Vibration Attenuation in Thin Laminated Cylindrical Composite Shells using Active and Passive Constrained Layered Damping Treatment: A Review

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Abstract

This review article presents a systematic study of the selected past literature dealing with the Passive Controlled Layered Damping (PCLD) and Active Controlled Layered Damping (ACLD) modes of vibration control of thin cylindrical composite laminated shells. The Finite Element Model (FEM) and geometric modeling approach adopted by the selected authors has been briefly described along with the considered boundary conditions for the layered damping system. The effectiveness of the different models generated by the authors has been shown by comparing the results obtained from the models and those obtained from the analytical methods of previous researches. Overall observations and findings from the selected literature review have been further elucidated in the end of the article.

Keywords: Vibration control, Thin cylindrical shell, ACLD treatment, PCLD treatment, Frequency response function.

Introduction

Cylindrical shell shaped geometry has numerous applications in terms of mechanical structure fabrication in different industrial sectors like automotive applications, power generation, aerospace applications, mineral handling and many others. These entire industrial sectors typically operate under an environment full of noise and disturbance. Henceforth, these cylindrical shell shaped structures are more or less always subjected to external disturbing forces which create an unnecessary vibration in such structures.

Vibration Control is the branch of science which deals with the attempts to damp out the imposed vibrations on a mechanical system. In context of vibration control, Constrained Layer Damping (CLD) treatment has been an effective method for restraining the ill consequences of vibration and noise in civil and mechanical structures. Constrained Layer Damping (CLD) treatment has been categorized mainly into Passive Constrained Layered (PCLD) Treatment and Active Constrained Layered (ACLD) Treatment.

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In Passive Constrained Layered (PCLD) Treatment, the viscoelastic polymer which exhibits high material loss factor provides the major damping mechanism in vibrations due to its extensional and in-extensional deformation. The high damping capacities of passive constrained damped structures are mostly due to shear deformation of viscoelastic materials. Active Constrained Layered (ACLD) Treatment is a further enhancement of the PCLD treatment. ACLD is achieved by either replacing or augmenting the constraining layer with an active element, usually a piezoceramic or a piezoelectric layer. The ACLD treatment consists of a conventional passive constrained layer damping which is augmented with efficient active control means to control the strain of the constraining layer in response to the shell vibrations. The shear deformation of the viscoelastic damping layer is controlled by an active piezoelectric constraining layer which is energized by a control voltage. In this manner, the ACLD when bonded to the structure acts as a smart constraining layer damping treatment with built-in actuation capabilities. With appropriate strain control, through proper manipulation of control voltage, one or more of the structural modes of vibration can be targeted and damped out. The flexural vibration control by the constrained layer damping treatment is attributed to the dissipation of energy in the viscoelastic core undergoing transverse shear deformation. As the constraining layer of the ACLD treatment increases the passive transverse shear deformation of the viscoelastic constrained layer, the ACLD treatment improves the overall damping characteristics of the flexible structures over its passive counterpart. Also, the ACLD treatment provides a practical means for controlling the vibration of massive structures with the currently available piezoelectric actuators without the need for excessively large actuation voltages.

In this article, a systematic review of the selected past literature dealing with the PCLD and ACLD modes of vibration control of thin cylindrical composite laminated shells has been presented. The FEM and geometric modeling approach adopted by the selected authors has been briefly described along with the considered boundary conditions for the layered damping system. The effectiveness of the different models generated by the authors has been shown by comparing the results obtained from the models and those obtained from the analytical methods of previous researches. Overall observations and findings from the selected literature review have been further elucidated in the end.

Study of Past Literature

Baz A et al. [1] had developed a distributed parameter model of thin cylindrical shells treated with active constrained layered damping using Hamilton's principle to describe the axi-symmetric vibrations in shells. The main assumptions in the model included negligible shear strain in the piezoelectric layer and in the base shell. Also, the longitudinal and tangential stresses in the viscoelastic core were assumed to be negligible. The transverse displacements of all the points on the cross-section of the sandwiched shell were considered to be equal. Lastly, it was assumed that the thickness and modulus of elasticity of the sensor are negligible compared to those of the shell. Using Donnell-Mushtari theory of cylindrical shells, the expressions for longitudinal and tangential strains were derived for the base shell, viscoelastic layer and piezoelectric layers. Also, the expressions of corresponding longitudinal and tangential stresses were obtained for different layers and by integration of the stresses over the cross-section of the layers; the expressions for the longitudinal and tangential forces were derived. By the application of a control voltage law, the expressions for the induced strain and stresses in the piezoelectric layer were developed. The expressions for total potential energy, total kinetic energy and work done on the system were derived which were further utilized in obtaining the final equation of motion using Hamilton's principle. By application of simply supported condition for the shell, a sixth order partial differential equation in the transverse deflection of the shell was obtained. A distributed parameter control strategy was devised by the authors in order to ensure that the total energy of the system should never be a strictly increasing function of time. The performance of the ACLD treatment was demonstrated using a simply support aluminum shell, an acrylic base viscoelastic material and an active polymeric piezoelectric film with suitable dimensions and parameters. The effectiveness of the boundary controller was determined by subjecting the shell to a uniformly distributed transverse sinusoidal loading on the entire span of the shell. For a unit transverse load, the resulting deflection of the shell has been defined as the 'Compliance' of the shell. Using the mechanical compliance approach, the compliance at the mid-span was calculated separately for the ACLD and PCLD treated shells and it was found that there was more effective vibration attenuation in an ACLD treated shell as compared to the PCLD treatment.

