Vibration of Functionally Graded Cylindrical Shells under Effects Free-free and Clamped-clamped Boundary Conditions

M.R. Isvandzibaei¹,∗, A. Jahani²

Abstract—In the present work, study of the vibration of thin cylindrical shells made of a functionally gradient material (FGM) composed of stainless steel and nickel is presented. Material properties are graded in the thickness direction of the shell according to volume fraction power law distribution. The objective is to study the natural frequencies, the influence of constituent volume fractions and the effects of boundary conditions on the natural frequencies of the FG cylindrical shell. The study is carried out using third order shear deformation shell theory. Results are presented on the frequency characteristics, influence of constituent volume fractions and the effects of free-free and clamped-clamped boundary conditions.

Keywords—Vibration, FGM, Cylindrical shell, Hamilton’s principle.

I. INTRODUCTION

Cylindrical shells have found many applications in the industry. They are often used as load bearing structures for aircrafts, ships and buildings. Understanding of vibration behavior of cylindrical shells is an important aspect for the successful applications of cylindrical shells. Researches on free vibrations of cylindrical shells have been carried out extensively [1-5]. Recently, the present authors presented studies on the influence of boundary conditions on the frequencies of a multi-layered cylindrical shell [6]. In all the above works, different thin shell theories based on Love-hypothesis were used. Vibration of cylindrical shells with ring support is considered by Loy and Lam [7]. The concept of functionally graded materials (FGMs) was first introduced in 1984 by a group of materials scientists in Japan [8-9] as a means of preparing thermal barrier materials. Since then, FGMs have attracted much interest as heat-shielding materials. FGMs are made by combining different materials using power metallurgy methods [10]. They possess variations in constituent volume fractions that lead to continuous change in the composition, microstructure, porosity, etc., resulting in gradients in the mechanical and thermal properties [11-12]. Vibration study of FGM shell structures is important. In this paper a study on the vibration of FG cylindrical shells is presented. The FGMs considered are composed of stainless steel and nickel where the volume fractions follow a power-law distribution. The study is carried out based on third order shear deformation shell theory. Results are presented on the frequency characteristics, influence of constituent volume fractions and the effects of free-free boundary conditions.

II. FUNCTIONALLY GRADED MATERIALS

For the cylindrical shell made of FGM the material properties such as the modulus of elasticity $E$, Poisson ratio $ν$ and the mass density $ρ$ are assumed to be functions of the volume fraction of the constituent materials when the coordinate axis across the shell thickness is denoted by $z$ and measured from the shell’s middle plane. The functional relationships between $E, ν$ and $ρ$ with $z$ for a stainless steel and nickel FGM shell are assumed as [13].

$$E = (E_1 - E_2) \left( \frac{2Z + h}{2h} \right)^\alpha + E_2 \tag{1}$$

$$ν = (ν_1 - ν_2) \left( \frac{2Z + h}{2h} \right)^\alpha + ν_2 \tag{2}$$

$$ρ = (ρ_1 - ρ_2) \left( \frac{2Z + h}{2h} \right)^\alpha + ρ_2 \tag{3}$$

The strain-displacement relationships for a thin shell [14].

$$ε_{11} = \frac{1}{A_j(1 + \frac{α_3}{R_j})} \left[ \frac{∂U_1}{∂α_1} + \frac{U_2}{A_j} \frac{∂A_1}{∂α_2} + \frac{U_3}{A_j} \frac{∂A_1}{∂α_3} \right] \tag{4}$$

$$ε_{22} = \frac{1}{A_j(1 + \frac{α_3}{R_j})} \left[ \frac{∂U_2}{∂α_2} + \frac{U_1}{A_j} \frac{∂A_2}{∂α_1} + \frac{U_3}{A_j} \frac{∂A_2}{∂α_3} \right] \tag{5}$$

$$ε_{33} = \frac{∂U_3}{∂α_3} \tag{6}$$
used in the present study is based on the following conditions on the top and bottom faces of the laminates, which

\[
\begin{bmatrix}
\varepsilon_{12} = \frac{A_1(1 + \frac{\alpha_1}{R_2}) \phi \left( U_1 \right)}{A_2(1 + \frac{\alpha_2}{R_1})} + \frac{A_1(1 + \frac{\alpha_1}{R_2}) \phi \left( U_2 \right)}{A_2(1 + \frac{\alpha_2}{R_1})}, \\
\varepsilon_{i3} = A_2(1 + \frac{\alpha_2}{R_2}) \phi \left( U_1 \right) + \frac{1}{A_2(1 + \frac{\alpha_2}{R_2})} \phi \left( U_2 \right) \\
\varepsilon_{23} = A_2(1 + \frac{\alpha_2}{R_2}) \phi \left( U_1 \right) + \frac{1}{A_2(1 + \frac{\alpha_2}{R_2})} \phi \left( U_2 \right)
\end{bmatrix}
\]

