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Theoretical and experimental vibration analysis of rotating beams with combined ACLD and Stressed Layer Damping treatment

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ABSTRACT

Active constrained layer damping (ACLD) treatment increases the efficiency of passive constrained layer damping (PCLD) treatment, but in case of circuit failure, only the decreased efficiency of PCLD treatment is available. The efficiency of the ordinary PCLD treatment can be enhanced by adding a stressed poly vinyl chloride (PVC) layers on the base beam instead of using viscoelastic materials. Hamilton Principle in conjunction with finite element method is used to derive the non-linear differential equations of motion for a rotating beam. Using proportional feedback controllers, the complex closed loop eigenvalue problem is developed and solved numerically. The effect of rotational speed of the beam, initial strain and other parameters of the PVC layer is investigated. To prove the effectiveness of the new technique, experimental investigations have also been carried out.

1. Introduction and problem formulation

Researchers have been intensifying over the past two decades regarding active vibration control methods for structures using smart materials. The potential and suitability of using smart composite structures for active suppression of vibration in aerospace industry is a widely investigated topic of research. Due to limited efficiency of purely active control techniques, research is directed towards the combination of active and passive techniques. PCLD is an old technique to suppress vibrations. In combination with active control techniques, PCLD treatment can be made even more effective. This technique is called ACLD treatment. Present work is based on the development of newer passive techniques, which can enhance the damping performance of PCLD and ACLD systems. First of all the brief history of PCLD and ACLD treatment will be discussed.

Swallow [1], first introduced the concept of structural vibration reduction with constrained layer damping treatment. A large amount of work has been published since late 1950s on the vibration damping of three layer plates and beams. Kervin [2] presented the first analysis of the problem. Ross [3] outlined the dominant design parameters on which effectiveness of the treatment is dependant. Di Taranto [4] and Mead and Markus [5] extended Ross's analysis to beams with general boundary conditions in which sinusoidal spacial dependence cannot be assumed. In their analysis sixth – order equations of motion were developed. Yan and Dowel [6] developed an analysis including longitudinal and rotary inertia in all the layers. Mead [7] compared the results using Euler–Bernoulli and Timoshenko beam theory, that the former theory yields adequate results for most of the practical applications. However, in beams made of composite materials, better predictions can be made using the later theory. Further, Huang et al. [8] noticed that these theories of layer damping treatment are not suitable for predicting the results of practical designs of thin layer damping treatment because an extremely thin layer of viscoelastic material (VEM) layer would predict the modal parameters varying highly from the experimental results.

Due to constraints of cost, full length VEM layer is not preferable. Partial treatments with certain length of VEM layers or multiple patches of small length are more beneficial. Energy methods are quite suitable and give best results regardless of the thickness of VEM layer. Modeling by these methods eliminates the need of analysis of complex force and moment equations. Hence, this method can be used to analyze more complex systems, as is done in this direction by Kung and Singh [9], Fasana and Marchesiello [10] and Gao and Shen [11].

ACLD treatment has been explored to improve the damping ability of PCLD treatment by Baz and Ro [12], Azvine et al. [13], Shen [14], Liao and Wang [15]. As mentioned above, a typical ACLD treatment generally consists of a piece of passive VEM layer sandwiched between an active piezoelectric layer and the base structure. With a proper control, the shear deformation of VEM can be increased and thus the energy dissipation can be enhanced by the active action of piezoelectric cover sheet. Gao and Liao [16]

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recently proposed an analytical method for enhanced ACLD (EACLD) treatment. Hamilton principle and Rayleigh–Ritz method was employed in their analysis. Oh et al. [17] developed the vibration control of beams using electro-magnetic compressional damping treatment given due consideration to shear as well as compressional energy.

Several other researchers provided some useful ways to increase the efficiency of PCLD treatment. Whittier [18] proposed that the shear angle of the VEM layer could further be increased using a stand-off-layer (SOL) or spacer layer to the PCLD treatment between the vibrating structure and the constraining layer. This SOL layer moves the VEM layer and constraining layer farther from the neutral axis of the vibrating structure. This displacement caused by SOL layer magnifies the shear strain in the VEM layer and results in energy dissipation. If the SOL layer possesses internal damping properties, the overall damping of the treatment would increase dramatically. This concept works practically and was reported by Falugi [19,20] and Parin et al. [21]. Rogers and Parin [22] demonstrated experimentally that these treatments provide significant damping in aeronautical structures.

Recently an experimental study supported by analytical model is presented by Yellin Jessica et al. [23]. The vibration of rotating beams or structures without ACLD treatment was studied extensively by various researchers as Kwak [24], Yoo and Shin [25], Khulief [26] and Mierovitch [27]. Modal analysis for gyroscopic system is complex but the complex eigenvalue problem can be transformed into real one by using the method in the study done by Zhang et al. [28]. By including the damping, the system becomes a damped gyroscopic system.