Yuh-Chun H et al. [2] had derived a general equation of motion of a 3 layer sandwich structure with a bonded viscoelastic core for vibration damping. The authors had selected Love's thin shell theory for analysis with an assumption that the viscoelastic layer undergoes pure shear only. The base shell and the constraining layer were considered to be purely isotropic and elastic. The shear modulus of the viscoelastic material was a function of frequency. On the basis of Love's theory, it was assumed that the tangential displacements for all the layers vary linearly through the thickness and to ensure a no slip condition between the layers, a proper displacement field relation in terms of orthogonal curvilinear coordinates was set up by the authors. The total strain energy, kinetic energy and potential energy of the system were calculated and using Hamilton's principle and Donnell-Mushtari analogy, total 5 generalized equations were obtained which included 4 in-plane equations and 1 transverse dynamic equation. Using these generalized mathematical formulations, the authors had then deduced the equations of motion for some commonly used geometries like cylindrical shells, rectangular plates and beams. The frequency response function and vibration attenuation effect were further calculated by the authors for each of the geometries considering suitable boundary conditions. It was found by the authors through numerical examples of the model that there was a significant reduction in vibration levels by the incorporation of the viscoelastic layer.

Ray MC et al. [3] had analyzed the effectiveness of ACLD treatments in thin cylindrical shells. An FEM model was formulated based on FSDT that described the interactions between the shells and ACLD treatments. The displacement fields, i.e., the longitudinal and circumferential deformations of any point on the shell-ACLD system were represented by FSDT. The strain-displacement relations for translational and rotational strains were utilized for formulating the overall strain vector and finally the stress vector for the piezoelectric and viscoelastic layer layers separately. An eight-noded 2D isoparametric element was used for FEM analysis of the system. The total strain energy and kinetic energy of the element was then calculated. Preliminary equations of motions were formulated using Hamilton's variational principle and by application of suitable boundary conditions. A control law between the control voltage and mid-point displacement of free width of the ACLD patches was finally introduced into the set of formerly obtained equations of motion. The results of FEM model were first verified with those mentioned in a reference paper for untreated shells. Finally, the results of FEM model and physical experimentation were verified foe a complete shell-ACLD system. There was a good agreement in the results from different approaches considered.

Saravanan C et al. [4] had further studied the active constrained layered damping in cylindrical shells of revolution using a semi-analytical finite element method for analysis in order to enhance computational efficiency. For the formulation of the finite element model, the authors had selected a multilayered, isoparametric shell element with a variation of displacement field. The base shell was assumed to be comprised of several layers with the piezoelectric sensor either pasted on the surface of the base shell or sandwiched between the layers of the base shell. The viscoelastic layer was bonded on one of the surfaces of the base shell. The piezoelectric layer was then pasted over the viscoelastic layer. With reference to the middle layer of the base shell, the 3-dimensional displacement relations were formulated by the authors. Using certain linear interpolation functions, a layer wise theory was considered by the authors for the piezoelectric potential. By relating the electromechanical coupling coefficients and stiffness coefficients, the constitutive equations were obtained for the piezoelectric material. The piezoelectric sensors and actuators were assumed to be distributed circumferentially on the base shell. The expressions for the total kinetic energy and total potential energy of the system were derived and finally, by the application of Hamilton's variational principle, the equation of motion for the system was obtained. For the active vibration control, a negative velocity feedback type of control was considered. For analyzing the damping effect, the authors had further calculated the damping ratio of the system using the Eigen value method. In order to validate the model, the authors had compared the values of non-dimensional frequencies for the circumferential modes of vibration with those obtained from a previous research. The results were in good agreement with each other. Also, it was found by the authors that the ACLD treatment was more efficient at higher modes of vibration as compared to the PCLD treatment.

