

Thermal Stresses of a Hollow Cylinder Due to Heat Generation: Steady State Problem

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Abstract-In this paper, an attempt has been made to study thermoelastic response of a hollow cylinder occupying the space $D: a \leq r \leq b, -h \leq z \leq h$, due to heat generation with radiation type boundary conditions. Here we apply integral transform techniques to find the thermo elastic solution.

Keywords: Thermo elastic problem, hollow cylinder, Thermal Stresses, integral transform.

I. INTRODUCTION

Khobragade et al. [2-18] have investigated temperature distribution, displacement function, and stresses of a thin as well as thick hollow cylinder and **Khobragade et al.** [13] have established displacement function, temperature distribution and stresses of a semi-infinite cylinder.

In the present paper, an attempt is made to study the theoretical solution for a thermoelastic problem to determine the temperature distribution, displacement and stress functions of a hollow cylinder with boundary conditions occupying the space

$$D = \{(x, y, z) \in R^3 : a \leq (x^2 + y^2)^{1/2} \leq b, 0 \leq z \leq h\}$$

, where $r = (x^2 + y^2)^{1/2}$. A transform defined by Zgrablich et al. [2] is used for investigation which is a generalization of Hankel's double radiation finite transform and used to treat the problem with radiation type boundaries conditions.

II. FORMULATION OF THE PROBLEM

Consider a hollow cylinder as shown in the figure 1. The material of the cylinder is isotropic, homogenous and all properties are assumed to be constant. We assume that the cylinder is of a small thickness and its boundary surfaces remain traction free. The initial temperature of the cylinder is the same as the temperature of the surrounding medium, which is kept constant.

The displacement function $\phi(r, z)$ satisfying the differential equation as Khobragade [2] is

$$\frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r} \frac{\partial \phi}{\partial r} + \frac{\partial^2 \phi}{\partial z^2} = \left(\frac{1+\nu}{1-\nu} \right) a_t T \quad (1)$$

$$\text{with } \phi = 0 \text{ at } r = a \text{ and } r = b \quad (2)$$

where ν and a_t are Poisson ratio and linear coefficient of thermal expansion of the material of the cylinder respectively and $T(r, z)$ is the heating temperature of the cylinder satisfying the differential equation as Khobragade

$$\left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} \right] + \frac{g(r, z)}{k} = 0 \quad (3)$$

where $\kappa = K / \rho C$ is the thermal diffusivity of the material of the cylinder, K is the conductivity of the medium, C is its specific heat and ρ is its calorific capacity (which is assumed to be constant) respectively, subject to the boundary conditions

$$M_r(T, 1, \bar{k}_1, a) = F_1(z), \quad \text{for all } 0 \leq z \leq h, \quad (4)$$

$$M_r(T, 1, \bar{k}_2, b) = F_2(z) \quad \text{for all } 0 \leq z \leq h, \quad (5)$$

$$M_z(T, 0, 1, 0) = F_3(r) \quad \text{for all } a \leq r \leq b, \quad (6)$$

$$M_z(T, 0, 1, \xi) = F_4(r) \quad \text{for all } a \leq r \leq b, \quad (7)$$

$$M_z(T, 1, 0, h) = G(r) \text{ (Unknown) for all } a \leq r \leq b \quad (8)$$

being:

$$M_{,g}(f, \bar{k}, \bar{k}, \xi) = (\bar{k} f + \bar{k} \hat{f})_{g=\xi} \quad (9)$$

Where the prime (\wedge) denotes differentiation with respect to g , radiation constants are \bar{k} and \bar{k} on the curved surfaces of the plate respectively.

