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Letter to the Editor

Structural vibration suppression via active/passive techniques

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1. Introduction

The notion of suppressing structural vibrations is of paramount importance for enhancing safety and improving system performance. This paper briefly reports the advances made in the area of vibration suppression via recently developed innovative techniques (for example, constrained layer damping (CLD) treatments) applied to civilian and military structures. A number of research projects have been sponsored and supported by the United States Army Research Office (ARO) that have led to very promising and exciting results in this area. Typically, these research projects relate to themes such as developing and evaluating the performance of novel active–passive hybrid smart structures for real-time vibration control; developing theoretical equations that govern the vibration of smart structural systems treated with piezo-magnetic constrained layer damping (PMCLD) treatments; and developing innovative surface damping treatments using micro-cellular foams and active standoff constrained layer (ASCL) treatments. The results obtained from the above and several other vibration suppression oriented research projects being carried out under the ARO sponsorship are included in the paper. In addition, recommendations are made for future research directions that are likely to yield most fruitful results and thus meet the urgent needs in this area for both the civilian and the military sectors.

Undesirable large-amplitude vibrations and radiated noise often impede the effective operation of various types of dynamic civilian and military systems such as rotorcrafts, missiles, land vehicles, and weapon systems. It is prudent to introduce structural damping into a dynamic system to achieve a more satisfactory response. The development of effective and economical structural damping approaches that can suitably adjust mechanical properties to appropriate specifications could be beneficial in designing future systems [1,2]. Recently, new concepts for enhancing the structural damping characteristics were introduced in the study of adaptive structures [3]. Such active damping techniques, based on combinations of viscoelastic, magnetic,

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and/or piezoelectric materials, magnetorheological (MR) fluids, shunted electric circuits, and active non-linear control strategies, have emerged as several likely candidates for improving structural performance and reliability [4]. The availability of integrated methods using smart materials and passive circuits to dissipate energy provide yet another possibility of enhancing performance through the use of electronic damping technology.

2. Typical recent research projects

Several research projects dealing with active and passive damping have recently been completed or are currently in progress under the sponsorship of Structures and Dynamics Program of the ARO. In addition, various other Department of Defense (DoD) agencies such as the Office of Naval Research (ONR), Air Force Office of Scientific Research (AFOSR), and the Defense Advanced Research Projects Agency (DARPA) have been providing funds for sponsored research projects in these areas. Typical examples of a few of these projects are described in the following sections. These projects have a primary emphasis on basic research. However, the investigations are carried out keeping in view the applicability and relevance of the research results to meet the needs of the DoD and the civilian environment.

2.1. Surface damping treatment techniques

2.1.1. Projects at Pennsylvania State University

Professor Kon-Well Wang of the Department of Mechanical and Nuclear Engineering at Pennsylvania State University, State College, PA, has carried out a research project entitled "Active–Passive Hybrid Adaptive Structures for Vibration Controls: An Integrated Approach" [5–8]. The main objective of this research effort was to develop and evaluate novel active–passive hybrid smart structures for real-time vibration controls. His investigation was aimed to advance the available active–passive hybrid technology (the active–passive piezoelectric network (APPN) and the active constrained layer (ACL) approaches) and to eventually achieve an optimally control-configured, high-performance vibration damping system with low power requirements and high reliability and robustness. Being an optimized hybrid structure, it had the benefits of both the passive (stability, fail-safe, and lower power consumption) and active (high performance, feedback and feed-forward actions) systems.

In this project the major research activities included (1) actuator concept development, (2) actuator/structure modelling and characterization, (3) control law development and system integration, (4) control-configured adaptive structure design methodology development, and (5) experimental validations. Some of the achievements in this context are described in the following paragraphs.