Shann-Chewn Y et al. [5] had conducted an analysis on damping the vibration of a three-layer sandwich circular plate with the aid of a viscoelastic core. The geometric model of the sandwich assembly included a base host plate, a middle layer of viscoelastic material and a top constraining layer. All the layers were assumed to be homogeneous, isotropic and elastic. Cylindrical coordinate system was selected for the purpose of analysis. On the basis of thin shell theory, the transverse shear deformations of base plate and the constraining layer were assumed to be negligible. Also, the normal stresses in the transverse direction were neglected. Using the stress-strain relations, the constitutive equations were set up for all the layers separately. With the further utilization of Love's thin shell theory, the in-plane displacement field was formulated assuming a linear variation of displacement along the thickness. Using the strain-displacement relations, the membrane strains and bending strains of the host plate and constraining layer were obtained. Also, the expressions for strains were computed for the viscoelastic core by imposing no-slip constraints between the layers. The total strain energy, total kinetic energy and the energy put into the system by the applied forces and moments resultants were formulated and the governing equations of motion for the system were generated using Hamilton's principle and the obtained equations were further simplified with the help of Donnell-Mushtari-Vlasov assumptions. In the numerical validation, the frequency response functions for the first 5 modes of vibration of the system were plotted with and without the addition of viscoelastic layer separately and it was found that the amplitude of vibration was reduced significantly by the use of viscoelastic layer. It was also concluded by the authors that the damping does not increase by increasing the thickness of the viscoelastic layer. By analysis, it was found that damping increases with an increase in the thickness ratio (Core thickness/Face thickness) initially, followed by a steady decrease and finally, an increase again.

Lin-Hung C et al. [6] had developed a mathematical model to investigate the damping effects of a constrained layered damping treatment of strip type on a thin cylindrical shell. In the geometric modeling of the problem, each CLD strip was treated as a shallow shell having a specific covering angle. The CLD strips were further assumed to be thin and homogeneous and therefore, on the basis of thin shell theory, the transverse deformations of the base shell and the constraining layer were neglected. Considering all the layers of the system to be isotropic, the corresponding stress-strain relations were then formulated. Using Love's theory, a generalized displacement field at a point in the system was set up and by the utilization of strain-displacement relations, the expressions for normal and shear strains were obtained. A set of compatibility relations between the layers were also derived by the authors. Donnell-Mushtari-Vlasov assumptions were applied to the viscoelastic layer assuming pure shear only. Further, the total strain energy and total kinetic energy expressions were derived for all the layers separately. Using the assumed mode method and Langrange's equation, the final equations of motion were obtained in terms of transverse generalized coordinates. By using a unit harmonic point load applied at a general location on the shell system and by considering a complex shear modulus for the viscoelastic material, a Frequency Response Function was calculated at the loading point. In order to validate the derived mathematical model, the authors had presented numerical example of a simply supported thin aluminum cylindrical shell. To avoid dimension dependence, the authors had defined certain dimensionless parameters such as power dissipation coefficients, width, constraining layer thickness and viscoelastic layer thickness. The Frequency Response Functions for a CLD treated shell with 3, 6 and 9 CLD strips were plotted and on comparing the results with those of the untreated shell, it was revealed that as the number of CLD strips increases, the damping capability of the system also increases. It was also observed by the authors that the damping characteristics of the system could be improved by increasing the thickness of the constraining layer. The final conclusion of the authors from the conducted research was that the damping capability improves by increasing the thickness of the viscoelastic layer but up to a certain critical thickness value of the constraining layer.

Ray MC et al. [7] had performed an analysis on the active constrained layered damping (ACLD) treatment of thin composite shells using piezoelectric fiber reinforced composite (PFRC) materials. In the finite element model generation, the authors had considered a laminated cylindrical shell comprised of a number of orthotropic layers. The top surface of the shell was integrated with the rectangular patches of ACLD treatment. The mid-plane of the substrate shell was considered as the reference plane. Separate nomenclature was given for fiber angle orientation in the substrate layer and in the active constraining layer of piezoelectric material. First Order Shear Deformation (FSDT) theory was utilized for formulating the displacement field at any point on the cross-section of the shell system. The displacement along the radial direction was assumed to be constant through the thickness of all the layers. The overall displacement variables were grouped into a translational vector and a rotational vector. Using the strain-displacement relations, the state of strain at a point in the system was represented by 2 separate vectors of in-plane strains and transverse shear strains. Considering the isotropy types for different layers, the state of stress was further computed & was grouped into normal stress vector and shear stress vector. The electric field vector, electric displacement vector and transformed piezoelectric constant matrices were also formulated for the piezoelectric layer. The material for the viscoelastic layer was assumed to be linearly viscoelastic and isotropic and was modeled by using the complex modulus approach. The expressions for the total kinetic energy and total potential energy of the shell with ACLD treatment were derived. The authors had selected an 8-noded isoparametric quadrilateral element for discretizing the shell. With the further usage of nodal shape functions, refined expressions for the kinetic and potential energies of the system were obtained. Finally, the governing equation of motion was obtained by applying the principle of virtual work. For the activation of the ACLD patches, a velocity feedback control law was employed. The validation of the finite element model was done using both cross-ply and angle-ply thin cantilevered cylindrical shells integrated with 2 patches of ACLD treatment. The natural frequencies of the shell with inactivated patches were first computed and compared with values from a previous research which showed good agreement with each other. It was further found by the authors from the frequency response functions that the active patches significantly improved the damping characteristics of the shell for the first 2 modes as compared to passive damping. Lastly, the authors had examined the vibration attenuation effect by varying the piezoelectric fiber angle.