The radial and axial displacement U and W satisfy the uncoupled thermoelastic equation as Khobragade [2] are

$$\nabla^2 U - \frac{U}{r^2} + (1-2\nu)^{-1} \frac{\partial e}{\partial r} = 2 \left(\frac{1+\nu}{1-2\nu} \right) a_t \frac{\partial T}{\partial r} \quad (10)$$

$$\nabla^2 W + (1-2\nu)^{-1} \frac{\partial e}{\partial z} = 2 \left(\frac{1+\nu}{1-2\nu} \right) a_t \frac{\partial T}{\partial z} \quad (11)$$

Where

$$e = \frac{\partial U}{\partial r} + \frac{U}{r} + \frac{\partial W}{\partial r} \quad (12)$$

$$U = \frac{\partial \phi}{\partial r}, \quad (13)$$

$$W = \frac{\partial \phi}{\partial z} \quad (14)$$

The stress functions are given by

$$\tau_{rz}(a, z) = 0, \tau_{rz}(b, z) = 0, \tau_{rz}(r, 0) = 0 \quad (15)$$

$$\sigma_r(a, z) = p_i, \sigma_r(b, z) = -p_o, \sigma_z(r, 0) = 0 \quad (16)$$

where p_i and p_o are the surface pressure assumed to be

uniform over the boundaries of the cylinder. The stress functions are expressed in terms of the displacement components by the following relations as Khobragade [2] are

$$\sigma_z = (\lambda + 2G) \frac{\partial W}{\partial z} + \lambda \left(\frac{\partial U}{\partial r} + \frac{U}{r} \right) \quad (17)$$

$$\sigma_\theta = (\lambda + 2G) \frac{U}{r} + \lambda \left(\frac{\partial U}{\partial r} + \frac{\partial W}{\partial z} \right) \quad (18)$$

$$\tau_{rz} = G \left(\frac{\partial W}{\partial r} + \frac{\partial U}{\partial z} \right) \quad (19)$$

where $\lambda = 2G\nu/(1-2\nu)$ is the Lamé's constant, G is the shear modulus and U, W are the displacement components.

Equations (1)-(19) constitute the mathematical formulation of the problem under consideration.

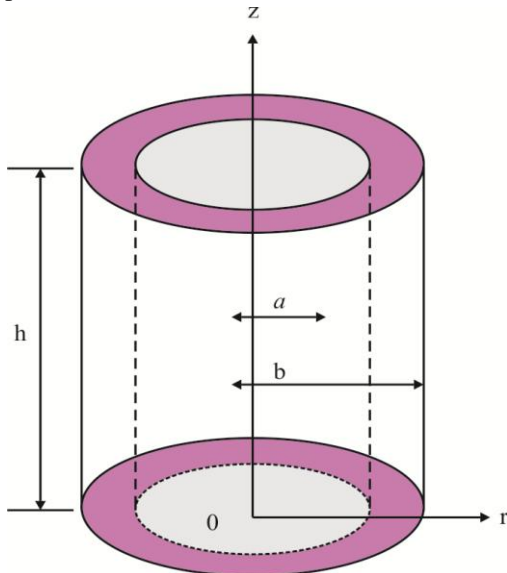


Fig 1: Geometry of the problem

III. SOLUTION OF THE OF THE PROBLEM

Applying finite March Zgrablich transform to (3), (6) & (7) & using (4) & (5), one obtains

$$\frac{d^2 \bar{T}}{dz^2} - \mu_n^2 \bar{T} = Q(z) \quad (20)$$

Where

$$Q(z) = \frac{a}{k_1} S_0(k_1, k_2, \mu_n a) F_1(z) - \frac{b}{k_2} S_0(k_1, k_2, \mu_n b) F_2(z) - \frac{\bar{g}(n, z)}{k}$$

$$\left[\frac{d\bar{T}}{dz} \right]_{z=0} = \bar{F}_3(n) \quad (21)$$

$$\left[\frac{d\bar{T}}{dz} \right]_{z=\xi} = \bar{F}_4(n) \quad (22)$$

Where \bar{T} is the Marchi-Zgrablich transform of T & n is the Marchi-Zgrablich transform parameter equation (20) is a second order differential equation whose solution is given by

$$\bar{T}(n, z) = Ae^{\mu_n z} + Be^{-\mu_n z} + P.I \quad (23)$$

Using equation (21) & (22) in (23) we obtain the values of A & B .

