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# Fluid Inertia Force Effects in Hydromagnetic Circular Stepped Squeeze Films

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**Keywords**：circular stepped disks, inertia forces, electrically conducting fluids, momentum integral method.

## ABSTRACT

On the basis of the hydromagnetic flow theory, an inertia hydromagnetic lubrication equation has been derived for circular stepped squeeze film disks by applying the momentum integral method. Analytical solution of the film pressure, the load capacity and the squeeze film time are obtained in the present paper. It is found that the hydromagnetic squeeze film including the influences of fluid inertia forces provides an increased load capacity as well as a longer squeeze film time as compared to the non-inertia non-conducting-lubricant case. The improved squeeze film characteristics are further emphasized for the circular stepped disks operating at larger values of the density parameter and the magnetic Hartmann number, and smaller values of the radius ratio and the step height ratio.

## INTRODUCTION

In order to prevent viscosity variation with temperature, the use of electrically conducting fluids as lubricants has received great interest. According to the hydromagnetic flow theory of Cowling (1957), electrically conducting fluids possess higher thermal and electrical conductivity properties. Therefore, the viscous friction heat in thin lubricated films can be readily taken away.

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In addition, by the application of external magnetic fields, a produced Lorentz body force can provide a component to the direction of lubricant flow. As a result, the bearing characteristics are improved. A number of works have investigated the lubrication performances of hydromagnetic thin film bearings in the presence of an external magnetic field, such as the externally pressured bearings by Huges and Elco (1962), Maki and Kuzma (1966) and Choy and Halloran (2008); the journal bearings by Kuzma (1963), Kamiyama (1969) and Malik, Singh (1980) and Deheri et al (2015); the slider bearings by Gupta and Bhat (1979), Das (1998) and Lin (2012). On the other hand, squeeze film mechanisms play important roles in many areas of applied science and engineering practice, such as bio-lubrication, skeletal joints, hydraulic dampers, disc clutches and machine tools. Many authors have also investigated the hydromagnetic performance characteristics for various squeeze film bearings, such as non-cyclic journal bearings by Agrawal (1970), the conical plates by Vadher *et al.* (2010), the sphere-plate system by Chou *et al.* (2013), the rectangular plates by Bujurke and Kudenatti (2007), Lin et al. (2015), the circular disks by Patel (1980), the annular disks by Lin (2001) and the curved disks by Lin et al. (2014).According to their results, the squeeze film bearings lubricated with an electrically conducting fluid together with the application of magnetic fields result in an increase in the load capacity and the approaching time. Squeeze film performances are improved. In the above studies of squeeze films, fluid inertia forces are assumed to be small and neglected as compared to the viscous forces. However, the running speed of modern machine systems may increase depending on the operating requirements. Therefore, the effects of fluid inertia forces may become more and more significant and should be considered in the analysis.

In the present study, the influences of fluid inertia forces in circular stepped squeeze films under the application of transverse magnetic fields are investigated. Based upon the hydromagnetic flow theory together with the momentum integral method, a hydromagnetic lubrication equation including fluid inertia effects for circular stepped disks has been derived. Comparing with the non-inertia non-conducting-lubricant case, the squeeze film characteristics of circular stepped disks are presented for different values of the density parameter, Hartmann number, step height ratio, and radius ratio.

## ANALYSIS

Fig. 1 shows the squeeze film geometry of circular stepped disks lubricated with an incompressible electrical conducting fluid in the presence of an external magnetic field $B_0$ in the $z-$ direction. The upper stepped disk with outer radius $a$ and inner radius $b$ is approaching the lower fixed plate with a squeezing velocity $v_{sq} = -\partial h / \partial t$, where $t$ denotes the time. The local film height $h$ can be expressed as

$$h = \begin{cases} h_b \\ h_a \end{cases} \text{for} \begin{cases} 0 \le r \le b \\ b \le r \le a \end{cases}. \tag{1}$$

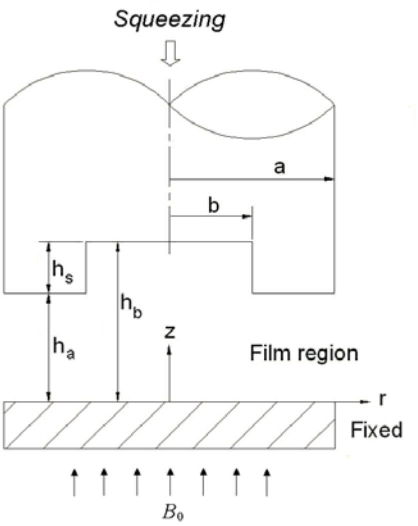


Fig. 1. Squeeze film geometry of circular stepped disks with an electrical conducting fluid in the presence of an external magnetic field.

