Dynamic Characteristics of a Squeeze Film Damper Lubricated with Electro - Rheological Fluid in Terms of Reynolds Number

B. Rajneesh Kumar, S. Ranganatha

Abstract*— Smart fluid technology is an emerging field of research that leads to the introduction of Electro-rheological (ER) fluids. ER fluids are such smart materials whose rheological properties (viscosity, yield stress, shear modulus etc.) can be readily controlled upon external electric field. The use of ER fluids introduces a new philosophy on the fact that the stiffness and damping can be changed by applying high electric field and thus minimizing the vibration of the structure during normal operation. In the rotor vibration control of high speed engines squeeze film dampers are currently used. The dynamic characteristics (stiffness and damping) of a squeeze film damper lubricated with electro-rheological fluids are important in many practical engineering applications are studied for high accuracy and efficiency. The Reynolds equation of hydro-dynamic lubrication is normally used to determine the dynamic characteristics in the analysis of rotor dynamic system with squeeze film damper, which neglect the inertia effects. At high speeds both inertia and visco-elasticity introduce phase shifting effects into the fluid motion. As a result, prediction derived from Reynolds equation can be significantly in error. Here an improved expression is developed for the dynamic characteristic in terms of Reynolds's number for a particular electro-rheological fluid. Bingham model has been used to describe the behavior of the electro-rheological fluids. The result leads to improvements and explain why it is significant to include fluid inertia forces which have large effects on dynamic characteristics.

***Index Terms*—Dynamic characteristics, Squeeze film damper, Electro-rheological fluid, Reynolds number.**

I. INTRODUCTION

Aircraft engine rotors are supported on roller bearings which offer very little damping. The amount of damping produced in bearing is a critical design consideration. When the damping is large, bearing acts as a rigid constraint with larger forces transmitted to the supporting structure. On other hand when the damping is small, the damper is inactive and permits large amplitude vibratory motion **[1]**. The mechanical response of roller bearing, considering low L/D ratio (less than one), is characterized in terms of stiffness and damping co-efficients. The hydrodynamic theory is used to derive the stiffness (K_d) and damping (C_d) coefficients for the conventional roller bearing. Gunter **[2],** derived the equivalent stiffness and damping co-efficients assuming short bearing approximations and are;

$$K_d = \frac{2\mu R L^3 e\omega}{c^3(1-e^2)^2} \tag{1}$$

$$C_d = \frac{\mu R L^3 \pi}{2c^3(1-e^2)^{3/2}} \tag{2}$$

The aero engines run at high speeds. The high speed necessitates at least once crossing the system critical speed, which results in self-excited instability called "whirl instability" [3]. Equations (1) and (2) for stiffness and damping are derived on the basis of Reynolds's equation, which do not consider inertia forces, can be significantly in error. Though the equations have limitations at higher speeds, they provide information that, some parameters like viscosity can be manipulated. Researchers have taken the advantage and employed smart fluids which offer variable viscosity for achieving desired values of stiffness ($K_d)$ and damping (C_d) coefficients. Electro-rheological fluids are one such class of smart fluids.

The rheological properties (viscosity, yield stress, shear modulus etc.) of electro-rheological fluids are readily controlled by an external electric field. Electro- rheological fluids are the suspensions of fine particles in liquids such as non-conducting oils. When subjected to an electric field; the suspended particles becoming polarized and aligned into chains along the direction of field in spontaneously make the fluid a gel-like solid. These chains resist shear along the direction vertical making the liquid to respond like a solid. When the field is removed, within milliseconds, the material reverts back to a liquid state. The degree of gelling is proportional to the strength of the electric field. Varying the voltage, any state between liquid and solid can be quickly selected. In absence of electric field the electro-rheological fluid exhibits Newtonian flow where the shear stress is proportional to shear rate. When an electric field is applied a yield stress phenomenon appears and no shearing takes place until the shear exceeds a minimum yield value that increases with the field strength, i.e., the fluid appears to behave like Bingham plastic [4]. The electro-rheological effect was first described by Willis Winslow in 1949; previously this phenomenon was referred to as the electro-viscous effect [5].

Electro-rheological fluids require electric field strength in the order of tens kilovolts per millimeter. Winslow's, in his initial experimentation found that 3 kV/mm field strength was sufficient. The electro-rheological fluids are continued to be explored and implemented with the advent of new technology, like nanotechnology.

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A typical squeeze film damper is shown in figure (1) [6]. Squeeze film dampers have proved extremely useful in high speed rotors for vibration isolation.