Substituting these values in (23) & then inversion of finite Marchi-Zgrablich transform leads to

$$T(r, z) = \sum_{n=1}^{\infty} \frac{1}{C_n} \left[\frac{\left[\bar{F}_4(n) - \left(\frac{d}{dz}(P.I) \right)_{z=\xi} \right] \cosh(\mu_n z) - \left[\bar{F}_3(n) - \left(\frac{d}{dz}(P.I) \right)_{z=0} \right] \cosh(\mu_n(z-\xi))}{\mu_n \sinh(\mu_n \xi)} \right] \times S_0(k_1, k_2, \mu_n r) \quad (24)$$

Also,

$$G(r) = \sum_{n=1}^{\infty} \frac{1}{C_n} \left[\frac{\left[\bar{F}_4(n) - \left(\frac{d}{dz}(P.I) \right)_{z=\xi} \right] \cosh(\mu_n h) - \left[\bar{F}_3(n) - \left(\frac{d}{dz}(P.I) \right)_{z=0} \right] \cosh(\mu_n(h-\xi))}{\mu_n \sinh(\mu_n \xi)} + [(P.I)] \right] \times S_0(k_1, k_2, \mu_n r) \quad (25)$$

IV. THERMO ELASTIC DISPLACEMENT

Substituting value of $T(r, z)$ from (24) in equation (1), we get

$$\phi(r, z, t) = \frac{r^2}{4} a_i \left(\frac{1+\nu}{1-\nu} \right) \sum_{n=1}^{\infty} \frac{1}{C_n} \left[\frac{\left[\bar{F}_4(n) - \left(\frac{d}{dz}(P.I) \right)_{z=\xi} \right] \cosh(\mu_n z) - \left[\bar{F}_3(n) - \left(\frac{d}{dz}(P.I) \right)_{z=0} \right] \cosh(\mu_n(z-\xi))}{\mu_n \sinh(\mu_n \xi)} + P.I \right] \times S_0(k_1, k_2, \mu_n r) \quad (4.1)$$

Using equation (4.1) in (2.13) and (2.14), one obtains the radial & axial displacement U & W as,

$$U = \left(\frac{1+\nu}{1-\nu} \right) \frac{a_i}{4} \sum_{n=1}^{\infty} \frac{1}{C_n} \left\{ \frac{\left[\begin{array}{l} \left[\bar{F}_4(n) - \left(\frac{d}{dz}(P.I) \right)_{z=\xi} \right] \cosh(\mu_n z) \\ - \left[\bar{F}_3(n) - \left(\frac{d}{dz}(P.I) \right)_{z=0} \right] \cosh(\mu_n(z-\xi)) \end{array} \right]}{\mu_n \sinh(\mu_n \xi)} + P.I \right\} \times [2rS_0(k_1, k_2, \mu_n r) + r^2 \mu_n S'_0(k_1, k_2, \mu_n r)] \quad (26)$$

$$W = \frac{r^2}{4} a_i \left(\frac{1+\nu}{1-\nu} \right) \sum_{n=1}^{\infty} \frac{1}{C_n} \left\{ \frac{\left[\begin{array}{l} \left[\bar{F}_4(n) - \left(\frac{d}{dz}(P.I) \right)_{z=\xi} \right] \cosh(\mu_n z) \\ - \left[\bar{F}_3(n) - \left(\frac{d}{dz}(P.I) \right)_{z=0} \right] \cosh(\mu_n(z-\xi)) \end{array} \right]}{\mu_n \sinh(\mu_n \xi)} + \frac{d}{dz}(P.I) \right\} \times S_0(k_1, k_2, \mu_n r) \quad (27)$$