Zheng H et al. [8] had conducted a study on an optimum design of partial PCLD treatment of cylindrical shells by using a Genetic Algorithm (GA) based penalty function method to find the optimal layout of multiple rectangular PCLD patches of fixed thickness and material properties. For the formulation of the analytical model of the problem, a composite cylindrical shell consisting of the base, viscoelastic and constraining layers was considered with simply supported ends. The authors had approximated the cylindrical shell as a thin shell and accordingly, the displacement field at a point was defined in terms of cylindrical coordinates. Using the strain-displacement relations, the strains were computed and by further utilization of Donnell-Mushtari-Vlasov assumptions, the state of stress was obtained for the base shell and constraining layer. The expressions for strains and stresses for the viscoelastic layer were also formulated using Love's theory and an assumption of no slip between the layers. The expressions for total kinetic energy and strain energy of the system were then derived. By assuming a transverse harmonic load applied on the shell's surface, the work done by the force was computed. The dynamic response of the PCLD treated cylindrical shell was calculated by employing Langrange's equation. For the purpose of PCLD layout optimization, the authors had defined a quantity called 'Structural Volume Displacement' (SVD) which was the integration of the displacement over the shell surface. The SVD function was selected as the objective function for employing the Genetic Algorithm (GA). Four design variables namely, axial length, axial location, angular length and angular location were assigned to the system. The total amount of PCLD material was fixed in each computational run for layout optimization. To implement the Genetic Algorithm (GA), four different approaches were used to restrict the number of design variables. For the validation of the derived mathematical model, the frequency responses at the force location of a PCLD treated cylindrical shell were compared with the results obtained from a multi-physics finite element code. A good agreement in results was observed from both the approaches; the authors had further concluded that for a fixed number of PCLD patches and PCLD material, there were 2 attributes for an optimal layout. Firstly, the patches tend to increase their coverage in the axial direction and secondly, the patches tend to distribute over the shell's surface. Other findings from the research were that for a larger axial length to angular length ratio of the patches, a better damping tendency was observed. Also, the vibration attenuation capability of the system could be improved by increasing the amount of the PCLD material.

Ray MC [9] had further extended his study on active constrained layered damping in laminated thin cylindrical panels using piezoelectric fiber reinforced composite (PFRC) material. Referring to the research work done in [7], the author had done a subsequent numerical analysis on anti-symmetric cross-ply and angle-ply thin cylindrical simply supported panels with an integration of 2 rectangular ACLD patches. It was found by the author from the frequency response functions that ACLD treatment enhances the vibration damping capability of the system as compared to passive treatment. The author had also investigated the effect of variation of shallowness angle of the panel on the performance of the ACLD treatment. Based on previous researches, the value of the shallowness angle for the panel was kept limited to 30^o. By imposing this constraint, it was revealed by analysis that as the value of the shallowness angle increases, the vibration attenuation tendency of the ACLD treatment also increases. Finally, the author had concluded that for both anti-symmetric cross-ply and angle-ply conditions, the performance of the ACLD treatment was marginally affected by increasing the number of layers in the orthotropic substrate panel while maintaining a constant thickness of the panel.

