. The blocked force constraint is active for the minimum weight designs, and the free displacement constraint is active for the maximum efficiency designs. Because the efficiency of the actuator is expected to have a large influence on the design of the electronics, it is concluded that energy efficiency is the most appropriate objective function for this problem.

The effect of the maximum voltage on the optimal weights and efficiencies was found to be negligible. The maximum voltage does affect the physical configuration of the actuator, however. The low voltage designs (100-200 *V*) are more complex than the high voltage designs (400-500 V) in the sense that are made up of larger numbers of thinner PZT layers. High voltages, therefore, will result in more easily constructed actuators, but will place greater demands on the electronics.

3. Integrated Design Optimization of a Recurve Actuator and Drive Electronics

In this task we considered a smart actuator that consists of a recurve actuator driven by a switching amplifier. We investigated the use of design optimization methodology to do integrated design of this system. That is to say, we extended the optimization methodology for the recurve actuator to include the design optimization of the switching amplifier. It should be noted that the design optimization of electronic circuits, as reported here, is a relatively new research topic.

A key component in any smart actuator is the drive electronics. The primary function of the drive electronic is to condition the electrical power from the power bus and deliver this power to the active material in an appropriate form in response to a reference signal. Furthermore, since most active materials have a reactive impedance, most of the electrical power that is delivered to the smart material is regenerated to the amplifier. If the amplifier dissipates this reactive power as heat, the overall efficiency of the actuator is very poor. Therefore, in our research we selected a switching power supply that recycles the regenerative power with relatively low (but positive) loss.

The design optimization methodology for the switching power converter developed here produces a completely realistic design (includes component selection). The optimization formulation is developed to include all realistic losses. For example, realistic power switches used for smart structures applications exhibit power loss due to their imperfect switching characteristics. Also, those regenerative drive circuits tend to have large inductors to suppress current ripples in the output waveform due to the capacitive nature of the piezoceramic actuator. These large inductors cause power loss through their parasite resistance. Design variables included the inductor, the MOSFETs, the capacitors, the heat sink, and the switching frequency. Limits were imposed on the bus voltage transient, the inductor current ripple, and on the filter crossover frequency. Constraints were also imposed to ensure internal stability and to ensure that the switch junction temperature was not exceeded. A mathematical model was developed to predict the power dissipation (conduction and switching losses) in the MOSFET.

Since the drive amplifier delivers power from the power source to the active material, it is also appropriate to consider the power source in the optimization. The extreme situation is when the power source is finite; i.e. it is a rechargeable battery. The objective of the optimization is to minimize the size and maximum the life time of the battery that drives the system. While the battery size can be minimized by minimizing the overall reactive power in the combined system, the battery lifetime can be maximized by minimizing the real power. Because the electronics and actuator subsystems are coupled, the input reactive power required by the system cannot be computed separately for each subsystem. Thus, it is necessary to design the electronics and actuator simultaneously.

Genetic algorithm is used as design optimization platform keeping in view that some of the design variables are continuous and some are discrete type. That is, the GA is used to do component selection for the electronics and material selection for the actuator. A typical GA usually consists of the following – population initialization, rank population, analyze population, crossover, and mutation. Crossover is a GA operator that produces child population from the parent population and mutation operator does not allow the population to become too uniform thus ensuring proper search of the design space. There are several variations of the operator particularly suited to a problem.

The initial research decomposed the optimization problem into two part– actuator optimization for maximum energy and minimum weight design, and optimization of the power electronic driving circuit for minimum power loss, minimum weight and maximum mechanical output energy. But it was found that such decomposition is not viable and simultaneous optimization of both actuator and the driving circuit is required. However, choice of objective function is very important in this type of complicated design problem and presence of conflicting objectives necessitates a multi-objective approach. In multi-objective approach, instead of giving preference to one objective, a weighted sum of the different objectives or min-max approach is employed. This approach has an added advantage of providing the designer with a range of optimal solutions. It also provides the trade-off information between the objectives (referred to as pareto curve). The optimization results below show the trade-off between real power loss or reactive power as objective function is not appropriate. The trade-off between P_{loss} and Qe circulating in the system is shown in the figure 6.

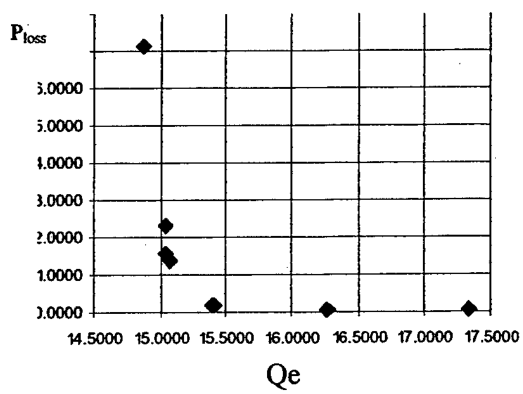

Figure 6: Pareto-optimal curve showing trade-off between P_{loss} and Q_e

It is evident from the pareto-optimal curve that if we try to minimize reactive power circulating in the system which indirectly determines the battery size, the power losses in the system is very high. On the contrary, minimization of power loss will lead to large battery size. However, power loss increases manifold when reactive power decreases beyond 15.2 (even for a small decrease in reactive power) and vice versa. Thus a better balanced solution can be obtained in the range [(2.4,15.1) and (0.1,15.4)], which has both smaller power losses in the system and the reactive power. Also it is noteworthy that though the reactive power in the above range increases from 15.1 to 15.4, the decrease in power loss if very high i.e. from 2.4 to 0.1. To get the above optimization result, the weight for the real power in the objective function, α, should be in the range of 0.25~0.72.