Basically, an APPN hybrid network consists of piezoelectric materials in series with an active voltage source and passive shunt circuits. It is shown that in comparison to a purely active arrangement, the shunt circuits can provide not only passive damping, they can also enhance the active action authority around the tuned frequency. Therefore, the integrated APPN design is more effective than a system with separated active and passive elements, and thus achieves more vibration reduction with less control effort. However, it is also evident that the enhanced active authority is due to the voltage amplification characteristics of the circuit around the tuned frequency. During some operating conditions, this high voltage (electric field) across the piezoelectric material is likely to cause significant non-linear effects.

Classical ACL treatment can improve system damping when compared to a traditional passive constrained damping layer approach. However, when compared to a purely active case (i.e., no viscoelastic layers), the ACL viscoelastic materials (VEM) layer will reduce the direct control authorities from the active source to the host structure. To address this issue, the research team created an "enhanced" active constrained layer (EACL) configuration to improve the transmissibility and active action authority of the classical ACL treatment. Introducing a pair of "edge elements", the active action from the piezoelectric cover sheet can be transmitted to the host structure more directly in the EACL. On the other hand, such a configuration still possesses the damping ability of the passive VEM. Combining the overall active and passive actions, the EACL can achieve better performance (smaller vibration amplitude) with less control effort (lower voltage or power) as compared to the classical ACL systems. Results confirmed that the edge elements could significantly improve the effectiveness of the active constrained layer damping (ACLD) treatment.

In order to enhance the control bandwidth of the APPN actuator and achieve the dual-functional (narrowband and broadband control) effect, the Penn State researchers explored the feasibility of combining the APPN with the EACL configuration. It was shown that by adding the shunt circuit to a classical ACL, one could not obtain much additional damping because of low transmissibility between the piezoelectric coversheet and the host structure. This can be resolved by utilizing the edge elements—the EACL treatment. Since transmissibility is increased, an APPN–EACL combination can achieve significantly more damping around the tuned frequency than the APPN–ACL combination. On the other hand, the EACL broadband damping ability can greatly enhance the control bandwidth of the APPN treatment. Analysis of results has illustrated that the integrated APPN–EACL approach can outperform the individual EACL or APPN configurations throughout a wide frequency range.

The Penn State researchers explored the feasibility of using the hybrid constraining layer (HCL) configuration also. That is, combining both the active and passive materials into the constraining layer (coversheet). In both the ACL and EACL treatments, the constraining layer (coversheet) is completely made of piezoelectric materials (e.g., PZT ceramics or PVDF polymer) because of their active action capabilities. PZT materials are in general much better than PVDF polymers for this purpose. Nevertheless, having a density similar to steel (relatively heavy) and a modulus close to aluminum (moderate stiffness), PZTs are not ideal as constraining materials. Because of the limited selections of active materials, it is difficult to find one with both features—good material property for constraining purpose and strong active action.

More recently, Professor Wang and his associates have developed a HCL configuration. In this design, the viscoelastic material is constrained by an active–passive hybrid coversheet. The active part is made of piezoceramics and the passive part can be designed differently for different purposes. It is shown that by selecting a passive material stiffer than PZT, the HCL could obtain higher open-loop damping than the treatment with a pure PZT cover sheet (ACL or EACL). Furthermore, when the active constraining length and passive constraining length are optimally designed, the overall closed-loop damping of the HCL is also higher than that of the configuration with a pure PZT coversheet.

A closed form transfer function model for an HCL-treated beam was derived and used by the research team to study the effect of active and passive material distribution in the constraining layer. It was found from this study that, other than the active material coverage ratio, the distribution of the active and passive materials in the constraining layer will also influence the HCL damping effectiveness. It was possible to improve the performance of the HCL by optimizing the distribution of the active and passive constraining materials. The effectiveness of a constraining material distribution also depends on the mode shape (strain distribution) of the structure. For example, for a constant strain field in the host structure, placing the active material in the middle section of the constraining layer yields the most effective distribution for a given active material coverage ratio. This HCL configuration achieved more closed-loop vibration reduction than ACL and the other HCLs with active element(s) placed off-center.