Sainsbury MG et al. [10] had performed an analysis on passive constrained layer viscoelastic damping on a cylindrical shell shaped mechanical structures using a partial structure coverage analogy. The authors had considered the weight of the PCLD treatment as a design constraint. Finite Element analysis had been deployed for computational analysis of the shell with the shell structure discretized into a mesh of 4-noded rectangular curved shell element. Similar element configuration was used to model the layer of viscoelastic material. The reference coordinate system was chosen along the mid surface of the shell. Displacement variables considered were in the axial direction (x), circumferential direction (θ) and radial direction (z). A suitable polynomial displacement function was established for relating the displacement 'z' as a function of 'x' and 'θ' which gave 80 independent coefficients or 80 degrees of freedoms. A generalized displacement field at any point was calculated using FSDT. Using the strain-displacement relations for a cylindrical shell, the strains were calculated for the shell. Considering an isotropic material for the shell, the corresponding stresses were then calculated using stress-strain relations. The total strain energy and kinetic energy of the system was then calculated considering the contributions from the viscoelastic layer and the constraining layer. The obtained expressions were used to formulate the elemental stiffness and mass matrices and then after, the equation of motion was derived using Langrange's equation. Clamped free and simply supported boundary conditions were considered for calculations. For the validation of results, a convergence test was carried out by refining the mesh size and studying its effect on the natural frequencies for the first 4 modes of vibration. These values were compared with 3 reference values and the results were in good agreement. A physical experiment was done by performing a stepped-sine frequency response test on a thin cylindrical tube using an electro-dynamic shaker. The obtained results were compared with the analytical results and were in good agreement. For the effective weight of the damping treatment, a strain energy intensity map was obtained for the first 5 target modes of vibration. Finally, the damping effect was examined by treating the regions of high strain energy distribution in the shell.

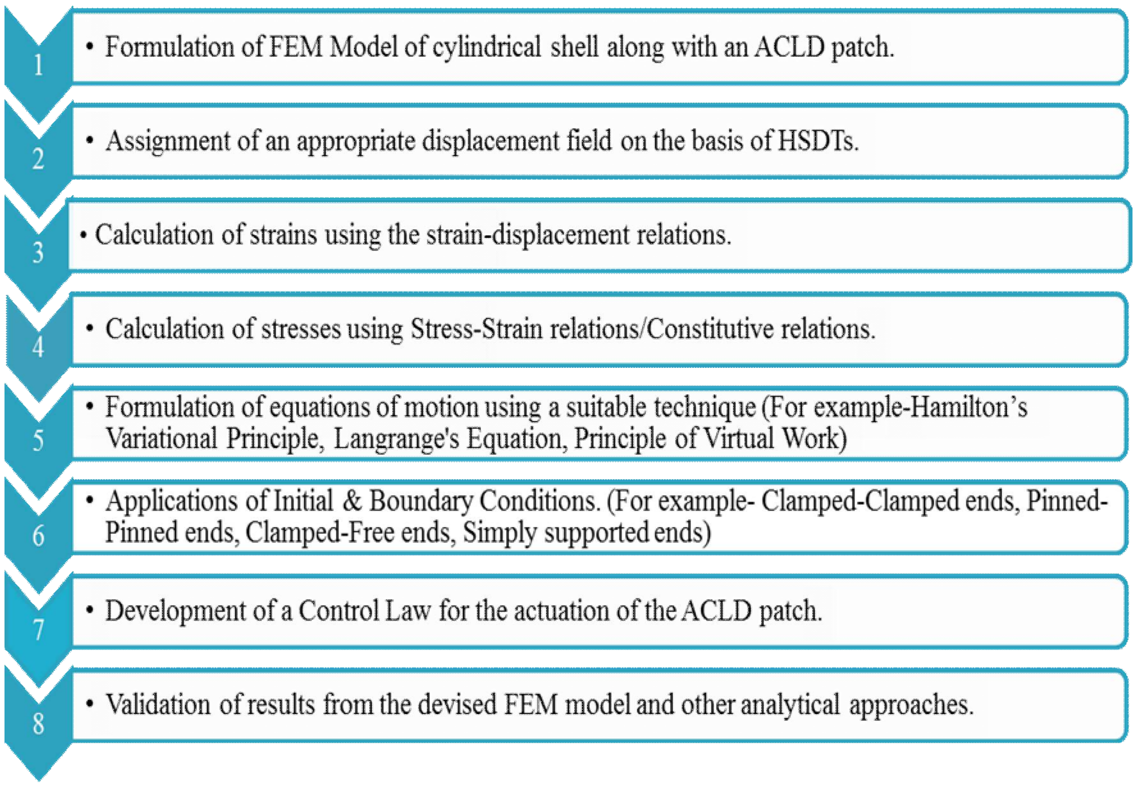
Ray MC et al. [11] had further investigated the performance of the ACLD treatment for vibration control and additionally, an active acoustic control of sound radiated by vibrating elastic thin cylindrical laminated composite panels backed by an acoustic cavity. The authors had formulated a finite element model of the coupled structural-acoustic behavior of the laminated cylindrical composite panels integrated with the patches of ACLD treatment. In the geometric modeling, a thin and shallow laminated cylindrical panel comprising of a number of orthotropic layers was considered and was backed by a rectangular parallelepiped cavity. The layers of the base panel were assumed to be homogeneous, orthotropic and linearly elastic with a perfect bonding. The subsequent finite element modeling was done using the finite element approach used in [7] with the difference being the utilization of 9-noded elements in place of 8 noded elements for better accuracy. For the formulation of the finite element model of the acoustic fluid, it was assumed that the fluid in the enclosed cavity was compressible. Using the 3-dimensional wave equation known as 'Helmholtz Equation' for governing the acoustic behavior of the cavity, a set of acoustic elemental equations was obtained. The global sets of equation for structural control and acoustic control were combined together to yield the open loop governing equations of coupled panel-cavity system. The closed loop control of the system was modeled by using a negative velocity constant gain feedback law and a pressure rate feedback law. The numerical validation of the structural finite element model was done by considering both cross-ply and angle-ply thin cylindrical simply supported panels with 2 integrated patches of ACLD treatment. The values of the natural frequencies for the untreated and treated panels were computed separately and compared with those obtained from previous researches and they were found to be in excellent agreement with each other. It was revealed that the ACLD treatment was superior in vibration damping as compared to the PCLD treatment. To verify the acoustic finite element model, the natural frequencies of the cavity were computed and compared with the values calculated analytically from previous researches and also with those computed by ANSYS 8.0 software. There was a good matching in results achieved from both the approaches. By analyzing the system for coupled structural-acoustic behavior, it was revealed that for the reduction of sound levels in the cavity, the control voltage law was not suitable and instead, the pressure rate feedback law should be implemented in such cases. Finally, the authors had found that the orientation of fibers in the constraining layer of PFRC material also plays an important role in the vibration attenuation capability of the system.