And the step height $h_s$ can be described by

$$h_s = h_b - h_a, \tag{2}$$

where $h_a$ represents the minimum film height. It is assumed that the thin-film lubrication theory of Hamrock (1994) is applicable, the induced magnetic field is small as compared to the applied magnetic field, the body force can be neglected except for the Lorentz force, but the influences of convective inertia forces resulting from temporal acceleration of the fluid are included in the present study. Based on to the hydromagnetic flow theory of Cowling (1957), the hydromagnetic momentum equations, the continuity equation and the equation for squeeze motion can be expressed in axially cylindrical coordinates ( $r, \theta, z$ ) as follows.

$$\rho\left( u\frac{\partial u}{\partial r} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial p}{\partial r} + \eta\frac{\partial^2 u}{\partial z^2} - cB_0^{\,2}u, \tag{3}$$

$$\frac{\partial p}{\partial z} = 0, \tag{4}$$

$$\frac{u}{r} + \frac{\partial u}{\partial r} + \frac{\partial w}{\partial z} = 0, \tag{5}$$

$$2\pi r\int_{z=0}^{z=h} u dz = \pi r^2 v_{sq}, \tag{6}$$

where $\rho$ denotes the mass density of the fluid, $\eta$ is the dynamic viscosity, $c$ is the electrical conductivity, $p$ is the pressure, and $u$ and $w$ are the velocity components in the $r-$ and $z-$directions, respectively. The boundary conditions for velocity components are the non-slip conditions at the disk surfaces.

$$u\big|_{z=0} = 0, \quad w_{z=0} = 0, \tag{7}$$

$$u_{z=h} = 0, \quad w_{z=h} = -v_{sq} = \partial h / \partial t. \tag{8}$$

Since the local film height is thin, the convective inertia forces of the fluid can be treated as constant over the film height. Applying momentum integral method, integrating the hydromagnetic momentum equation (1) across the film height gives

$$\rho\left( u\frac{\partial u}{\partial r} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial p}{\partial r} + \eta\frac{\partial^2 u}{\partial z^2} - cB_0^{\,2}u. \tag{9}$$

Using the relationship of continuity equation (5) and performing the integration, one can rewrite the momentum integral equation.

$$\frac{\partial^2 u}{\partial z^2} - \frac{cB_0^{\,2}}{\eta}u = \frac{1}{\eta}\left[\frac{\partial p}{\partial r} + \frac{\rho}{h}\left(\frac{1}{r}\int_{z=0}^{z=h} u^2 dz + \frac{\partial}{\partial r}\int_{z=0}^{z=h} u^2 dz\right)\right]. \tag{10}$$

In order to obtain the fluid velocity, a modified pressure gradient function $\varphi$ is introduced.

$$\varphi = \frac{\partial p}{\partial r} + \frac{\rho}{h}\left(\frac{1}{r}\int_{z=0}^{z=h} u^2 dz + \frac{\partial}{\partial r}\int_{z=0}^{z=h} u^2 dz\right). \quad (11)$$

Then the momentum integral equation is expressed as

$$\frac{\partial^2 u}{\partial z^2} - \frac{c{B_0}^2}{\eta}u = \frac{1}{\eta}\varphi. \quad (12)$$

The velocity component can be obtained after integrating the differential equation and applying the velocity boundary conditions.