where

\[
\begin{bmatrix}
\varepsilon_{11} = \frac{1}{A_1} \left( \phi_1 + \phi_2 \right), \\
\varepsilon_{12} = A_2 \left( \phi_1 + \phi_2 \right), \\
\varepsilon_{22} = A_2 \left( \phi_1 + \phi_2 \right), \\
\varepsilon_{13} = A_2 \left( \phi_1 + \phi_2 \right), \\
\varepsilon_{23} = A_2 \left( \phi_1 + \phi_2 \right)
\end{bmatrix}
\]

\[
\begin{bmatrix}
k_{11} = \frac{1}{A_2} \left( \phi_1 + \phi_2 \right), \\
k_{12} = A_2 \left( \phi_1 + \phi_2 \right), \\
k_{22} = A_2 \left( \phi_1 + \phi_2 \right), \\
k_{13} = A_2 \left( \phi_1 + \phi_2 \right)
\end{bmatrix}
\]

\[
\begin{bmatrix}
g_{10} = \phi_1, \\
g_{12} = \phi_1, \\
g_{22} = \phi_1, \\
g_{23} = \phi_1
\end{bmatrix}
\]

\[
\begin{bmatrix}
g_{10} = \phi_1, \\
g_{12} = \phi_1, \\
g_{22} = \phi_1, \\
g_{23} = \phi_1
\end{bmatrix}
\]

where \(A_1\) and \(A_2\) are the fundamental form parameters or Lame parameters, \(U_1\), \(U_2\) and \(U_3\) are the displacement at any point \((\alpha_1, \alpha_2, \alpha_3)\), \(R_1\) and \(R_2\) are the radius of curvature related to \(\alpha_1\), \(\alpha_2\) and \(\alpha_3\) respectively. The third-order theory of Reddy used in the present study is based on the following displacement field:

\[
\begin{bmatrix}
U_1 = u_1(\alpha_1, \alpha_2) + \alpha_1 \phi(\alpha_2, \alpha_3) + \alpha_2 \phi(\alpha_1, \alpha_3) + \alpha_3 \phi(\alpha_1, \alpha_2) \\
U_2 = u_2(\alpha_1, \alpha_2) + \alpha_1 \phi(\alpha_2, \alpha_3) + \alpha_2 \phi(\alpha_1, \alpha_3) + \alpha_3 \phi(\alpha_1, \alpha_2) \\
U_3 = u_3(\alpha_1, \alpha_2)
\end{bmatrix}
\]

These equations can be reduced by satisfying the stress-free conditions on the top and bottom faces of the laminates, which are equivalent to \(\varepsilon_{13} = \varepsilon_{23} = 0\) at \(Z = \pm \frac{h}{2}\). Thus, \(\varepsilon_{13} = \varepsilon_{23} = 0\) at \(Z = \pm \frac{h}{2}\). Thus,

\[
\begin{bmatrix}
U_1 = n_1(\alpha_1, \alpha_2) + \alpha_1 \phi(\alpha_2, \alpha_3) - C_1 \alpha_1 \phi(\alpha_2, \alpha_3) + \frac{u_1}{R_1} \phi(\alpha_2, \alpha_3) \\
U_2 = n_2(\alpha_1, \alpha_2) + \alpha_1 \phi(\alpha_2, \alpha_3) - C_1 \alpha_1 \phi(\alpha_2, \alpha_3) + \frac{u_2}{R_2} \phi(\alpha_2, \alpha_3) \\
U_3 = n_3(\alpha_1, \alpha_2)
\end{bmatrix}
\]

Where \(C_1 = \frac{4}{3b} \). Substituting Eq. (12) into nonlinear strain-displacement relation (4) - (9), it can be obtained for the third-order theory of Reddy

\[
\begin{bmatrix}
\gamma_{10} = \phi_1, \\
\gamma_{12} = \phi_1, \\
\gamma_{22} = \phi_1 \\
\gamma_{23} = \phi_1
\end{bmatrix}
\]

\[
\begin{bmatrix}
\gamma_{10} = \phi_1, \\
\gamma_{12} = \phi_1, \\
\gamma_{22} = \phi_1 \\
\gamma_{23} = \phi_1
\end{bmatrix}
\]