Kumar N et al. [12] had presented the design of partial constrained layered damping treatment of a curved panel using the concept of modal strain energy distribution to find out the optimum layout of the constrained layer patches. For formulating the finite element model of the curved panel assembly, the authors had utilized an 8-noded serendipity element with 5 degrees of freedom associated with each node. Each node had 3 translational and 2 rotational degrees of freedom. Natural coordinate system was used to represent the elemental geometry. The reference coordinate system was selected on the middle surface of the base curved panel which included the axial (x), circumferential (θ) and radial (z) displacement coordinates. The axial, circumferential and radial deformations at any point on the system were defined by 'u', 'v' and 'w' respectively. Using these parameters, the total displacement field at a point was formulated and with the further utilization of Donnell's approximation method, the normal and shear strain expressions were derived. Considering an isotropic geometry for the base curved panel, the strain expressions were used to obtain the corresponding stress equations. The total strain energy, kinetic energy and potential energy expressions were formulated and using those expressions along with Hamilton's principle, the final equation of motion for the system was derived. For the validation of the present model, the authors had compared the values of natural frequencies for the first 4 modes of vibration with those given in 4 earlier researches. The curved panel was assumed to be clamped at both the ends and the material properties were chosen from the reference papers. There was a good agreement in results from both the current and previous approaches. For the optimal placement of the CLD patches, the expression for the modal strain energy was formulated using the Eigen vector of the untreated curved panel. Strain energy distributions for the first 4 modes of vibration were plotted and the regions of the highest values of strain energy in each mode were located. The authors had finally concluded that the CLD patches should be placed on the obtained locations for effective vibration attenuation. The authors had also conducted a physical experiment on the CLD treated assembly with a clamped-free boundary condition. The curved panel was disturbed using an impact hammer with a piezoelectric sensor fitted at its tip. Both the hammer and sensor responses were stored in the Fourier Transformation Analyzer and data acquisition unit and were further processed to get the frequency response function. In the next step, based on the modal strain energy distribution, viscoelastic layer patches of specific sizes were cut and bonded with the base panel. Both time and frequency responses were obtained for different patch configurations for the first 4 modes of vibration and finally, the authors had calculated the reduction in the corresponding vibration levels (in decibels).