$$u = \frac{{h_{a0}}^2\varphi}{\eta M^2}\left[\cosh\left(\frac{Mz}{h_{a0}}\right) - \tanh\left(\frac{Mh}{2h_{a0}}\right)\sinh\left(\frac{Mz}{h_{a0}}\right) - 1\right]. \quad (13)$$

where $h_{a0}$ represents the initial minimum film height, and $M$ is the magnetic Hartmann number describing the influences of applied magnetic fields.

$$M = B_0 h_{a0}\sqrt{c/\eta}. \quad (14)$$

Using the expression of the velocity component (13), the following integrals can be achieved.

$$\int_{z=0}^{z=h} u dz = \frac{\varphi}{-12\eta} g_0(M,h), \quad (15)$$

$$\int_{z=0}^{z=h} u^2 dz = \frac{\varphi^2}{4\eta^2} g_1(M,h). \quad (16)$$

where the functions $g_1(M,h)$ and $g_2(M,h)$ are

$$g_0(M,h) = 12\frac{{h_{a0}}^2 h}{M^2} - 24\frac{{h_{a0}}^3}{M^3}\tanh\left(\frac{Mh}{2h_{a0}}\right), \quad (17)$$

$$g_1(M,h) = \begin{cases} 4\frac{{h_{a0}}^4 h}{M^4} + 4\frac{{h_{a0}}^5}{M^5}\sinh\left(\frac{Mh}{h_{a0}}\right) \\ + \frac{{h_{a0}}^5}{M^5}\sec h^2\left(\frac{Mh}{2h_{a0}}\right)\left[\frac{2Mh}{h_{a0}} - \sinh\left(\frac{2Mh}{h_{a0}}\right) - 8\sinh\left(\frac{Mh}{h_{a0}}\right)\right]\end{cases}. \quad (18)$$

Now substituting equation (15) into the equation for squeeze motion, one can obtain another expression of the modified pressure gradient function $\varphi$.

$$\varphi = -\frac{6\eta r v_{sq}}{g_0(M,h)}. \quad (19)$$

Equating the right hand side of equations (11) and (19) and applying the results of the integral (16), one can derive a hydromagnetic lubrication equation for the circular stepped disks including convective fluid inertia effects.

$$\frac{\partial p_i}{\partial r} = -\frac{3v_s r}{g_{0i}}\left(2\eta + \frac{9\rho g_{1i}}{h_i g_{0i}}v_s\right), (i = a, b). \quad (20)$$

where $p_i = p(h = h_i)$, $g_{0i} = g_0(M, h_i)$ and $g_{1i} = g_1(M, h_i)$.

Neglecting the effects of fluid inertia forces, the term $(9\rho g_{1i} v_s / h_i g_{0i})$ is excluded. Then the lubrication equation reduces to the situation of hydromagnetic circular stepped squeeze films without fluid inertia forces. Furthermore, if the fluid inertia forces are excluded and the step height $h_s$ is zero, the derived lubrication equation reduces to the case of non-inertia hydromagnetic circular squeeze film disks.

## SQUEEZE FILM CHARACTERISTICS

The derived lubrication equation is now applied to investigate the squeeze film characteristics of hydromagnetic circular stepped disks including convective fluid inertia forces. To analyze the problem, the non-dimensional variables and parameters are introduced as follows.

$$R = \frac{r}{a}, P = \frac{p}{p_r}, P_a = \frac{p_a}{p_r}, P_b = \frac{p_b}{p_r}, V = \frac{6\eta a^2 v_{sq}}{p_r {h_{a0}}^3}, \quad (21)$$

$$G_0 = \frac{g_0}{{h_{a0}}^3}, G_1 = \frac{g_1}{{h_{a0}}^5}, H_a = \frac{h_a}{h_{a0}}, H_b = \frac{h_b}{h_{a0}}, H = \frac{h}{h_{a0}}. \quad (22)$$

$$k = \frac{b}{a}, \quad s = \frac{h_s}{h_{a0}}, \quad D = \frac{\rho p_r {h_{a0}}^4}{6\eta^2 a^2}. \quad (23)$$

where $p_r$ represents the reference pressure. As a consequence, the non-dimensional hydromagnetic lubrication equation for the circular stepped squeeze films including the influences of convective inertia forces can written as