V. DETERMINATION OF STRESS FUNCTIONS

Using (4.2) & (4.3) in the equation (2.17) to (2.20) the stress function are obtained as

$$\sigma_r = (\lambda + 2G) \left(\frac{1+\nu}{1-\nu} \right) \frac{a_i}{4} \sum_{n=1}^{\infty} \frac{1}{C_n} \left\{ \frac{\left[\begin{array}{l} \left[\bar{F}_4(n) - \left(\frac{d}{dz}(P.I) \right)_{z=\xi} \right] \cosh(\mu_n z) \\ - \left[\bar{F}_3(n) - \left(\frac{d}{dz}(P.I) \right)_{z=0} \right] \cosh(\mu_n(z-\xi)) \end{array} \right]}{\mu_n \sinh(\mu_n \xi)} + P.I \right\} \times [2S_0(k_1, k_2, \mu_n r) + 4r\mu_n S'_0(k_1, k_2, \mu_n r) + r^2 \mu_n^2 S''_0(k_1, k_2, \mu_n r)] + \lambda \left(\frac{1+\nu}{1-\nu} \right) \frac{a_i}{4} \sum_{n=1}^{\infty} \frac{1}{C_n} \left\{ \frac{\left[\begin{array}{l} \left[\bar{F}_4(n) - \left(\frac{d}{dz}(P.I) \right)_{z=\xi} \right] \cosh(\mu_n z) \\ - \left[\bar{F}_3(n) - \left(\frac{d}{dz}(P.I) \right)_{z=0} \right] \cosh(\mu_n(z-\xi)) \end{array} \right]}{\mu_n \sinh(\mu_n \xi)} + P.I \right\} \times S_0(k_1, k_2, \mu_n r) \quad (28)$$

$$\sigma_z = (\lambda + 2G) \frac{r^2}{4} a_i \left(\frac{1+\nu}{1-\nu} \right) \sum_{n=1}^{\infty} \frac{1}{C_n} \left\{ \frac{\mu_n \left[\begin{array}{l} \left[\bar{F}_4(n) - \left(\frac{d}{dz}(P.I) \right)_{z=\xi} \right] \cosh(\mu_n z) \\ - \left[\bar{F}_3(n) - \left(\frac{d}{dz}(P.I) \right)_{z=0} \right] \cosh(\mu_n(z-\xi)) \end{array} \right]}{\mu_n \sinh(\mu_n \xi)} + \frac{d^2}{dz^2}(P.I) \right\} \times S_0(k_1, k_2, \mu_n r)$$

$$+ \frac{r^2}{4} a_i \left(\frac{1+\nu}{1-\nu} \right) \sum_{n=1}^{\infty} \frac{1}{C_n} \left\{ \frac{\mu_n \left[\begin{array}{l} \left[\bar{F}_4(n) - \left(\frac{d}{dz}(P.I) \right)_{z=\xi} \right] \cosh(\mu_n z) \\ - \left[\bar{F}_3(n) - \left(\frac{d}{dz}(P.I) \right)_{z=0} \right] \cosh(\mu_n(z-\xi)) \end{array} \right]}{\mu_n \sinh(\mu_n \xi)} + \frac{d^2}{dz^2}(P.I) \right\} \times S_0(k_1, k_2, \mu_n r)$$