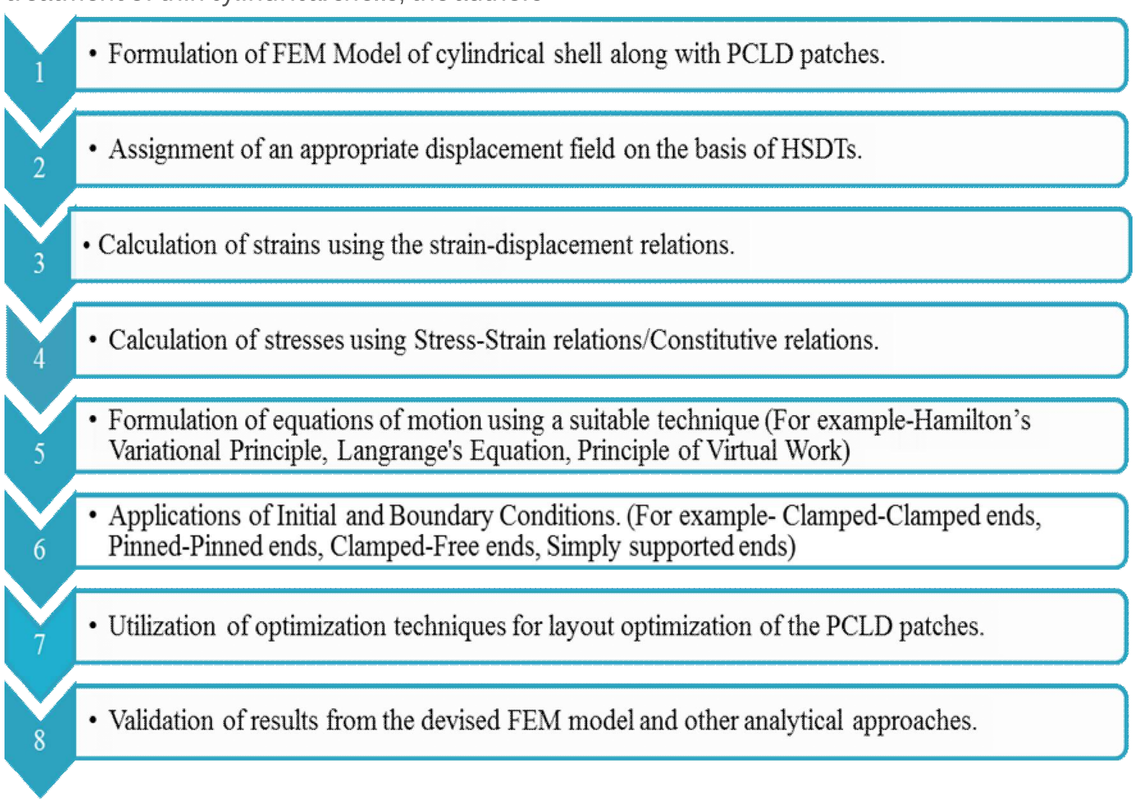
Shah PH et al. [13] had utilized the functional features of a 1-3 piezoelectric composite material to control the vibrations in a laminated truncated conical shell. The arrangement of the piezoelectric fibers was considered to be vertical and oblique for analysis. An FEM model of the truncated conical shell was developed with an integration of ACLD treatment. The ply configuration in the shell was considered to be orthotropic, homogeneous and linearly elastic with a perfect bonding between the individual plies. The mid plane of the shell was considered to be the reference frame with appropriate shell dimensions. The displacement field was based on FSDT with both rotational and translational components. The strains were calculated using Sander's strain-displacement theory for shells and corresponding stresses were then calculated. An electric field of suitable magnitude was applied along the thickness direction of the shell. The total potential and kinetic energy of the shell were calculated using the constitutive stress-strain relations and the piezoelectric coefficients. The overall shell was discretized using eight-noded isoparametric quadrilateral elements. Using the shape function approach, the strain vector was expressed in terms of global nodal displacements and was re-substituted in the expression for total potential energy. Elemental stiffness matrix, electro-elastic coupling vector, elemental load vector, Mass matrix and rigidity vector were also formulated. Equations of motion were derived using Hamilton's variational principle. A velocity feedback control law was deployed for the activation of the ACLD patches. In the numerical analysis, both ends of the shell were assumed to be clamped. Finally, the values of fundamental natural frequencies were compared from the FEM approach and analytical approach.

Findings from the Literature Review

The study of past literature reveal that the researches enveloping an active constrained layered damping (ACLD) treatment of thin cylindrical shells have some basic common steps for the problem fabrication and problem solution for vibration control. The step-wise algorithm which was utilized in researches of ACLD treatment has been shown below:



Similarly, for the purpose of implementing the passive constrained layered damping (PCLD) treatment of thin cylindrical shells, the authors had adopted an approximated algorithm which is shown below:



As seen from the literature review, most of the authors had targeted the first 5 modes of vibration of the cylindrical shell for treatment as the system behavior is critical under these 5 modes.

It was further observed from the literature review that the vibration attenuation levels in cylindrical structures could be reduced with the incorporation of viscoelastic layered damping or PCLD treatment as compared to untreated structures.

This capability of vibration damping of the system could further be improved by utilizing active constrained layered damping (ACLD) treatment over passive constrained layered damping (PCLD) treatment at higher modes of vibration.

It was also found that the amount of material used in the viscoelastic layer of the PCLD treatment and in the constraining layer of the ACLD treatment also play an important role in deciding the vibration damping characteristics of the system, though a strict increase or decrease in vibration damping tendency of the system has not been found by the variation of the amount of damping material in both techniques.