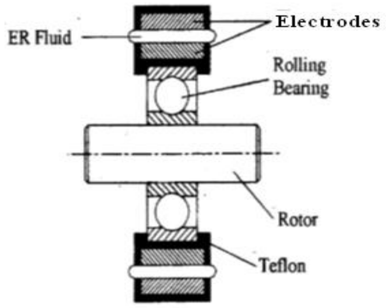

Fig: 1- Typical ER Fluid squeeze film damper

The outer race of the ball bearing (inner damper element) supports the shaft and adds additional external damping to the bearing support. A fluid film separates the inner and outer elements of the damper. The inner damper element does not rotate; the destabilizing effects that associated with cross coupled stiffness of the hydro dynamic films, thus eliminated [**7**].

Models have been developed to explain the behavior of electro rheological fluids. One of such model is Bingham model. The behavior of electro rheological fluid is described by the Bingham plastic model **[8]**. A simplified model of electro rheological fluid is shown in the figure (2).

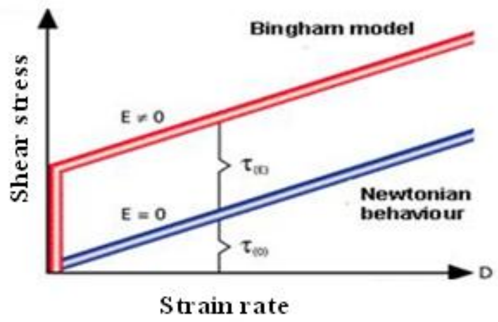

Fig: 2- Simplified Bingham model

According to the model; a material behaves like a solid until a minimum yield shear stress τ_y is applied, when the applied shear stress τ exceeds τ_y, the material behaves like a fluid. In this domain the shear stress is proportional to shear strain rate **[9].** According to this model; the total shear stress is given by

$$\tau = \tau_y \; Sgn(\dot{\gamma}) + \mu \dot{\gamma} \qquad (3)$$

In practice, when shear rates are larger the electro rheological fluids exhibits shear thinning and shear thickening which is shown in the figure (3).The Herschel-Bulkley visco-plasticity model is employed to accommodate this effect instead of Bingham model.

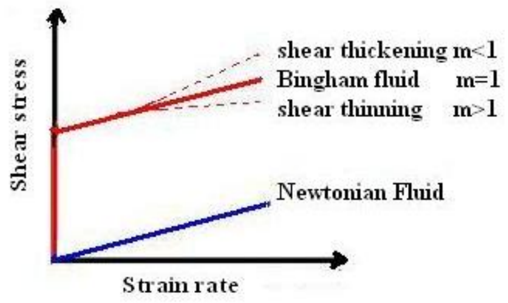

Fig: 3 -Visco-plasticityHerschel-Bulkley model

Herschel-Bulkley model, replaces the constant post-yield plastic viscosity in the Bingham model with a power law model which depends on shear strain rate and is;

$$\tau = \left(\tau_o(E) + K|\dot{\gamma}|^{\frac{1}{m}} \right) Sgn\dot{\gamma} \qquad (4)$$

Where m and K are fluid parameters which are positive integers.

Comparing equation (3) and (4), the plastic viscosity of the Herschel Bulkley model μ_e is;

$$\mu_e = K|\dot{\gamma}|^{\frac{1}{m}-1} \qquad (5)$$

Equation (5) indicates that the equivalent plastic viscosity μ_e decreases as the shear strain rate $\dot{\gamma}$ increases when m >1 (Shear thinning). Further, this model can also be used to describe the fluid shear thickening effect when m < 1. The Herschel-Bulkley model reduces to the Bingham model when m =1 **[10]**. Hence,

$$\mu_e = K.$$

II. MODELLING OF ELECTRO RHEOLOGICAL FLUID RESPONSE - DIMENSIONAL ANALYSIS APPROACH:

In the present work, a dimensional analysis approach is used for finding the effect of strain rate ‘ $\dot{\gamma}$ ’and intensity of applied electric field ‘E’ on the viscosity of electro-rheological fluid. Assuming μ_e is largely depends on $\dot{\gamma}$ and E, it is possible to obtain a relation between the viscosity, shear strain rate and the intensity of the applied electric field using Rayleigh’s method of dimensional analysis.

Using the equation of the form;

$$\mu_e(E) = K|\dot{\gamma}|^p (E)^q \qquad (6)$$

Introducing the corresponding MLT units,

$$ML^{-1}T^{-1} = K\left(T^{-1}\right)^p \left(M^{\frac{1}{2}} L^{-\frac{1}{2}} T^{-1} \right)^q \qquad (7)$$

Equating the coefficients of M, L, and T on both sides and simplifying, we get;

p = -1, q = 2

Introducing these values in equation (6) one can obtain;

$$\mu_e(E) = K|\dot{\gamma}|^{-1} (E)^2 \qquad (8)$$

This is the incremental viscosity produced due to the application of the electric field.