The research team also investigated the damping ability of the integrated EACL and HCL treatments. A genetic optimization routine is combined with gradient-based optimization methods to find the best design variables for the integrated system as well as the corresponding loss factors. The objective of the optimization is to maximize the closed-loop damping and the major constraint is to maintain a fail-safe damping (open-loop damping with no active actions) margin in the system. It is demonstrated from this study that the integration of the EACL and HCL can obtain a better combination of the open- and closed-loop damping.

A design with two stiff edge elements and an active–passive hybrid constraining layer can be used to provide the required fail-safe damping with significant closed-loop damping when the open-loop damping requirement is not very high. A closer look at the design reveals that the difference of the extensional stiffness of the active and passive constraining sections creates large shear deformation in the middle section of the viscoelastic material, although the shear at the boundaries is very small because of the stiff edge elements. The stiff edge elements at the boundaries in the mean time serve to enhance the direct active control action from the constraining layer. Consequently, the closed-loop damping of such a design is higher than that of a pure EACL treatment when the same amount of fail-safe damping is obtained. When the fail-safe damping requirement is relatively high, the EACL design alone cannot provide enough open-loop damping. Although a pure HCL can provide the required fail-safe damping, it produces less closed-loop damping. Therefore, the integration of the EACL and HCL actually broadens the damping ability of the individual EACL and HCL designs.

In summary, this research effort at Pennsylvania State University, (1) created various new self-contained active–passive actuators and adaptive structures, wherein hybrid actions were effectively utilized to suppress structural vibrations, and (2) developed systematic methods for designing the passive control elements and the active gains simultaneously to obtain optimal performance. The systems and methods were generic and applicable to any complex structure. This study successfully illustrated that the performance of the active–passive system was superior to those of the passive damping cases. It was also shown that a well-designed active–passive system could outperform purely active cases with less or similar control power requirement. With the benefits of both the active and passive methods, the technology developed in this research would potentially eliminate the concern that is generally expressed in the context of purely active systems (instability, high power requirement, hardware complexity, and fail-safe issues), and would still outperform the classical passive systems greatly.

Apart from the civilian applications, the major Army missions that would have the greatest potential for benefiting from this research are the vibration controls of rotorcraft and flexible weapon structures. Potential Army applications of the research findings have been identified. Examples include damping for gun-fuselage structures and adaptive flexbeam for helicopter stability augmentation. The knowledge base created through this project will facilitate the realization of smart structures for military and industrial applications, and stimulate continuing research efforts in this area.

2.1.2. Projects at the University of Maryland

Professor Amr Baz of the University of Maryland, College Park, MD, is carrying out a project entitled "Active–Passive Control of Smart Structures" [9–11]. The major emphasis of this research effort is on the development of a "Distributed-Parameter Finite Element Method (DPFEM)". This method is aimed to efficiently analyze the static and dynamic characteristics of structures. The DPFEM provides an exact model of the structures without any mode truncation or without the need for assuming shape or interpolation functions while using the smallest number of distributed-parameter elements (DPE). The method is based on the "transition matrix approach."

As a part of this research, Professor Baz is engaged in the development of DPFEM to describe the dynamic interaction between the viscoelastic damping layer, magnets, the piezo-electric sensor, the piezo-electric constraining layer, and the base structure (beam, plate or cylinder) which are treated with the PMCLD treatments. In addition, he is developing DPFEM models to describe the interaction between the vibration and sound radiation from the smart structural systems with the PMCLD treatments. The effect of using simple proportional, and proportional plus derivative control strategies on the sound pressure field, sound intensity and directivity of the radiated sound waves are being investigated in detail.