Song et al. [29] researched the vibrations of rotating blades modeled as anisotropic thin walled beams containing piezoelectric materials by proportional and velocity control law. Chandirammani et al. [30] worked on the optimal vibration control of a rotating composite beam with distributed piezoelectric sensing and actuation. Recently, Choi and Han [31] enhanced the damping performance of rotating composite thin walled beams using Macro Fiber Composite (MFC) actuators and polyvinylene Di fluoride (PVDF) sensors.

ACLD treatment is quite effective. However, only PCLD treatment is available in case of circuit failure. There is a need to develop effective methods for enhancing the effectiveness of PCLD treatment so that even in the presence of circuit failure rich damping is available to the system. Application of hybrid constraining layer is useful in this situation. However, certain researchers were not fully satisfied with the performance of PCLD treatment and tried to develop other types of damping treatments. Only recently, in this direction, Mostafa and Hany [32] proposed a new technique for passive vibration control problems. They emphasized that by applying **Pre-tensed** PVC Layers on both the sides of the base beam, the damping performance of the overall system can be improved.

PVC layer has certain value of loss factors which can enhance the energy losses of the overall system in the form of damping. This treatment can be named as stressed layer damping as the PVC layer attached was always under stress. They experimented on a cantilever beam. The damping performance was increased for the first mode as the initial stress in PVC layers was increased. However, for the rest of modes, the damping performance was decreased initially. After certain critical value, the damping ratios of these modes were increased exponentially.

The basic limitation of this treatment was that it can be applied to thin walled structures only. For thick structures, more and more value of initial stress was required. This could be possible at high values of initial strain in PVC layers. Maximum strain up to 1% was tolerable in these materials due to creep limitations. Although the first and second modal damping was enhanced by several times with this technique, the damping ratios of higher modes were very less as compared to ordinary PCLD treatment. This limitation was removed in the present work by combining the Stressed Layer Damping (SLD) with PCLD and ACLD treatment. The first mode damping ratio was slightly decreased with the application of constraining layers but the damping ratio of all other modes improved dramatically. Present paper investigates the vibration behavior and control of axial deformation and chordwise bending of a clamped – free rotating flexible beam with partially covered ACLD treatment with **stressed PVC layers** instead of Visco-elastic Material (VEM) layers. Since the beam taken is rotating in horizontal plane, gravitational effect and rotary inertia are neglected. The stress strain relationship for the PVC layer is described by complex modulus. Hamilton principle in conjunction with Finite Element Method (FEM) is used to derive the equation of motion. The effect of centrifugal stiffening due to rotation is also considered. Proportional feedback controller is designed for piezo-sensor and actuator. The closed loop equation of motion for the system is derived and complex eigenvalue problem is solved numerically. The effects of different rotating speeds, thickness of PVC layer, and loss factor of PVC layers, initial compressive and tensile strain in PVC layers are studied. The effect of each parameter on the damping ratios and damped natural frequencies is investigated. The study will be useful for rotating structures like rotorcraft blades, helicopter wings and robotic systems.

The main contribution of the present work is divided into following parts: (1) A Finite Element Method is employed in the present work, so that partial treatment can be accommodated easily for SLD techniques which is not easily possible for analytical methods, (2) Effect of initial strain in PVC layers attached to base beam is investigated with combination of PCLD and ACLD treatment which is never considered earlier in literature, (3) Normally, active control increases efficiency of the PCLD system, but it has been investigated that only by using passive techniques (i.e. SLD treatment) similar increase in efficiency of PCLD system can be made. However, active constrained layer further enhances the damping performance of the overall system. (4) In the paper by Mostafa (2006), the pre-tensed PVC layers which cause tensile stress in PVC layers are used, here pre-tensing of base beam which causes compressive stresses in PVC layers is also analyzed which has certain desirable properties w.r.t. the former technique.

2. System description and finite element modeling

2.1. Basic Relationships

The schematic of the rotating beam with ACLD treatment combined with SLD treatment is shown in Fig. 1. The upper and lower surface of host structure or the base beam is attached with a PVC layer. Each of the PVC layer in turn is constrained by an active piezoelectric material PZT (Lead Zirconiated Titnate). It acts as a constraining layer, a sensor and an actuator. For simplicity, the constrained layer (i.e. PZT patch on one side) is numbered as 1, PVC layer as No. 2, the base beam as No. 3 and sensor layer (i.e. PZT patch on the opposite side of the base beam) as No. 4. Fig. 2 shows the cross-section of the beam with ACLD treatment combined with SLD treatment. The following assumptions are made in deriving the model:

1. Face-layers i.e. constraining layers and base beam are purely elastic and suffer no shear deformation normal to the layer faces.
2. Inertial effects of transverse flexural motion are dominant while in plane inertia effects are negligible i.e. Rotary and axial inertia are negligible.
3. Longitudinal displacement u is different for all the layers.
4. Transverse displacement w is same for all the layers.