$$\frac{\partial P_i}{\partial R} = -\frac{RV}{G_{0i}}\left(1 + \frac{9DG_{1i}}{2h_i^* G_{0i}}V\right), \quad (i = a, b), \quad (24)$$

where $P_i = P(H = H_i)$, $G_{0i} = G_0(M, H_i)$, $G_{1i} = G_1(M, H_i)$, and

$$H = \begin{cases} H_b \\ H_a \end{cases} \text{for} \begin{cases} 0 \le R \le k \\ k \le R \le 1 \end{cases}, \quad (25)$$

$$s = H_b - H_a \cdot \tag{26}$$

$$G_0(M,H) = 12H/M^2 - 24\tanh(0.5MH)/M^3, \tag{27}$$

$$G_1(M,H) = \begin{cases} 4H/M^4 + 4\sinh(MH)/M^5 \\ +[2MH - \sinh(2MH) - 8\sinh(MH)]\sec h^2(0.5MH)/M^5 \end{cases} . \tag{28}$$

Integrate the non-dimensional lubrication equation with the pressure boundary conditions: $P = P_b$ for $0 \le R \le k$; $P = P_a$ for $k \le R \le 1$; $P_b = P_a$ at $R = k$; $P_a = 1$ at $R = 1$. The squeeze film pressure is then obtained.

$$P_b = \begin{cases} 1 + \dfrac{k^2 G_{0a}{}^* + (1-k^2)G_{0b} - R^2 G_{0a}}{2G_{0a}G_{0b}} V \\ + \dfrac{9D}{4}\left[\dfrac{k^2 G_{1b} - R^2 G_{1b}}{H_b G_{0b}{}^2} + \dfrac{(1-k^2)G_{1a}}{H_a G_{0a}{}^2}\right] V^2 \end{cases}, 0 \le R \le k, \tag{29}$$

$$P_a = 1 + \frac{V(1-R^2)}{2G_{0a}}\left(1 + \frac{9DG_{1a}}{2H_a G_{0a}} V\right), \quad k \le R \le 1. \tag{30}$$

Integrating the film pressure acting on the disk surface results in the load capacity $W$.

$$W = 2\pi\left[\int_{r=0}^{b} (p_b - p_r) r dr + \int_{r=b}^{a} (p_a - p_r) r dr\right] \cdot \tag{31}$$

Substituting the expression of film pressure and performing the integration, the non-dimensional load capacity $L$ can be derived.

$$L = \frac{8W}{p_r \pi a^2} = L_{NI} V + D L_I V^2, \tag{32}$$

where

$$L_{NI} = \frac{2k^4 G_{0a} + 2(1-k^4)G_{0b}}{G_{0a}G_{0b}}, \tag{33}$$

$$L_I = \frac{9k^4 H_a G_{0a}{}^2 G_{1b} + 9(1-k^4) H_b G_{1a} G_{0b}{}^2}{H_a H_b G_{0a}{}^2 G_{0b}{}^2}. \tag{34}$$

In order to obtain the elapsed time for the stepped disk to achieve a film height, a non-dimensional squeeze film time $T$ is introduced.

$$T = \frac{p_r h_{a0}{}^2}{6\eta a^2} t \cdot \tag{31}$$

From the definition of non-dimensional squeeze film velocity (21), one can obtain

$$V = \frac{6\eta a^2 v_{sq}}{p_r h_{a0}{}^3} = -\frac{dH_a}{dT}, \tag{32}$$

Substituting into the equation of (32) gives the nonlinear differential equation.

$$\frac{dH_a}{dT} = \frac{L_{NI} - \sqrt{L_{NI}{}^2 + 4DLL_I}}{2DL_I}. \tag{33}$$

Separating the variables and integrating the equation subject to the initial condition, $H_a(T=0) = 1$, one can derive the solution for the height-time relationship.

$$T = 2D\int_{H_a}^{H_a=1} \frac{L_I}{\sqrt{L_{NI}{}^2 + 4DLL_I} - L_{NI}} dH_a \cdot \tag{34}$$

The values of the squeeze film time $T$ can be calculated by the numerical integration method of Gaussian Quadrature.