Using the DPFEM approach, the frequency domain description of the dynamics of the smart structures/PMCLD treatment lends itself to the use of the H_2/H_∞ robust control theory where constraints can be imposed to ensure disturbance rejection and to the accommodation of parametric uncertainty. The distributed and modal parameters of the smart structural systems (stationary and rotating beams, plates and cylinders) treated with the PMCLD are identified using time and frequency domain methods. The parameters identified are used to validate the developed mathematical models. Experimental smart structures (beams, plates and cylinders) are built for the various PMCLD configurations. The effect of varying the properties of the viscoelastic cores as well as the magnetic and the piezo-electric actuators on the overall performance of the smart structures are investigated. Comparisons are made with conventional passive constrained layer damping (PCLD) and ACLD treatments in order to define the merits and limitations of the proposed PMCLD.

Evaluation tests are carried out by placing the smart structural systems (plates and cylinders) inside an anechoic chamber. The performances of the structures are monitored under various types of external excitations (tonal and random vibrations) in order to evaluate the effectiveness of the PMCLD in attenuating the sound radiation from these structures. Software packages are developed to model the static and dynamic characteristics of structures using DPFEM. The packages include plain untreated structures as well as structures treated with PCLD, ACLD, magnetic constrained layer damping (MCLD) and PMCLD treatments. Such packages are invaluable tools for the analysis and synthesis of structures in general and of smart structures in particular.

There exist numerous potential military and commercial applications using the proposed concepts. In the military, active and passive smart structures can be utilized for manufacturing stable platforms for observation, communications and battlefield applications. Also, the outcome of the proposed study includes the development of comprehensive analytical, computational, and experimental tools that will enable practicing engineers to design, build, and test the new class of smart PMCLD treatments. It is expected that Professor Baz and his research team will produce a simple and reliable class of smart passive/active treatments which is practical, energy efficient, and affordable. With such capabilities, it is envisioned that the MCLD and the PMCLD treatments will be the "sought after" means for suppressing the vibration and noise of vehicles, automobiles, aircrafts, high-rise buildings as well as home and office equipment.

2.1.3. Projects at the University of Washington

In the project entitled "Surface Damping Treatments: Innovation, Design, and Analysis" Professors Steve Shen and Per Reinhall of the Department of Mechanical Engineering, University of Washington, Seattle, WA, are emphasizing fundamental research on the use of micro-cellular foams and ASCL surface damping treatments [12–14]. Their project has two main objectives. The first objective is to develop the innovative surface damping treatments; namely, use of micro-cellular foams and ASCL treatments. It should be remarked that these two novel treatments can potentially increase the damping capacity of existing damping treatments by a factor ranging anywhere from 5 to 10. The second main objective is to conduct basic studies on surface damping treatments for beams, plates, and shells. These fundamental studies are motivated by difficulties encountered in the development of next-generation rotorcraft and jet fighters.

The research consists of the following procedures in the case of micro-cellular foams. The first one is to experimentally measure storage modulus and loss factor of micro-cellular foams. The purpose is to study the feasibility of using micro-cellular foams as a potential new damping material. The second procedure includes developing a manufacturing process to collapse the bubbles in micro-cellular foams in order to increase damping (loss factor), studying the feasibility of using micro-cellular foams as standoff layers in constrained layer treatments, and experimentally evaluating the absorption coefficients of micro-cellular foams for noise attenuation.

For ASCL treatments, the project consists of several research segments. First is to develop a mathematical model for passive standoff layer damping treatments. In this model, the standoff layer has finite bending and shearing rigidity. (Existing models assumed that the standoff layer had a zero bending rigidity and an infinite shearing rigidity.) Second is to validate the mathematical model with experimental results. The third is to develop a mathematical model for passive slotted standoff layer damping treatments. This treatment is used substantially in many defense and civilian applications. The fourth is to validate the proposed mathematical model via calibrated experimental results. The fifth is to develop ACL treatments by integrating the passive slotted standoff layer and piezoelectric actuators developed at the NASA/Langley Research Center. The sixth is to conduct finite element analysis and experiments for one- and two-dimensional structures. And, the final research segment is to optimize the location and geometry of the slots and actuators to maximize damping performance of ACL treatments.

