

VIBRATION OF SKEW PLATE HAVING EXPONENTIAL VARIATION IN YOUNG'S MODULUS AND DENSITY

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ABSTRACT: Computation of time period of first four modes of vibration of non-homogeneous, clamped and simply supported skew plate, with variable thickness has been presented, using Rayleigh-Ritz method, on CCCC and SSSS boundary conditions, on different variation of parameters. The thickness variation is assumed to be bi-linear. Non-homogeneity arises in the material because of exponential variation in Young's modulus and density. All the results are presented with the help of figures. A comparative analysis of frequency modes of parallelogram and square plate is also presented with the help of tables.

KEY WORDS: density, exponential variation, natural vibration, skew plate, time period, Young's modulus.

SYMBOLS USED

a, b	: length and breadth of plate
ζ, ψ	: plate's coordinate
E	: Young's modulus
D_1	: flexural rigidity
$\Phi(\zeta, \psi)$	: deflection function
ρ	: mass density per unit volume of the plate material
l	: plate's thickness
μ_1	: non-homogeneity parameter due to exponential variation in Young's modulus
μ_2	: non-homogeneity parameter due to exponential variation in density
α_1, α_2	: tapering parameters
λ	: frequency parameter
ν	: Poisson's ratio
ω	: natural frequency
θ	: skew angle
CCCC	: all edges of plate are clamped
SSSS	: all edges of plate are simply supported

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1 INTRODUCTION

In order to design accurate structures or have to know about the system characteristics in better way, it is very much essential to know the vibration characteristics of plate because almost all sciences and engineering applications/structures are made from plates. The dynamic behavior of the plate depends on the plate parameters like tapering, non-homogeneity and temperature. In order to optimize the vibration or to get required frequency of vibration, we have to control or choose appropriate variations in the plate parameters.

An analysis of frequency of non-uniform plate having variation in non-homogeneity has been presented [1] to analyze the temperature effect, tapering and skew angle on time period of first two modes of vibrations. Analysis of vibration of thin isotropic skew plate on simply supported edge condition has been presented [2] based on the variational principle and obtained frequencies and mode shapes. Semi analytical method has been developed [3] to analyze the vibration effect, on thin orthotropic skew plates, and effect of the skew angle, aspect ratio, and the prescribed boundary conditions are calculated. The skew and fiber orientation angle effect [4] has been analyzed on natural frequencies and mode shapes of symmetrically laminated skew plate on clamped boundary condition using, Green function. The free vibration skewed plates with various boundary conditions, using the Rayleigh-Ritz method [5] has been studied to showed the effects of skew angles and aspect ratio of plates. Rayleigh-Ritz method [6] has been used to calculate the frequency of skew plate, on various boundary conditions. Effect of circular variation in thickness and exponential variation in Poisson's ratio on frequencies of rectangle plate [7] has been computed under temperature field using Rayleigh-Ritz method.

Variational Ritz method [8] has been applied to study the vibration of skew plates with different edge conditions and natural frequencies and modes of vibration have been obtained for different combinations of side ratio and skew angle. Natural frequency of tapered skew plate (non-homogeneous) [9] with temperature variation has been presented using Rayleigh-Ritz technique on clamped boundary condition and first two modes of vibration on different variation of plate parameters has been obtained. The circular variation [10] linear variation [11] in density, on frequency of non-homogeneous clamped square plate with variable thickness and temperature effect has been investigated using Rayleigh-Ritz method. Transverse vibration of a rectangle or a skew plate has been investigated, by employing boundary characteristic orthogonal polynomials [12] on Rayleigh-Ritz method, on different boundary conditions with different skew angles, and first five frequencies has been obtained. Transverse vibrations of non-uniform parallelogram plate has been discussed using Rayleigh-Ritz method on various boundary conditions and using successive approx-