## RESULTS AND DISCUSSIONS

According to the above analysis and derivation, the squeeze film characteristics of hydromagnetic circular stepped disks including the fluid inertia force effects are dominated by the density parameter $D$ defined in equation (23), the magnetic number $M$ defined in equation (14), the radius ratio $k$ and the step height ratio $s$ defined in equation (23).

For $D \to 0$, the study reduces to the non-inertia case. For $M \to 0$, it is the case with a non-conducting lubricant considering fluid inertia effects. For $D \to 0$ and $M \to 0$, it is the non-inertia case with a non-conducting lubricant. For $k \to 0$ (or $s \to 0$), it is the case with inertia force effects. When $D \to 0$, $M \to 0$ and $k \to 0$ (or $s \to 0$), the present study reduces to the case of non-inertia non-conducting fluid lubricated circular squeeze film plates of Hamrock (1994).

Figure 2 presents the load capacity $L$ varying with film height $H_a$ for different $M$ and $D$ with $k$=0.5 and $s$=0.5. The value of $L$ increases with decreasing $H_a$. Under the non-conducting-fluid case ($M$=0), the fluid inertia effects ($D$=4) provide a higher value of the load capacity as compared to the non-inertia case ($D$=0). Increasing the density parameter ($D$=8) increases the increments of $L$. When the circular stepped disks lubricated with an electrical conducting fluid with an applied magnetic field ($M$=2), further higher values of $L$ are obtained. Figure 3 describes the load capacity $L$ varying with Hartmann number $M$ for different

$H_a$ and $D$ with $k$=0.5 and $s$=0.5. The load $L$ increases with the Hartmann number $M$. Comparing with the non-inertia case ($D$=0), the fluid inertia effects ($D$=4, 8) increase the value of $L$. Figure 4 shows the load $L$ varying with density parameter $D$ for different $H_a$ and $M$ with $k$=0.5 and $s$=0.5. At $H_a$=0.6, the load $L$ increases with the density parameter $D$. Compared to the case of a non-conducting lubricant ($M$=0), increasing the Harmann number ($M$=2, 4, 6, 8, 10) increases the increment of the load. At a smaller height $H_a$=0.4, similar tendencies are observed for the variation of $L$ with $D$; but, higher values of the load capacity are predicted.

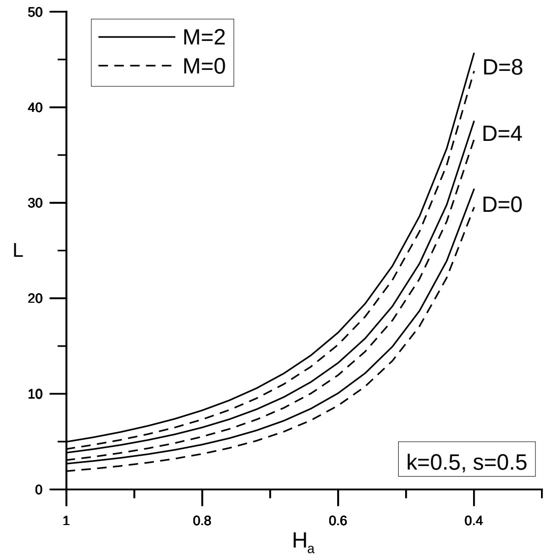


Fig. 2. Load capacity $L$ varying with film height $H_a$ for different $M$ and $D$ with $k$=0.5 and $s$=0.5.

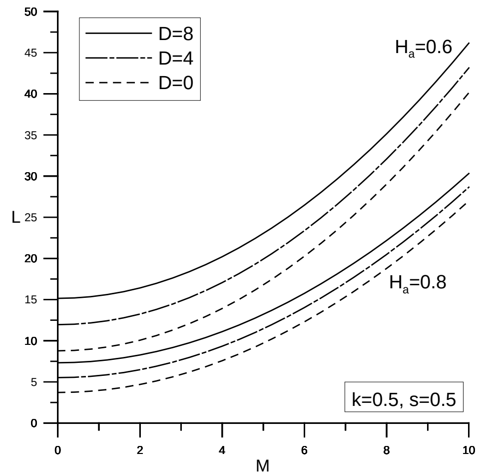


Fig 3. Load capacity $L$ varying with Hartmann number $M$ for different $H_a$ and $D$ with $k$=0.5 and $s$=0.5.