The research effort for carrying out fundamental studies of damping treatments for beam structures consists of the following objectives. Improve the currently available Mead–Markus model for CLD by modifying the boundary conditions. Verify the improvements through experiments. Experimentally detect the existence of thickness deformation in constrained layer treatments and predict the thickness deformation through Miles–Reinhall model. Similarly, for fundamental studies of damping treatments for plate and shell structures, the research consists of the following objectives. Develop an isoparametric finite element formulation for plates and shells with constrained layer treatments. Develop novel dampers (or structural materials with high damping) to control non-linear vibration of flat plates subjected to high acoustic loading ($>170\,\mathrm{dB}$) and high temperature ($400^\circ\mathrm{F}$).

The proposed innovative damping treatments can be applied to trailing edge flap and tab control of helicopter rotorblades for vibration suppression, Blade–vortex interaction (BVI) noise reduction, and for pointing/tracking control of weapon systems. The proposed fundamental studies on shell damping treatments can be used to suppress noise inside helicopter fuselages. The fundamental study on non-linear vibration control of plates can be used in helicopter rotor blades to suppress non-linear vibration and BVI noise from strong aerodynamic forces interacting with the rotor blades. The issue of non-linear vibration control has also arisen in the development of Joint Strike Fighters because of severe fuselage vibration due to acoustic excitations from the jet engine.

The research effort from this project has led to the following principal findings for the case of micro-cellular foams. Micro-cellular foams have high storage modulus (100 Mpa–1 GPa) but low loss factor (6–8%). Therefore, micro-cellular foam does not have high enough damping to qualify as a useful damping material. The researchers have developed a manufacturing process to collapse the bubbles in micro-cellular foams. The process consists of applying high mechanical pressure, annealing the foam above the glass transition temperature, and thermal cycling. The collapsed micro-cellular foams, however, do not have larger loss factors. To increase the loss factor, an initial pre-load might be needed to completely close the collapsed bubbles. It was found that micro-cellular foam was an excellent material for building standoff layers. It can increase the damping of constrained layer treatments by 80% with only 2% of weight penalty. In addition, micro-cellular foams have good sound absorption coefficients (ranging from 0.5 to 0.8) at specific frequencies, which depend on the bubble size and number of layers. Therefore, micro-cellular foam can be engineered to attenuate acoustics at a certain frequency by changing its bubble size and foam density.

The University of Washington research team has realized the following accomplishments for ASCL treatments. The team members have developed a mathematical model for passive standoff layer damping treatments with the assumption that the standoff layer had finite bending and shearing rigidity. In addition, they have validated the mathematical model via calibrated experiments. A mathematical model has been developed for passive slotted standoff layer damping treatments also, and the research team has produced a prototype to demonstrate the feasibility of ACL treatments.

This research effort has led to the following findings related to the damping treatments for beam structures. The Mead–Markus model, which had been used for modelling constrained layer treatments for almost 30 years, could result in significant errors for some specific boundary conditions. The researchers have corrected the Mead–Markus model by posing more accurate boundary conditions, and verifying the improvements through experiments. They have experimentally demonstrated and quantified the existence of thickness deformation in constrained layer treatments. It must be noted that thickness deformation could be significant in partial treatments. The thickness deformation is predicted through a model proposed by Miles and Reinhall. Theoretical predictions agree well with experimental results.

In terms of specific achievements, the team has developed an 18-node, degenerate constrained layer element for plate and shell structures. For thin plate structures, numerical results show that the isoparametric element can predict natural frequencies, loss factors, and mechanical impedance as accurately as NASTRAN with substantially fewer elements. For thin shell structures, applications of the isoparametric formulation are possible, if spurious mode control can be implemented. The research team has experimentally measured the damping of nitinol-aluminum metal matrix composite. The experimental results indicate that the nitinol-aluminum metal matrix composite presents important passive damping characteristics compared with other structural materials (e.g., 1% at 20°C and 2% at -20°C). In addition, the damping can be turned on or off via temperature control.