imations [13] has been obtained first three frequencies and mode shapes. Natural vibration of skew orthotropic plates with point supports [14] has been presented by using higher degree skew finite strips and frequencies and mode shapes for different parameters have been evaluated. Natural vibration of skew fiber-reinforced composite laminates [15] has been investigated using B-spline Rayleigh-Ritz method (RRM) and various numerical applications have been presented. The moving least square Ritz (MLS-Ritz) method [16] has been analyzed the vibration of parallelogram plates and presented cases for rhombic plates of various edge support conditions. Vibration analysis of rectangle and skew plate [17] has been carried using Rayleigh-Ritz method and frequencies have been obtained. Vibration of rectangle plate with circular variation in Poisson's ratio [18] has been studied and frequency modes have been computed under temperature effect. Rayleigh-Ritz method has been used to investigate vibration of FG rectangle plate [19] on various edge conditions and effect of volume and aspect ratio on frequencies has been computed. Chebyshev-Ritz method has been applied to investigate three-dimensional free vibration of FG annular plates [20] with different boundary conditions. Time period of frequencies of parallelogram plate with circular variation in density and two-dimensional thickness has been presented on CCCC and CSCS edge condition under two-dimensional temperature variation.

In present study, an effect of exponential variation in Young's modulus and density on time period of natural frequencies of skew plate having variable thickness is presented, on both CCCC and SSSS edge conditions.

2 ANALYSIS

Kinetic energy T_s and strain energy V_s for parallelogram plate referred to skew coordinates $\zeta = x - y \tan \theta$, $\psi = y \sec \theta$ is given by

$$(1) \quad T_s = \frac{1}{2} \omega^2 \cos \theta \iint_R \rho l \Phi^2 d\zeta d\psi,$$

$$(2) \quad V_s = \frac{1}{2 \cos^3 \theta} \iint_R D_1 \left[\left(\frac{\partial^2 \Phi}{\partial \zeta^2} \right)^2 - 4 \sin \theta \left(\frac{\partial^2 \Phi}{\partial \zeta^2} \right) \left(\frac{\partial^2 \Phi}{\partial \zeta \partial \psi} \right) + 2(\sin^2 \theta + \nu \cos^2 \theta) \left(\frac{\partial^2 \Phi}{\partial \zeta^2} \right) \left(\frac{\partial^2 \Phi}{\partial \psi^2} \right) + 2(1 + \sin^2 \theta - \nu \cos^2 \theta) \left(\frac{\partial^2 \Phi}{\partial \zeta \partial \psi} \right)^2 - 4 \sin \theta \left(\frac{\partial^2 \Phi}{\partial \zeta \partial \psi} \right) \left(\frac{\partial^2 \Phi}{\partial \psi^2} \right) + \left(\frac{\partial^2 \Phi}{\partial \psi^2} \right)^2 \right] d\zeta d\psi,$$

where l is the thickness, ρ is the density, ν is Poisson's ratio, θ is the skew angle, ω is the natural frequency, Φ is the deflection function and $D_1 = \frac{El^3}{12(1 - \nu^2)}$ is the

known as flexural rigidity; R is the region of the parallelogram plate.

Applying Rayleigh Ritz method, we have

$$(3) \quad I = \delta(V_s - T_s) = 0.$$

Substituting Eqs. (1) and (2) in Eq. (3)

$$(4) \quad I = \frac{1}{2 \cos^3 \theta} \iint_R D_1 \left[\left(\frac{\partial^2 \Phi}{\partial \zeta^2} \right)^2 - 4 \sin \theta \left(\frac{\partial^2 \Phi}{\partial \zeta^2} \right) \left(\frac{\partial^2 \Phi}{\partial \zeta \partial \psi} \right) \right. \\ + 2(\sin^2 \theta + \nu \cos^2 \theta) \left(\frac{\partial^2 \Phi}{\partial \zeta^2} \right) \left(\frac{\partial^2 \Phi}{\partial \psi^2} \right) + 2(1 + \sin^2 \theta - \nu \cos^2 \theta) \left(\frac{\partial^2 \Phi}{\partial \zeta \partial \psi} \right)^2 \\ \left. - 4 \sin \theta \left(\frac{\partial^2 \Phi}{\partial \zeta \partial \psi} \right) \left(\frac{\partial^2 \Phi}{\partial \psi^2} \right) + \left(\frac{\partial^2 \Phi}{\partial \psi^2} \right)^2 \right] d\zeta d\psi \\ - \frac{1}{2} \omega^2 \cos \theta \iint_R \rho l \Phi^2 d\zeta d\psi = 0.$$