$$+ \lambda \left(\frac{1+\nu}{1-\nu} \right) \frac{a_i}{4} \sum_{n=1}^{\infty} \frac{1}{C_n} \left\{ \frac{\left[\begin{array}{l} \left[\bar{F}_4(n) - \left(\frac{d}{dz}(P.I) \right)_{z=\xi} \right] \cosh(\mu_n z) \\ - \left[\bar{F}_3(n) - \left(\frac{d}{dz}(P.I) \right)_{z=0} \right] \cosh(\mu_n(z-\xi)) \end{array} \right]}{\mu_n \sinh(\mu_n \xi)} + P.I \right\} \times [2S_0(k_1, k_2, \mu_n r) + 4r\mu_n S'_0(k_1, k_2, \mu_n r) + r^2 \mu_n^2 S''_0(k_1, k_2, \mu_n r)] + \left(\frac{1+\nu}{1-\nu} \right) \frac{a_i}{4} \sum_{n=1}^{\infty} \frac{1}{C_n} \left\{ \frac{\mu_n \left[\begin{array}{l} \left[\bar{F}_4(n) - \left(\frac{d}{dz}(P.I) \right)_{z=\xi} \right] \cosh(\mu_n z) \\ - \left[\bar{F}_3(n) - \left(\frac{d}{dz}(P.I) \right)_{z=0} \right] \cosh(\mu_n(z-\xi)) \end{array} \right]}{\mu_n \sinh(\mu_n \xi)} + (P.I) \right\} \times [2S_0(k_1, k_2, \mu_n r) + r\mu_n S'_0(k_1, k_2, \mu_n r)] \quad (29)$$

$$\sigma_\theta = (\lambda + 2G) \left(\frac{1+\nu}{1-\nu} \right) \frac{a_i}{4} \sum_{n=1}^{\infty} \frac{1}{C_n} \left\{ \frac{\mu_n \left[\begin{array}{l} \left[\bar{F}_4(n) - \left(\frac{d}{dz}(P.I) \right)_{z=\xi} \right] \cosh(\mu_n z) \\ - \left[\bar{F}_3(n) - \left(\frac{d}{dz}(P.I) \right)_{z=0} \right] \cosh(\mu_n(z-\xi)) \end{array} \right]}{\mu_n \sinh(\mu_n \xi)} + (P.I) \right\} \times [2S_0(k_1, k_2, \mu_n r) + r\mu_n S'_0(k_1, k_2, \mu_n r)]$$

$$\left. \begin{aligned}
 & \left(\frac{1+\nu}{1-\nu} \right) \frac{a_i}{4} \sum_{n=1}^{\infty} \frac{1}{C_n} \left\{ \frac{\left[\begin{aligned} & \left[\bar{F}_4(n) - \left(\frac{d}{dz} (P.I) \right)_{z=\xi} \right] \cosh(\mu_n z) \\ & - \left[\bar{F}_3(n) - \left(\frac{d}{dz} (P.I) \right)_{z=0} \right] \cosh(\mu_n (z-\xi)) \end{aligned} \right]}{\mu_n \sinh(\mu_n \xi)} + P.I \right\} \\
 & \times \left[2S_0(k_1, k_2, \mu_n r) + 4r\mu_n S'_0(k_1, k_2, \mu_n r) + r^2 \mu_n^2 S''_0(k_1, k_2, \mu_n r) \right] \\
 & + \frac{r^2}{4} a_i \left(\frac{1+\nu}{1-\nu} \right) \sum_{n=1}^{\infty} \frac{1}{C_n} \left\{ \frac{\mu_n \left[\begin{aligned} & \left[\bar{F}_4(n) - \left(\frac{d}{dz} (P.I) \right)_{z=\xi} \right] \cosh(\mu_n z) \\ & - \left[\bar{F}_3(n) - \left(\frac{d}{dz} (P.I) \right)_{z=0} \right] \cosh(\mu_n (z-\xi)) \end{aligned} \right]}{\mu_n \sinh(\mu_n \xi)} + \frac{d^2}{dz^2} (P.I) \right\} \\
 & \times S_0(k_1, k_2, \mu_n r)
 \end{aligned} \right\} \quad (30)$$