Publications

A summary of the publications generated by this research grant is given below.

The following journal papers were published:

M. M. Abdalla, C. Song, D. K. Lindner, and Z. Gürdal, "Combined Optimization of a Recurve Actuator and its Drive Circuit," *Journal of Intelligent Material Systems and Structures*, Vol. 140, April/May, 2003, pp. 275-286.

Maddisetty, H., and M. Frecker. , 2002. Dynamic Topology Optimization of Compliant Mechanisms and Piezoceramic Actuators. *ASME Journal of Mechanical Design*, in press.

The following journal papers have been submitted:

Abdulla, M. M., M. Frecker, Z. Gurdal, T. Johnson, and D. K. Lindner, "Maximum Energy-Efficiency Compliant Mechanism Design for Piezoelectric Stack Actuators," submitted to the AIAA Journal, April 2004.

The following refereed conference papers have been published:

O. Seresta, M. M. Abdulla, Z. Gurdal, and D. K. Lindner, "Topology Design of Active Trusses with Energy Constraint," *Proceedings of the AIAA/ASME/ASCE/AHS/ASC 43th Structures, Structural Dynamics, and Materials Conference*, Palm Springs, CA, April, 2004, paper number AIAA-2004-1720.

M. M. Abdalla, Z. Gürdal, and D. K. Lindner, "Design of a Recurve Actuator for Maximum Energy Efficiency", AIAA-2003-1804, Presented at the 11th AIAA/ASME/AHS Adaptive Structures Conference, Norfolk VA, April 2003, CD-ROM 6 pages. (Journal paper in preparation.)

O. Seresta, S. Ragon, H. Zhu, Z. Gurdal, and D. K. Lindner, "Combined Design of Recurve Actuators and Drive Electronics for Maximum Energy Efficiency," *Proceedings of SPIE's11th Annual International Symposium on Smart Structures and Materials: Modeling, Signal Processing, and Control*, San Diego, CA, March 14-18, 2004, Paper Number 5383-25, pp. 174-182. (Journal paper in preparation.)

Abdulla, M. M., M. Frecker, Z. Gurdal, T. Johnson, and D. K. Lindner, "Maximum Energy-Efficiency Compliant Mechanism Design for Piezoelectric Stack Actuators," *Proceeding of 2003 ASME International Mechanical Engineering Congress and R&D Exposition*, Washington, DC, Nov. 15-21, 2003, Paper number IMECE2003-41509.

Zhu, H., S. Ragon, D. K. Lindner, M. M. Abdulla, O. Seresta, and Z. Gurdal, "Optimization of Driving Amplifiers for Smart Actuators Using Genetic Algorithm," *Proceedings of the 29th Annual Conference of the IEEE Industrial Electronics Society*, Roanoke, VA, November 2-6, 2003, pp. 2951 – 2956.

Zhu, H., S. Ragon, D. K. Lindner, M. M. Abdulla, O. Seresta, and Z. Gurdal, "Combined Optimization for Smart Materials and the Driving Circuit," *Proceeding of the 6th CanSmart*

Workshop on Smart Materials and Structures, Montreal, Quebec, Canada, October 16-17, 2003, pp. 293 – 302.

Maddisetty, H., and M. Frecker., Dynamic Topology Optimization of Compliant Mechanisms and Piezoceramic Actuators, *Proceedings ASME International Mechanical Engineering Congress and Exposition, Adaptive Structures Symposium,* New Orleans, LA, November. 17-22, 2002. Paper IMECE2002-33993.

Maddisetty, H., and M. Frecker , 2002. Topology Optimization of Compliant Mechanisms and Piezoelectric Actuators for Dynamic Applications. Proceedings *39th Annual Technical Meeting Society of Engineering Science,* University Park, PA, October 13-16th, 2002, p. 2-1.

Song, C., D. K. Lindner, M. M. Abdalla, and Z. Gürdal, "Energy Optimization of Drive Amplifiers for Smart Actuators," *Proceedings of SPIE's International Symposium on Smart Structures and Materials: Modeling, Signal Processing, and Control,* Ralph Smith, Ed., San Diego, CA, March 2-6, 2003.

Song, C. and D. K. Lindner, "Optimization of Drive Amplifiers for Smart Materials," *Proceedings of the Canada-US CanSmart Workshop on Smart Materials and Structures,* Montreal, Quebec, Canada, Oct. 10-11, 2002, pp 273-284.

Song, C., M. M. Abdalla, D. K. Lindner, and Z. Gürdal, "Combined Optimization of Active Structural Systems and Drive Circuits," *Proceedings of SPIE's 2002 North American Symposium on Smart Structures and Materials: Modeling, Signal Processing, and Control,* Vital S. Rao, Ed., San Diego, CA, Vol. 4693, March 18-21, 2002, pp. 136 – 147.

Johnson, T., and M. Frecker. 2004. Optimal Placement of Active Material Actuators Using Genetic Algorithm. *Proceedings SPIE 11th International Symposium on Smart Structures and Materials,* San Diego, CA, March, 2004.