Now introducing bi-linear thickness and exponential Young's modulus, density as

$$(5) \quad l = l_0 \left(1 + \alpha_1 \frac{\zeta}{a} \right) \left(1 + \alpha_2 \frac{\psi}{b} \right), \quad E = E_0 e^{\mu_1 \frac{\zeta}{a}}, \quad \rho = \rho_0 e^{\mu_2 \frac{\zeta}{a}},$$

where l_0 , E_0 and ρ_0 are the thickness, Young's modulus and the density at origin. α_1 , α_2 are tapering parameters and μ_1 , μ_2 are known as non-homogeneity parameters. Using Eq. (5), the functional in Eq. (4) becomes

$$(6) \quad I = \frac{D_0}{2} \int_0^a \int_0^b \left\{ \left(1 + \alpha_1 \frac{\zeta}{a} \right)^3 \left(1 + \alpha_2 \frac{\psi}{b} \right)^3 e^{\mu_1 \frac{\zeta}{a}} \right. \\ \times \left[\left(\frac{\partial^2 \Phi}{\partial \zeta^2} \right)^2 - 4 \left(\frac{a}{b} \right) \sin \theta \left(\frac{\partial^2 \Phi}{\partial \zeta^2} \right) \left(\frac{\partial^2 \Phi}{\partial \zeta \partial \psi} \right) \right. \\ + 2 \left(\frac{a}{b} \right)^2 (\sin^2 \theta + \nu \cos^2 \theta) \left(\frac{\partial^2 \Phi}{\partial \zeta^2} \right) \left(\frac{\partial^2 \Phi}{\partial \psi^2} \right) \\ + 2 \left(\frac{a}{b} \right)^2 (1 + \sin^2 \theta - \nu \cos^2 \theta) \left(\frac{\partial^2 \Phi}{\partial \zeta \partial \psi} \right)^2 \\ \left. \left. - 4 \left(\frac{a}{b} \right)^3 \sin \theta \left(\frac{\partial^2 \Phi}{\partial \zeta \partial \psi} \right) \left(\frac{\partial^2 \Phi}{\partial \psi^2} \right) + \left(\frac{a}{b} \right)^4 \left(\frac{\partial^2 \Phi}{\partial \psi^2} \right)^2 \right] \right\} d\psi d\zeta \\ - \lambda^2 \cos^4 \theta \int_0^a \int_0^b \left(1 + \alpha_1 \frac{\zeta}{a} \right) \left(1 + \alpha_2 \frac{\psi}{b} \right) e^{\mu_2 \frac{\zeta}{a}} \Phi^2 d\psi d\zeta = 0,$$

where $D_0 = E_0 l_0^3 / 12(1 - \nu^2)$ and $\lambda^2 = \rho_0 \omega^2 l_0 a^4 / D_0$.

Taking deflection function as [21]

$$(7) \quad \Phi(\zeta, \psi) = \left[\left(\frac{\zeta}{a} \right)^p \left(\frac{\psi}{b} \right)^q \left(1 - \frac{\zeta}{a} \right)^r \left(1 - \frac{\psi}{b} \right)^s \right] \\ \times \left[\sum_{i=0}^n \Omega_i \left\{ \left(\frac{\zeta}{a} \right) \left(\frac{\psi}{b} \right) \left(1 - \frac{\zeta}{a} \right) \left(1 - \frac{\psi}{b} \right) \right\}^i \right],$$

where Ω_i , $i = 0, 1, 2, \dots, n$ are unknowns and p, q, r, s are constants and can be 0 (free edge), 1 (simply supported) and 2 (clamped edges).

To minimize Eq. (6), we require that

$$(8) \quad \frac{\partial I}{\partial \Omega_i} = 0, \quad i = 0, 1, 2, \dots, n.$$

From Eq. (8), we get frequency equation as

$$(9) \quad |P - \lambda^2 Q| = 0,$$

where $P = [p_{ij}]_{n+1}$ and $Q = [q_{ij}]_{n+1}$ are square matrix and $i, j = 0, 1, 2, \dots, n$.

The time period is calculated as

$$(10) \quad K = \frac{2\pi}{\lambda},$$

where λ is the frequency obtained from Eq. (9).