$$\left. \begin{aligned}
 & \frac{a_i}{4} \left(\frac{1+\nu}{1-\nu} \right) \sum_{n=1}^{\infty} \frac{1}{C_n} \left\{ \frac{\left[\begin{aligned} & \left[\bar{F}_4(n) - \left(\frac{d}{dz} (P.I) \right)_{z=\xi} \right] \cosh(\mu_n z) \\ & - \left[\bar{F}_3(n) - \left(\frac{d}{dz} (P.I) \right)_{z=0} \right] \cosh(\mu_n (z-\xi)) \end{aligned} \right]}{\mu_n \sinh(\mu_n \xi)} + \frac{d}{dz} (P.I) \right\} \\
 & \times \left[2rS_0(k_1, k_2, \mu_n r) + r^2 \mu_n S'_0(k_1, k_2, \mu_n r) \right] \\
 & + \left(\frac{1+\nu}{1-\nu} \right) \frac{a_i}{4} \sum_{n=1}^{\infty} \frac{1}{C_n} \left\{ \frac{\left[\begin{aligned} & \left[\bar{F}_4(n) - \left(\frac{d}{dz} (P.I) \right)_{z=\xi} \right] \cosh(\mu_n z) \\ & - \left[\bar{F}_3(n) - \left(\frac{d}{dz} (P.I) \right)_{z=0} \right] \cosh(\mu_n (z-\xi)) \end{aligned} \right]}{\mu_n \sinh(\mu_n \xi)} + \frac{d}{dz} (P.I) \right\} \\
 & \times \left[2rS_0(k_1, k_2, \mu_n r) + r^2 \mu_n S'_0(k_1, k_2, \mu_n r) \right]
 \end{aligned} \right\} \quad (31)$$

VI. SPECIAL CASE

Set $f_3 = 0, f_4 = \delta(r - r_0)$ (32)

Applying finite Marchi Zgrablich transform defined in [2] to the equation (31) one obtains

$\bar{f}_3 = 0 \ \& \ \bar{f}_4 = r_0 S_0(k_1, k_2, \mu_n r_0)$ (33)

Substituting the value of (32) in the equation (21) to obtain

$$\begin{aligned}
 T(r, z) = & \sum_{n=1}^{\infty} \frac{1}{C_n} \left[r_0 S_0(k_1, k_2, \mu_n r_0) - \left(\frac{d}{dz} P.I \right)_{z=\xi} \right] \cosh(\mu_n z) \\
 & + \left(\frac{d}{dz} P.I \right)_{z=0} \cosh(\mu_n (z-\xi)) \\
 & \frac{\mu_n \sinh(\mu_n \xi)}{\mu_n \sinh(\mu_n \xi)} \\
 & \times S_0(k_1, k_2, \mu_n r)
 \end{aligned} \quad (34)$$

VII. NUMERICAL RESULTS

Take $k_1 = 0.25, k_2 = 0.25, r_0 = 1$

$$\begin{aligned}
 T(r, z) = & \sum_{n=1}^{\infty} \frac{1}{C_n} \left[S_0(0.25, 0.25, \mu_n) - \left(\frac{d}{dz} P.I \right)_{z=\xi} \right] \cosh(\mu_n z) \\
 & + \left(\frac{d}{dz} P.I \right)_{z=0} \cosh(\mu_n (z-\xi)) \\
 & \frac{\mu_n \sinh(\mu_n \xi)}{\mu_n \sinh(\mu_n \xi)} \\
 & \times S_0(0.25, 0.25, \mu_n r)
 \end{aligned} \quad (35)$$

VIII. CONCLUSION

In this paper, we modified the conceptual idea proposed by **Khobragade et al** [2] for hollow cylinder and the temperature distributions, displacement and stress functions at the edge $z = h$ occupying the region of the cylinder $a \leq r \leq b, 0 \leq z \leq h$ have been obtained with the known boundary conditions. We develop the analysis for the temperature field by introducing the transformation defined by Zgrablich et al with boundary conditions of radiation type. Since the thickness of cylinder is very small, the series solution given here will be definitely convergent. Assigning suitable values to the parameters and functions in the series expressions can derive any particular case. The temperature, displacement and thermal stresses that are obtained can be applied to the design of useful structures or machines in engineering applications.

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