Where \((\epsilon^m, \gamma^m)\) are the membranes strains and \((k, k', \gamma^b, \gamma^s)\) are the bending strains, known as the curvatures.
III. FORMULATION

Consider a cylindrical shell as shown in Fig. 2, where $R$ is the radius, $L$ the length and $h$ the thickness of the shell. The reference surface is chosen to be the middle surface of the cylindrical shell where an orthogonal coordinate system $x$, $\theta$, $z$ is fixed. The displacements of the shell with reference this coordinate system are denoted by $U_1$, $U_2$ and $U_3$ in the $x$, $\theta$ and $z$ directions, respectively.

For a thin cylindrical shell, the stress-strain relationship are

$$\begin{bmatrix}
\alpha_1 & \alpha_2 & \alpha_3 \\
\beta_1 & \beta_2 & \beta_3 \\
\gamma_1 & \gamma_2 & \gamma_3
\end{bmatrix}
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3
\end{bmatrix}
= \begin{bmatrix}
\epsilon_1 \\
\epsilon_2 \\
\epsilon_3
\end{bmatrix}$$

(21)

For an isotropic cylindrical shell the reduced stiffness $Q_{ij}$ ($i$, $j=1$, 2 and 6) are defined as

$$Q_{11} = Q_{22} = \frac{E}{1-\nu^2}, \quad Q_{12} = \frac{\nu E}{1-\nu^2}$$

(22)

$$Q_{44} = Q_{55} = Q_{66} = \frac{E}{2(1+\nu)}$$

(23)

where $E$ is the Young's modulus and $\nu$ is Poisson's ratio. Defining

$$\begin{align*}
A_{ij}, B_{ij}, F_{ij}, G_{ij}, H_{ij} = & \int_{-h/2}^{h/2} Q_{ij} \begin{bmatrix}
\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6
\end{bmatrix} \, d\eta
\end{align*}$$

(24)

where $Q_{ij}$ are functions of $z$ for functionally gradient materials. Here $A_{ij}$ denote the extensional stiffness, $D_{ij}$ the bending stiffness, $B_{ij}$ the bending-extensional coupling stiffness and $E_{ij}, F_{ij}, G_{ij}, H_{ij}$ are the extensional, bending, coupling, and higher-order stiffness. For a thin cylindrical shell the force and moment results are defined as

$$\begin{bmatrix}
N_{11} \\
N_{22} \\
N_{12}
\end{bmatrix}
= \int \begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3
\end{bmatrix} \, d\alpha, \quad
\begin{bmatrix}
M_{11} \\
M_{22} \\
M_{12}
\end{bmatrix}
= \int \begin{bmatrix}
\alpha_1^3 \\
\alpha_2^3 \\
\alpha_1 \alpha_2
\end{bmatrix} \, d\alpha$$

(25)

$$\begin{bmatrix}
P_{11} \\
P_{22} \\
P_{12}
\end{bmatrix}
= \int \begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3
\end{bmatrix} \, d\alpha, \quad
\begin{bmatrix}
P_{13} \\
P_{23} \\
P_{12}
\end{bmatrix}
= \int \begin{bmatrix}
\alpha_1^3 \\
\alpha_2^3 \\
\alpha_1 \alpha_2
\end{bmatrix} \, d\alpha$$

(26)

$$\begin{bmatrix}
Q_{11} \\
Q_{22} \\
Q_{23}
\end{bmatrix}
= \int \begin{bmatrix}
\epsilon_1 \\
\epsilon_2 \\
\epsilon_3
\end{bmatrix} \, d\alpha, \quad
\begin{bmatrix}
Q_{13} \\
Q_{23} \\
Q_{23}
\end{bmatrix}
= \int \begin{bmatrix}
\alpha_1^3 \\
\alpha_2^3 \\
\alpha_1 \alpha_2
\end{bmatrix} \, d\alpha$$

(27)

IV. THE EQUATIONS OF MOTION FOR VIBRATION OF A GENERIC SHELL

The equations of motion for vibration of a generic shell can be derived by using Hamilton's principle which is described by

$$\delta \int_{t_1}^{t_2} \pi (\pi - K) \, dt = 0 \quad \Rightarrow \quad \Pi = U - V$$

(28)