3 RESULTS DISCUSSION

Time period K on clamped and simply supported skew plate with variable thickness, are calculated for various value of tapering parameters α_1, α_2 and non-homogeneity parameters μ_1, μ_2 . The findings are displayed using figures.

Figure 1 presents the time period K on CCCC and SSSS edge conditions, for two different cases $\alpha_1 = \alpha_2 = -0.3, \mu_2 = -0.1$ and $\alpha_1 = \alpha_2 = 0.3, \mu_2 = 0.1$ with respect to non-homogeneity parameter μ_1 . Increase in non-homogeneity parameter μ_1 results the decrease in time period for both the above-mentioned cases, on both the edge conditions. The time period for first third mode is high on SSSS edge condition while the time period for fourth mode is high on CCCC edge condition. Also increase in number of modes decreases the time period. The time period is high on $\alpha_1 = \alpha_2 = -0.3, \mu_2 = -0.1$ in comparison to time period on $\alpha_1 = \alpha_2 = 0.3, \mu_2 = 0.1$, for both the edge conditions.

Non-homogeneity μ_2 effect on time period K , on CCCC and SSSS edge conditions for two different cases $\alpha_1 = \alpha_2 = -0.5, \mu_1 = -0.3$ and $\alpha_1 = \alpha_2 = 0.5, \mu_1 = 0.3$, are displayed in Figure 2.

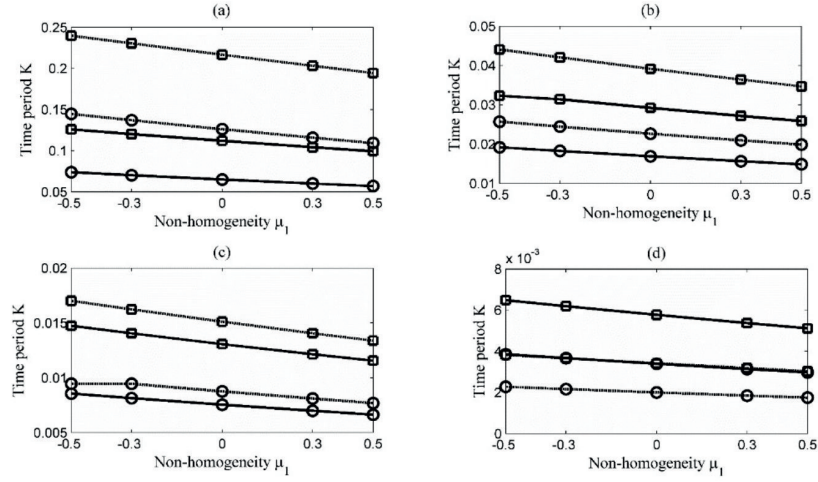


Fig. 1: Time period K : (a) fundamental mode; (b) second mode; (c) third mode; (d) fourth mode with respect to non-homogeneity μ_1 for — CCCC and --- SSSS boundary conditions; $\square$ — $\alpha_1 = \alpha_2 = -0.3$, $\mu_2 = -0.1$; $\bigcirc$ — $\alpha_1 = \alpha_2 = 0.3$, $\mu_2 = 0.1$.