2.2. *Other typical damping related projects*

Professor Aditi Chattopadhyay of the Department of Mechanical and Aerospace Engineering at Arizona State University and her research group have investigated "Modeling and Analysis of Composites Using Smart Materials and Optimization Techniques" [15–16]. The major objectives of this research project were the following. (1) Develop new composite rotating box beam models with surface-bonded piezoelectric (PZT) and segmented constrained layer (SCL) actuators to represent the principal load-carrying member in helicopter rotor blades. The models were to be based on a refined higher order displacement field theory. (2) Address vibration control of helicopter rotor blades built around the adaptive composite box beam models, (3) utilize a hybrid optimization technique and linear quadratic regulator to investigate the optimal use of smart materials for vibration control, (4) investigate the integrated structures/controls interaction problem, and (5) investigate rotor/fuselage coupled stability using segmented CLD treatment.

The use of self-sensing piezoelectric (PZT) actuators and segmented and constrained layer (SCL) damping treatment have been investigated for reducing rotor dynamic hub loads and improving aeromechanical and isolated rotor stability. The rotor blade load-carrying member was modelled using a composite box beam. In the first case, PZT actuators were surface bonded to all walls of the box beam to provide both lead-lag and flap actuation and to enhance control through structural coupling. In the second case, SCLs were bonded to the upper and lower surfaces to provide passive damping. A finite element model based on a higher order displacement theory was used to accurately capture the transverse shear effects in the composite beam with PZTs.

A hybrid displacement field theory was developed to accurately model the deformation in the various layers for the beam with SCLs. A quasi-steady aerodynamic model was used to calculate the aerodynamic loads along the span of the blade. The linear quadratic regulator method was used to design the control system for vibratory load reduction with PZTs. The non-linear aerodynamic model was linearized for control system design. The control system was coupled with a hybrid optimization technique to investigate the structures/control interaction problem associated with vibration reduction. Ground and air resonance models were implemented in the rotor blade built around the composite box beam with segmented SCLs to investigate the stability issues.

Structures/controls interaction is an important issue that needs detailed investigation and leads to improved smart structural systems design. The simultaneous design of structural (e.g., placement of actuators, ply stacking sequence) and controls parameters was addressed using a hybrid optimization technique. Aeromechanical stability is a key issue in helicopter design in which lead-lag modal damping plays an important role. To ensure helicopter stability in normal operation, adequate rotor damping and body damping are necessary. The use of distributed and segmented SCLs and PZTs showed significant improvements in both rotor lead-lag damping and aeromechanical stability.

Optimization studies were conducted on two different cases: first, with PZTs placed on the top and bottom surfaces (two pairs) and second, with PZTs on all surfaces (four pairs). Significant increases in the damping ratios were observed after optimization in both cases. Comparison of the two cases revealed that higher lead-lag and torsion mode damping were achieved with PZTs on walls, although a higher flap damping was achieved in the case with PZTs on top and bottom surfaces. Overall, the closed-loop response trends were generally better when PZTs were placed on all surfaces. The in-plane and out-of-plane fundamental modal damping of the box beam in vacuum was analyzed next with surface-bonded SCLs. A total of four cases, based on number and locations of the SCLs, were investigated for improved helicopter aeromechanical stability. All four cases led to stable coupled rotor-body systems in ground resonance analysis. As the SCL pairs were moved from the root elements towards mid-span, the lead-lag regressive (LR) modal damping for both ground and air resonance analysis increased.