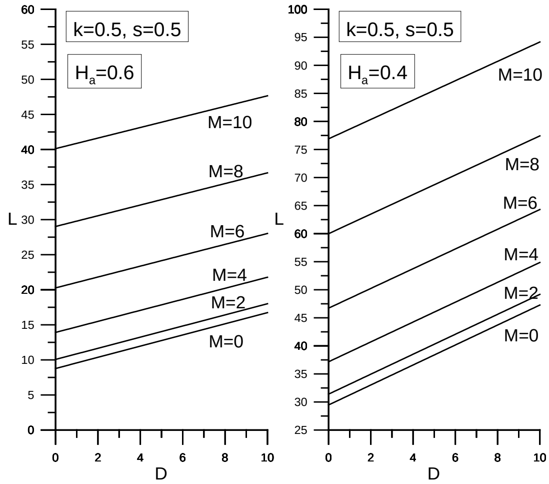


Fig. 4. Load capacity $L$ varying with density parameter $D$ for different $H_a$ and $M$ with $k$=0.5 and $s$=0.5.

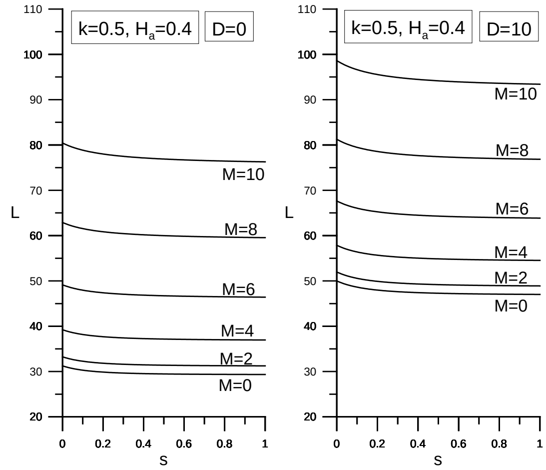


Fig.5. Load capacity $L$ varying with step height ratio $s$ for different $M$ with $k$=0.5 and $H_a$=0.4 under both the non-inertia ($D$=0) and inertia ($D$=10) cases.

Figure 5 and Figure 6 display the influences of the step height ratio $s$ and the radius ratio $k$ on the squeeze film characteristics. The load capacity $L$ varying with step height ratio $s$ for different $M$ with $k$=0.5 and $H_a$=0.4 under both the non-inertia ($D$=0) and inertia ($D$=10) cases are shown in Figure 5. Under the non-inertia ($D$=0) case with a non-conducting lubricant $M$=0), the load capacity $L$ is observed to decrease with the step height ratio $s$. By the use of an electrical conducting fluid with applied magnetic fields ($M$=2, 4, 6, 8, 10), higher values of the load capacity are predicted. When the influences of fluid inertia forces ($D$=10) are included, the hydromagnetic circular stepped disks provide further higher values of the load capacity. Figure 6 describes the load capacity $L$ varying with radius ratio $k$ for different $M$ with $S$ =0.2 and $H_a$ =0.4. Under the non-inertia ($D$=0) case, it is observed that the value of $L$ is observed to decrease with increasing values of $k$. Compared to the results with a non-conducting lubricant $M$ =0), the hydromagnetic squeeze films ($M$ =2, 4, 6, 8, 10) yield higher values of the load capacity. When the effects of fluid inertia forces ($D$=10) are included, further increments of the load capacity for hydromagnetic circular stepped disks are predicted.