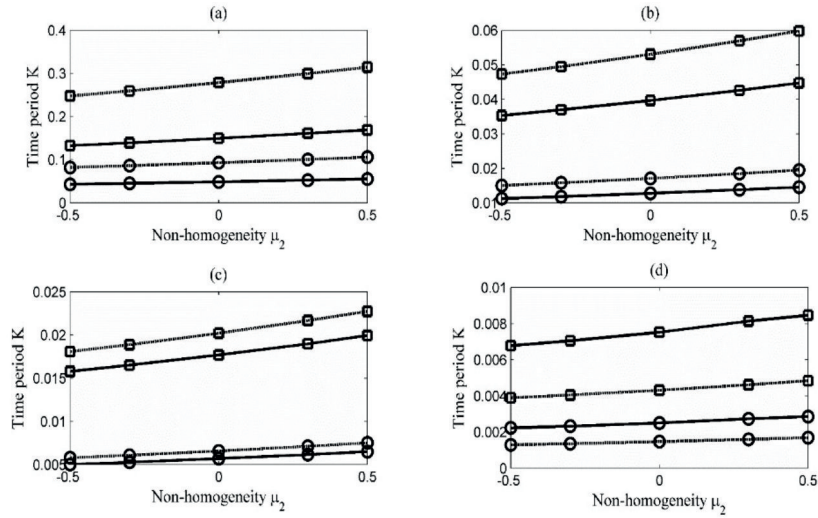


Fig. 2: Time period K : (a) fundamental mode; (b) second mode; (c) third mode; (d) fourth mode with respect to non-homogeneity μ_2 for — CCCC and --- SSSS boundary conditions; $\square$ — $\alpha_1 = \alpha_2 = -0.5$, $\mu_1 = -0.3$; $\bigcirc$ — $\alpha_1 = \alpha_2 = 0.5$, $\mu_2 = 0.3$.

$\mu_2 = 0.3$ is shown in Fig. 2. Increase in non-homogeneity parameter μ_2 results the increase in time period on both the cases, on both edge conditions. Time period for fourth mode is less on SSSS conditions while the time period for fundamental mode, second mode and third mode is less on CCCC edge condition. The time period is less on $\alpha_1 = \alpha_2 = 0.5$, $\mu_2 = 0.3$ in comparison to time period on $\alpha_1 = \alpha_2 = -0.5$, $\mu_1 = -0.3$, for both the edge conditions.

The effect of tapering parameters α_1, α_2 on time period K for two different cases $\mu_1 = -0.1, \mu_2 = -0.3$ and $\mu_1 = 0.1, \mu_2 = 0.3$, on CCCC and SSSS edge condition is displayed in Fig. 3. With the increasing value of tapering parameters α_1, α_2 , the time period of frequency modes are decreasing for each case, on each edge condition. Here, decrement rate in time period is high when compared with decrement rate reported in Fig. 1. The time period is high on $\mu_1 = 0.1, \mu_2 = 0.3$ in comparison to time period on $\mu_1 = -0.1, \mu_2 = -0.3$, for both the edge conditions.

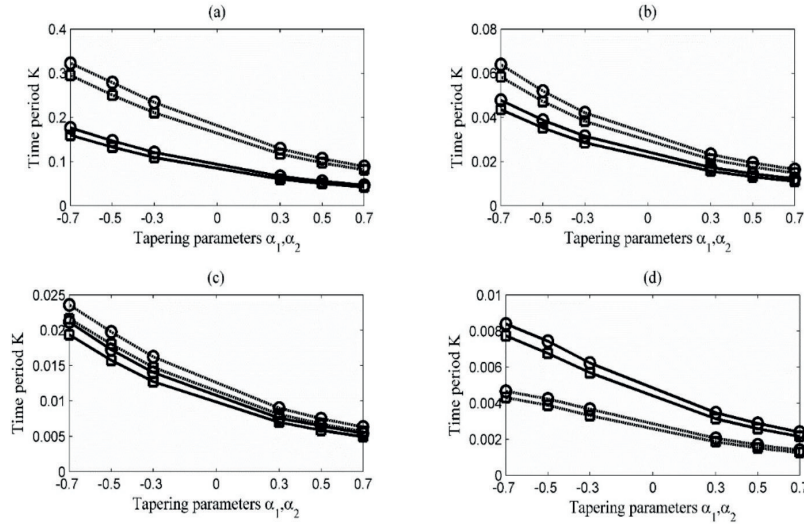


Fig. 3: Time period K : (a) fundamental mode; (b) second mode; (c) third mode; (d) fourth mode with respect to tapering parameters α_1, α_2 for — CCCC and - - - SSSS boundary conditions; $\square$ - $\mu_1 = -0.1, \mu_2 = -0.3$; $\circ$ - $\mu_1 = 0.1, \mu_2 = 0.3$.

4 RESULTS COMPARISON

A comparative analysis of frequency modes of present study (for parallelogram plate and square plate) and obtained by [9] on CCCC edge conditions and by [10, 11] on SSSS and CCCC edge conditions are given. Both comparisons are presented in Tables 1 and 2.

Table 1 presents the comparative analysis of frequencies for parallelogram plate with frequency obtained by [9] with respect to non-homogeneity μ_2 , on $\alpha_1 = \alpha_2 = \mu_1 = 0.0$, $a/b = 1.5$, $\theta = 30^\circ$, on CCCC edge condition. The results obtained in present study are less when compared with the results obtained by [9]. At $\mu_2 = 0.0$, the result of present study and the results obtained by [9] are coincides.