Where $K, \Pi, U$ and $V$ are the total kinetic, potential, strain and loading energies, $t_1$ and $t_2$ are arbitrary time. The kinetic, strain and loading energies of a cylindrical shell can be written as:

$$K = \frac{1}{2} \int \int \rho (U_1^2 + U_2^2 + U_3^2) \, dV$$

(29)

$$U = \int \int \left[ \sigma_{11} \epsilon_{11} + \sigma_{22} \epsilon_{22} + \sigma_{33} \epsilon_{33} + 2 \sigma_{12} \epsilon_{12} + \sigma_{13} \epsilon_{13} + \sigma_{23} \epsilon_{23} \right] \, dV$$

(30)

$$V = \int \int (q, \delta U_1 + q, \delta U_2 + q, \delta U_3) A_{ij} \, dx \, dz$$

(31)

The infinitesimal volume is given by

$$dV = A_{ij} \, dx \, dz \, \alpha x_4 \, dx_4$$

(32)

with the use of Eqs. (11)-(20) and substituting into Eq. (28), we get the equations of motions a generic shell.

$$\begin{align*}
\frac{\partial (N_{ij})}{\partial \alpha_4} + \frac{\partial (N_{ij})}{\partial \alpha_4} &= \frac{\partial (N_{ij})}{\partial \alpha_4} A_{44} - \frac{\partial (P_{ij} A_{44})}{\partial \alpha_4} R \frac{\partial (P_{ij} A_{44})}{\partial \alpha_4} R \frac{\partial (P_{ij} A_{44})}{\partial \alpha_4} R \frac{\partial (P_{ij} A_{44})}{\partial \alpha_4} R \\
\frac{\partial (P_{ij} A_{44})}{\partial \alpha_4} &= \frac{1}{R} X R A_{ij} C_{ij} A_{44} C_{ij} A_{44} - \frac{\partial (\tilde{\alpha} t_0)}{\partial \alpha_4} + \frac{\partial (\tilde{\alpha} t_0)}{\partial \alpha_4} + \frac{\partial (\tilde{\alpha} t_0)}{\partial \alpha_4} + \frac{\partial (\tilde{\alpha} t_0)}{\partial \alpha_4} + \frac{\partial (\tilde{\alpha} t_0)}{\partial \alpha_4} + \frac{\partial (\tilde{\alpha} t_0)}{\partial \alpha_4}
\end{align*}$$

(33)
\[
\frac{\partial (N_{x,A})}{\partial x} - N_{x,A} \frac{\partial(N_{x,A})}{\partial x} + \frac{\partial (N_{y,A})}{\partial y} - N_{y,A} \frac{\partial(N_{y,A})}{\partial y} + \frac{\partial (N_{z,A})}{\partial z} - N_{z,A} \frac{\partial(N_{z,A})}{\partial z} + \frac{\partial (P_{x,A})}{\partial x} - P_{x,A} \frac{\partial(P_{x,A})}{\partial x} + \frac{\partial (P_{y,A})}{\partial y} - P_{y,A} \frac{\partial(P_{y,A})}{\partial y} + \frac{\partial (P_{z,A})}{\partial z} - P_{z,A} \frac{\partial(P_{z,A})}{\partial z} \]

\[
\frac{\partial (N_{x,A})}{\partial x} - N_{x,A} \frac{\partial(N_{x,A})}{\partial x} + \frac{\partial (N_{y,A})}{\partial y} - N_{y,A} \frac{\partial(N_{y,A})}{\partial y} + \frac{\partial (N_{z,A})}{\partial z} - N_{z,A} \frac{\partial(N_{z,A})}{\partial z} + \frac{\partial (P_{x,A})}{\partial x} - P_{x,A} \frac{\partial(P_{x,A})}{\partial x} + \frac{\partial (P_{y,A})}{\partial y} - P_{y,A} \frac{\partial(P_{y,A})}{\partial y} + \frac{\partial (P_{z,A})}{\partial z} - P_{z,A} \frac{\partial(P_{z,A})}{\partial z} \]

\[
\frac{\partial (N_{x,A})}{\partial x} - N_{x,A} \frac{\partial(N_{x,A})}{\partial x} + \frac{\partial (N_{y,A})}{\partial y} - N_{y,A} \frac{\partial(N_{y,A})}{\partial y} + \frac{\partial (N_{z,A})}{\partial z} - N_{z,A} \frac{\partial(N_{z,A})}{\partial z} + \frac{\partial (P_{x,A})}{\partial x} - P_{x,A} \frac{\partial(P_{x,A})}{\partial x} + \frac{\partial (P_{y,A})}{\partial y} - P_{y,A} \frac{\partial(P_{y,A})}{\partial y} + \frac{\partial (P_{z,A})}{\partial z} - P_{z,A} \frac{\partial(P_{z,A})}{\partial z} \]