Another research project, entitled “State-Switched Absorber/Damper for Structural Vibration Control”, is currently being carried out under the direction of Professor Kenneth A. Cunefare of the Georgia Institute of Technology. The basic objective of this project is to improve the control and suppression of vibration through the modelling, analysis and development of state-switchable vibration absorbers [17–18]. Classical passive vibration absorbers comprise an inertial mass on a spring, with some damping incorporated for motion limitation. Such a passive absorber has but a single tuned frequency of most effective operation. A state-switched vibration absorber has the capability to instantaneously alter its stiffness state. This action re-tunes the absorber to a new frequency, permitting the device to be effective against multiple disturbance frequencies, over a broader bandwidth than a strictly passive device. The state-switch is accomplished through either electrically switching a stiffness element, such as a piezoelectric spring, or by mechanically engaging and disengaging mechanical springs in parallel, or by altering the magnetic field on a MR material.

The major aims of Professor Cunefare’s research project are to develop dynamical models of typical engineering systems (e.g., beams and plates) with attached state-switchable absorbers, and to analyze the response performance under conditions of multi-frequency vibration, time-variable vibration, and for different algorithms for switching the state of the system, and for experimentally validating the performance of the device. Classical passive vibration absorbers are not capable of adapting to changing operating conditions, nor is a single such device generally effective against multiple frequencies. With state-switching, a single absorber may be made more effective against both of these conditions, yielding increased vibration reduction performance as compared to passive devices. A state-switchable device, especially one with many possible tuning states, can be made to be highly adaptive and frequency-agile. In terms of Army issues, a state-switched absorber may find application in reduced vibrations transmitted into avionics, reduction of vibration levels on helicopter fuselage structures, and enhanced damping of gun barrels.

The Georgia Tech research team has made substantial progress in extending the simulation codes for a variety of dynamical systems, forcing excitations, and switching rules. It now has the capability to simulate state-switched absorbers with a distributed excitation applied to a single-degree-of-freedom beam and/or a two-degree-of-freedom structure individually or to a combination. In addition, it has implemented simulation code to permit analysis of time-varying and random disturbances, eliminating the limitation of considering combinations of simple harmonic excitations. The research team has implemented and evaluated several switching control strategies, including algorithms based on the objectives of maximum energy extraction, frequency time-sharing, and purely random switching. In all cases analyzed to date, the researchers have found that, in general, state-switched vibration absorbers performed significantly better than, and never worse, than the currently available passive vibration devices.

In addition to the above-mentioned simulation accomplishments, the team has been developing design concepts beyond the basic switched-spring approach. Different materials and mechanical configurations permit alternative switching configurations and controls, relaxing some of the constraints encountered when considering piezoelectric materials as the switchable element. For example, a literature search has revealed the existence of electrorheological (ER) and MR polymers. These materials, principally developed by researchers at the Ford Motor Company in the mid-1990s, exhibit variable stiffness and damping properties when subjected to electrical or magnetic fields. Since they are polymers, they offer the potential for developing compact, low tuning frequency, state-switchable vibration absorbers. Also, they are readily molded into whatever shapes are necessary. The researchers are currently investigating the feasibility of incorporating these materials into their research program.

Professor Cunefare and his colleagues have also made significant progress in experimentally validating the state-switching concept. They have constructed a two-degree-of-freedom state-switched vibration absorber system based on a switchable MR clamping device, and have implemented the state-switching control of this device using a digital signal processing system. The results in hand clearly demonstrate that the state-switched vibration absorber is capable of reducing the base motion of a two-degree-of-freedom system subjected to multiple harmonic forces to a greater extent than a passive vibration absorber. The researchers have also constructed a single-degree-of-freedom test system to validate the analytical developments related to energy absorption and optimal switch timing.

3. Suggestions for future research

Since currently used damping models are mostly fragmented and ad hoc, they must be generalized to become useful in design and analysis. Current research on active damping has been based primarily on the assumption and exploitation of linearity to achieve electronic energy dissipation. The possibility exists to increase the performance in active vibration suppression systems through the use of non-linear approaches, and subsequent exploration of the new design space holds the promise of higher energy dissipation capabilities, more robustness and adaptability to changing demands, and diminished requirements on resources and infrastructure. This promise can be realized only if a number of hurdles in system concept definition, non-linear systems modelling, and design are addressed.