It was also revealed that for a better implementation of the conventional PCLD treatment, a patch configuration optimization could be done by employing different optimization techniques, for example, Genetic Algorithm (GA).

Results and Discussion

Baz A et al. [1] had plotted the Frequency Response Functions (FRFs) for the ACLD treated thin cylindrical shells using boundary controller, proportional controller and derivative controller separately with suitable gain values. A comparison was done between the characteristic Frequency Response curves which indicated that the devised boundary controller was more effective in damping out the vibrations of cylindrical shells and required less control voltage than the conventional P and D controllers.

Yuh-Chun H et al. [2] had developed a passive controlled layered treatment for a 3-layer sandwich cylindrical shell. The authors had also constructed the Frequency Response Function (FRF) characteristics for a PCLD treated shell and a bare shell. From the FRF characteristics, it was found that the there was a better vibration amplitude reduction in case of a CLD treated shell as compared to a bare shell.

Ray MC et al. [3] had plotted the Frequency Response Functions for a clamped-free boundary condition of a thin cylindrical shell and a significant reduction in vibration was observed when the smart ACLD actuators were actuated through control voltage.

Saravanan C et al. [4] had found that the damping ration of the system is dependent on a particular mode of vibration and had the maximum value at an optimum location of the actuating patch. Also, ACLD treatment served a better purpose at higher modes of vibration as compared to conventional PCLD treatment.

Shann-Chewn Y et al. [5] had concluded that the addition of viscoelastic material increases the damping ability of the system but also, reduces the value of the modal natural frequencies leading to system failure.

Lin-Hung C et al. [6] had also studied the effect of increasing the number of CLD strips in case of a CLD treated shell and from the FRF curves; it was found that as the number of CLD strips in the shell system was increased, the vibration

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attenuation capability of the system also increased.

Ray MC et al. [7] had investigated the performance of ACLD treated cylindrical shells with a constraining layer made up of PFRC material. The authors had further shown the Frequency Responses for a symmetric cross-ply, an anti-symmetric angle ply and an anti-symmetric cross-ply boundary conditions. It was found by the authors that as the values of the gain of the control law for each of the lamination schemes were increased, there was a significant deterioration in the vibration levels of the shell system. Further, the effect of PFRC fiber angle orientation was graphically shown by the authors which revealed that the performance of the ACLD system was highly deteriorated for the first mode of vibration when the PFRC fiber angle orientation was 45^{o}.

Zheng H et al. [8] had concluded that for a larger axial length to angular length ratio of the actuator patches, a better damping tendency was observed. Also, the vibration attenuation capability of the system could be improved by increasing the amount of the PCLD material.

Ray MC [9] had investigated the performance of ACLD treatment in a thin cylindrical simply supported shell and had concluded that the performance of the ACLD treatment was marginally affected by increasing the number of layers in the base shell.

Sainsbury MG et al. [10] had concluded that while deploying a constrained viscoelastic layered damping treatment in a shell, it is advantageous to bind the treatment over regions of high strain energy intensity, rather than applying it over the entire surface.

Ray MC et al. [11] had revealed that for the reduction of sound levels in a cylindrical cavity, the control voltage law was not suitable and instead, the pressure rate feedback law should be implemented in such cases. It was also found that the orientation of fibers in the constraining layer of PFRC material plays an important role in vibration attenuation capability of the system.

Kumar N et al. [12] had concluded that by increasing the coverage of the damping patch on the basis of modal strain energy distribution approach, an effective amount of damping for a particular mode or for a number of modes can be achieved.

Shah PH et al. [13] had concluded that for a truncated conical shell, the effectiveness of the ACLD treatment is increased by keeping the semi-cone angle of the shell as small as possible. Also, the optimum performance of the ACLD patches was obtained when the fibers in the piezoelectric layers were vertically reinforced into the matrix.

Conclusion

A number of structural engineering applications involve the utilization of thin cylindrical shell shaped geometry. These structures are often subjected to external harmonic forces thereby inducing vibrations and noise into the system. Constrained Layered Damping (CLD) treatment of shells plays a vital role in damping out these vibrations to enable a smooth functioning of the structures. Systematic literature review of selected research papers encompassing Constrained Layered Damping (CLD) techniques of shells has been done in this review article. The Finite Element Model of the selected literature has been briefly described. The effectiveness of different methodologies has been shown by comparing the obtained results with those found in previous researches. A generalized algorithm of the approach adopted by the authors of the selected literature has been further formulated. From the literature review, it has been found that the Constrained Layered Damping (CLD) treatment of shells can reduce the induced vibration attenuation levels. With the further incorporation of optimization methods, a more efficient layout of the CLD treatment could be achieved with a reduction in the area of damping treatment and also, in damping material used for treatment.

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