(34) \[ a \frac{\partial N_{1x}}{\partial x} + \frac{\partial N_{12}}{\partial \theta} = I_0 \tilde{u}_1 + \left( I_1 - C_1 L_1 \right) \tilde{u}_2 \]
The geometric boundary conditions for free boundary conditions can be expressed mathematically in terms of $\phi(x)$ as:

Clamped boundary condition

$$\phi(x) = \phi'(x) = 0$$  \hspace{1cm} (47)

Free boundary condition

$$\phi''(0) = \phi''(L) = 0$$  \hspace{1cm} (48)

Substituting Eq. (45) into Eqs. (40) - (44) for third order theory we can be expressed

$$\det (C_{ij} - M_{ij} \omega^2) = 0$$  \hspace{1cm} (49)

Expanding this determinant, a polynomial in even powers of $\omega$ is obtained

$$\beta_0 \omega^{10} + \beta_1 \omega^8 + \beta_2 \omega^6 + \beta_3 \omega^4 + \beta_4 \omega^2 + \beta_5 = 0$$  \hspace{1cm} (50)

where $\beta_i (i = 0,1,2,3,4,5)$ are some constants. Eq. (50) is solved five positive and five negative roots are obtained. The five positive roots obtained are the natural angular frequencies of the cylindrical shell based third-order theory. The smallest of the five roots is the natural angular frequency studied in the present study. The FGM cylindrical shell is composed of Nickel at its inner surface and Stainless steel at its outer surface. The material properties for stainless steel and nickel, calculated at $T = 300K$, are presented in Table 1.

### Table 1: Properties of Materials

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Stainless Steel</th>
<th>Nickel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_0$</td>
<td>$201.04 \times 10^9$</td>
<td>0.3262</td>
</tr>
<tr>
<td>$P_{-1}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$P_1$</td>
<td>$3.079 \times 10^4$</td>
<td>-2.002$ \times 10^4$</td>
</tr>
<tr>
<td>$P_2$</td>
<td>$-6.534 \times 10^7$</td>
<td>$3.797 \times 10^7$</td>
</tr>
<tr>
<td>$P_3$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$2.0778 \times 10^{11}$</td>
<td>0.317756</td>
</tr>
</tbody>
</table>

Where $P_0, P_{-1}, P_1, P_2$ and $P_3$ are the coefficients of temperature $T(K)$ expressed in Kelvin and are unique to the constituent materials. The material properties $P$ of FGMs are a function of the material properties and volume fractions of the constituent material.

### VI. RESULTS AND DISCUSSION

In this paper, studies are presented for vibration of FG cylindrical shell. The boundary conditions, free-free (F-F) is considered in the study. Natural frequencies of the FG cylindrical shell for this boundary conditions is computed and plotted in Fig. 3. For this boundary conditions the frequency first decreases and then increases as the circumferential wave number $n$ increases.

![Fig. 3 Natural frequencies FG cylindrical shell associated with F-F boundary conditions. (m=1, h/R=0.002, L/R=20)](image)

For simplicity, we actually vary the value of power law exponent whenever we need to change the volume fraction. Varying the value of power law exponent $N$ of the FG cylindrical shell, natural frequencies are computed for simply supported-simply supported boundary conditions. Results are also computed for pure stainless steel and pure nickel shells. All these results are plotted in Fig. 5.
Fig. 5 Natural frequencies FG cylindrical shell associated with various power law exponent for F-F boundary condition.

VII. CONCLUSIONS

A study on the free vibration of functionally graded (FG) cylindrical shell composed of stainless steel and nickel has been presented. Material properties are graded in the thickness direction of the shell according to volume fraction power law distribution. The study is carried out using third order shear deformation shell theory. The analysis is carried out using Hamilton’s principle. Studies are carried out for cylindrical shells with free-free (F-F) boundary conditions. The study showed that in this boundary conditions the frequency first decreases and then increases as the circumferential wave number \( n \) increases. The minimum frequency occurs in between \( n \) equals 2 and 3 for this boundary conditions. The results showed that one could easily vary the natural frequency of the FG cylindrical shell by varying the volume fraction.

REFERENCES