Innovative approaches to the modelling of damping that include micromechanical, thermodynamical, uncertainty, probabilistic, and non-linear aspects, compatible with current finite element codes, and to the introduction of damping mechanisms into a structure are needed for vibration suppression, noise reduction, increased system performance, extended service life, and lower maintenance costs. Attention may also be focused on modelling errors, optimization of the analysis procedure (non-linear constitutive models, adaptive finite element solutions, adaptive time stepping methods, etc.), experimental error measurements, inverse methods, joint properties and modeling, and load-bearing damping materials. Thus, fundamental research is required to devise actuation schemes, derive, and validate experimentally new modelling methods and controller designs for damping mechanisms. The control-theoretic issues in this initiative are on the frontier of distributed non-linear control. These issues range from the structural modelling of the control elements, through the coupling and feedback to the elements of the system, to the study of the overall dynamics of the control system.

Several specific directions of research are required to accomplish the appropriate active and passive damping objectives. For example, structural engineering issues include an investigation of paradigms for maximizing energy dissipation, non-linear power electronics for high-efficiency actuation, adaptive time-varying systems to allow for plant and objective variation system damping modeling—leading to effective system representations for use in simulation and design.

Similarly, under control theory issues fall the investigation of appropriate physical models of the smart materials used in the control elements, models that incorporate both material and geometric non-linearities; investigation of the feedback and coupling mechanisms among the control elements; investigation of non-linear controllers using conventional and neural network based algorithms; investigation of distributed control techniques; and model reduction for equivalent reduced order systems.

Rotorcraft airframes and rotors are prone to vibratory motions that can become severe when resonance, limit cycle, chaotic, or aeromechanical instability conditions are approached. The introduction of damping into the system may lead to the alleviation of aeroelastic flutter, reduction of gust loading, increased fatigue life expectancy of helicopter rotor blades, improved rotorcraft maneuverability and handling, and diminished noise levels in the interior of the rotorcraft. Damping also holds the potential for improving the tracking and pointing characteristics and accuracy of weapon systems mounted on rotorcrafts and land vehicles and for facilitating the design, analysis, and testing of active suspension and steering systems in such vehicles. Successful incorporation of advanced, active damping schemes and/or treatments into commercial fixed wing and rotary wing aircraft would lead to more comfortable ride, quieter interiors for greater crew and passenger comfort, safer flight due to enhanced rotor stability, more economical operation because of extended fatigue life of airframe and rotor blades, and improved maneuverability. Applications may also be found in the aerospace and automotive industries.

4. Conclusions

The fundamental research in the area of active and passive vibration control must be primarily aimed at adapting, integrating, optimizing, and/or augmenting any potential damping schemes to accomplish a number of objectives. These areas, for example, include active/passive CLD treatments; active and passive self-contained magnetic dampers integrated into smart structures; dampers based on piezoceramics and shunted circuits; and MR and ER fluid dampers.

Since robust controllers are needed for practical applications, their design may include nonlinear coupling through an electronic circuit, shunted circuit, fuzzy logic, and artificial neural network approaches. It may be desirable to create new active dampers with power transfer among its various sensors and actuators realized through microwave integrated circuit antenna elements. Research should also include new modelling methods for structural damping mechanisms that are compatible with transient responses, capture physical phenomena, and fit within the structure of modern computational tools well beyond the complex modulus approach. For example, comprehensive modelling efforts are needed to model the magnetoelastic effects associated with the integration of magnetic dampers with ferrous, non-ferrous, conducting, and non-conducting structures. Attention must also be placed on the optimal design of active/passive magnetic damping treatments to determine their most advantageous size and placement with respect to weight and energy considerations.

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