Table 1: Comparative analysis of frequency (for parallelogram plate) with the frequency obtained by [9] vs. μ_2 on CCCC edge condition

μ_2	$\alpha_1 = \alpha_2 = \mu_1 = 0.0, a/b = 1.5, \theta = 30^\circ$			
	CCCC			
	λ_1	λ_2	λ_3	λ_4
0.0	74.00 74.00 ⁺	285.84 285.84 ⁺	640.86 640.86 ⁺	1405.42 1405.42 ⁺
0.3	68.62 72.37 ⁺	264.68 278.65 ⁺	592.86 624.57 ⁺	1311.41 1366.50 ⁺
0.6	63.11 70.84 ⁺	244.88 272.24 ⁺	548.30 608.15 ⁺	1209.71 1343.96 ⁺
0.9	58.82 69.41 ⁺	226.16 266.24 ⁺	506.19 594.77 ⁺	1110.16 1305.34 ⁺

(+ Value from [9])

Table 2 provides the comparative analysis of frequencies for square plate with the frequency obtained by [10] (for first two modes), [11] (for first four modes), corresponding to non-homogeneity μ_2 , on $\alpha_1 = \alpha_2 = \mu_1 = 0.0$, $a/b = 1$, $\theta = 0^\circ$, on CCCC and SSSS edge conditions. It is found that results of present study are less in comparison to results obtained by [10] and [11]. The results of present study and results obtained by [10] and [11] are coincides at $\mu_2 = 0.0$.

Table 2: Comparative analysis of frequency (for square plate) with the frequency obtained by [10] and [11] vs. μ_2 on SSSS and CCCC edge conditions

μ_2	$\alpha_1 = \alpha_2 = \mu_1 = 0.0, a/b = 1, \theta = 0^\circ$			
	CCCC			
	λ_1	λ_2	λ_3	λ_4
0.0	35.99	137.61	307.18	664.57
	35.99 ^a	137.61 ^a	307.18 ^a	664.57 ^a
	35.99 ^b	140.88 ^b	—	—
0.3	33.38	127.54	284.61	616.99
	33.56 ^a	128.32 ^a	286.45 ^a	619.91 ^a
	35.20 ^b	137.33 ^b	—	—
0.6	30.92	118.00	263.76	563.64
	31.57 ^a	120.69 ^a	269.42 ^a	582.91 ^a
	34.45 ^b	134.04 ^b	—	—
0.9	28.61	108.97	242.98	522.40
	29.89 ^a	114.28 ^a	254.86 ^a	553.84 ^a
	33.75 ^b	130.98 ^b	—	—
	SSSS			
0.0	19.78	103.62	263.21	1105.56
	19.78 ^a	103.62 ^a	263.21 ^a	1105.56 ^a
0.3	18.34	96.03	243.87	1023.27
	18.45 ^a	96.62 ^a	245.44 ^a	1031.01 ^a
0.6	16.97	88.81	225.35	943.56
	17.35 ^a	90.88 ^a	230.85 ^a	969.53 ^a
0.9	15.69	81.96	207.71	865.92
	16.43 ^a	86.05 ^a	218.58 ^a	918.20 ^a

(a – value from [11], b – value from [10])

5 CONCLUSIONS

On the basis of numerical results and comparative analysis, authors conclude the followings:

- Exponential variation in density (present study) provides less Vibrational frequency in comparison to circular variation in density [9] on clamped edge condition.
- Exponential variation in density (present study) provides less frequency in

comparison to circular variation in density [10] and linear variation in density [11] on both CCCC and SSSS edge conditions for square plate.

- The frequency obtained in present analysis and obtained by [9] for parallelogram plate and [10, 11] for square plate coincide at $\mu_2 = 0.0$ which shows the validity of the results.
- Increase in non-homogeneity μ_1 and tapering parameters α_1, α_2 decreases the time period on edge conditions.
- Increase in non-homogeneity μ_2 increases the time period on edge conditions.
- Increase in number of modes decreases the time period on edge conditions.
- Desired frequencies can be obtained by taking proper choice of parameters as well as by proper variations in parameters of the plates.

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