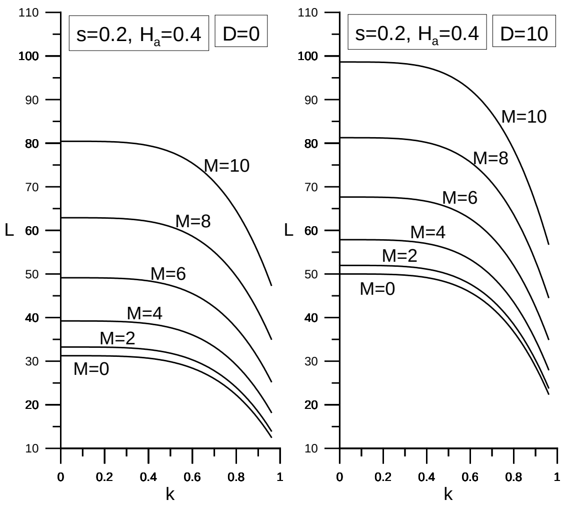


Fig.6. Load capacity $L$ varying with radius ratio $k$ for different $M$ with $S$ =0.2 and $H_a$ =0.4 under both the non-inertia ($D$=0) and inertia ($D$=10) cases.

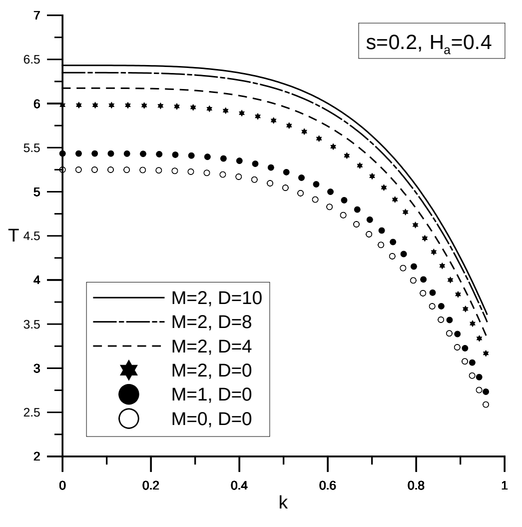


Fig. 7. Squeeze film time $T$ varying with radius ratio $k$ for different $M$ and $D$ under $S$ =0.2 and $H_a$ =0.4.

Figure 7 presents the squeeze film time $T$ varying with radius ratio $k$ for different $M$ and $D$ under $S$ =0.2 and $H_a$ =0.4. The squeeze film time decrease with increasing values of $k$. Comparing with the case of a non-conducting lubricant $M$ =0) without fluid inertia forces ($D$=0), the hydromagnetic circular stepped disks in the presence of external magnetic fields ($M$ =1, 2) result in an increase in the squeeze film time. When the effects of fluid inertia forces are included ($M$ = 2, $D$=4), a longer squeeze film time are observed. Increasing values of the density parameter ($M$ = 2, $D$=8; $M$ = 2, $D$=10), further longer values of the squeeze film time are predicted for the circular stepped squeeze film. On average, the inertia hydromagnetic squeeze film results in higher values of the film pressure and load capacity, and yield longer values of the squeeze film time as compared to the case with a non-conducting lubricant excluding the fluid inertia forces.

## CONCLUSIONS

In accordance with the above analysis and the results discussed, conclusions can be drawn as follows.

On the basis of the hydromagnetic flow theory together with the momentum integral method, an inertia hydromagnetic lubrication equation has been derived. Comparing with the non-inertia non-conducting-lubricant case, the hydromagnetic squeeze film including the influences of fluid inertia forces provides an increased load capacity as well as a longer squeeze film time. The improved squeeze film performances are more pronounced for the circular stepped disks operating at a larger value of the density parameter and the magnetic Hartmann number, and a smaller value of the radius ratio and the step height ratio.

## ACKNOWLEDGMENT

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# 流體慣性力對於液磁圓形階梯擠壓膜之影響

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## 摘 要

根據液磁動力理論並應用動量積分法，本研究推導得到一條具流體慣性力效應之液磁動力潤滑方程式，可用於圓形階梯板擠壓膜之性能分析。同時本文亦推導得到有關流體膜壓力、階梯板之承載能力以及擠壓膜時間等擠壓膜性能之解析解。若與傳統不考慮流體慣性力且使用非電導流體潤滑劑之情況做比較時，我們發現考慮流體慣性力效應之液磁動力圓形階梯板可以提供較高之承載能力與較長之擠壓膜時間。此種性能之改善，特別是在階梯擠壓板於具較大之密度參數值與哈特曼參數值且具較小之階梯半徑比值與階梯高度比值等情況下更為顯著。