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The total viscosity μ_t if the sum of the field dependent and field independent viscosities is,

$$\mu_t = K|\dot{\gamma}|^{-1}E^2 + K|\dot{\gamma}|^{\frac{1}{m}-1} \quad (9)$$

Janusz-et. al., [11] observed that the shear thinning is a common feature when shear strain rate are large. For such condition 'm' takes a value which is very larger compared to unity. (i.e., m>1), when 'm' is very large the equation (9) can be written as,

$$\mu_t = K|\dot{\gamma}|^{-1}E^2 + K|\dot{\gamma}|^{\frac{1}{m}-1} \quad (10)$$

$$\mu_t = \left[K|\dot{\gamma}|^{\frac{1}{m}-1}\right](1+E^2) \quad (11)$$

Equation (11) is applicable for electro-rheological fluids which undergo large degree of shear thinning.

$$\mu_t = \mu(E)(1+E^2) \quad (12)$$

where $\mu(E) = \left[K|\dot{\gamma}|^{\frac{1}{m}-1}\right]$

The equation (12) represents the total viscosity of the electro-rheological fluid under the action of the electric field. Viscosity is proportional to the square of the electric field intensity and hence the yield stress τ_y is proportional to E^2. Sharana Basavaraja et. al. **[12]** takes 1.100×10^{-7} Pa-s for $\mu_{0(\text{Zero field viscosity})}$ and a range 0 to 4 kV/mm for 'E'. Equation (12) is used to estimate *μt taking* the values of *μo* and E. The estimated value of *μt(E)* is plotted as a function of E and this is shown in the figure (4).

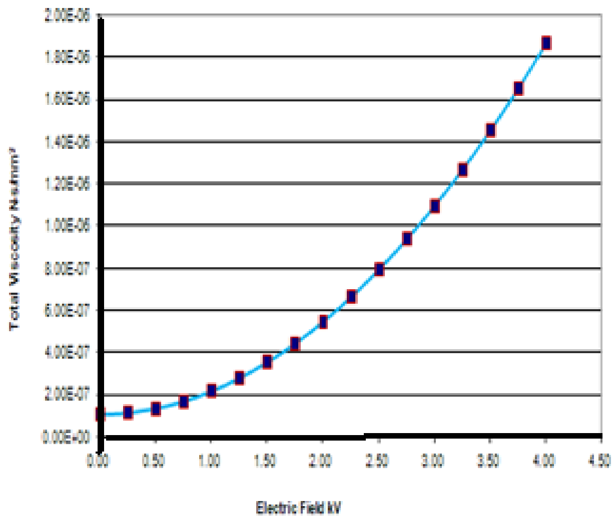

Fig: 4 - viscosity model for ER fluid

III. ANALYSIS OF SHORT BEARING LUBRICATED WITH SMART FLUIDS

The utility of electro-rheological fluids can be illustrated in case of aero engines. The aero engines rotor runs at a very high speed and equation (1) and (2) are inadequate in predicting the behaviour because they do not account the inertia forces. The inertia forces can be accounted considering Reynolds's number. Tichy **[13]** has expressed Reynolds number as a function of viscosity.

The expression is;

$$R_e = \frac{\rho\,\omega\,c^2}{\mu_{app}} \quad (13)$$

Substituting μ_t in place of μ_{app} in equation (13) which takes the form,

$$R_e = \frac{\rho\,\omega\,c^2}{\mu(\mathbf{E})\,(1+E^2)} \quad (14)$$

Equation (14) is an expression for Reynolds number as a function of 'E' which is applied voltage on smart fluid is used. The Reynolds number as a function of E for different constant angular velocities (ω) are plotted in figure (5).

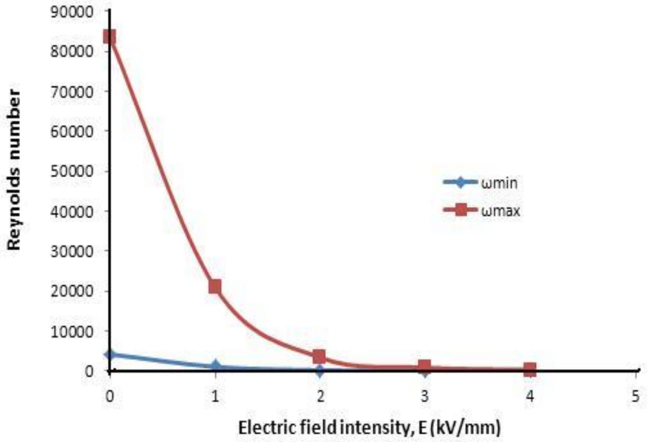

Figure-5 Reynolds number as a function of electric field intensity for different angular velocities

The two speeds ω are 32 and 630 rad/sec. These speeds correspond to a typical minimum and maximum speed of aero engines. The graph shows Reynolds number is still a strong function of speed, compared to E (Smart fluids). Thus, the smart fluids contribute for Reynolds number.

For finding the relative influence of μ(E) of smart fluids and speed ω of rotor on Reynolds's number, a ratio $\frac{\partial R_e}{\partial E} / \frac{\partial R_e}{\partial \omega}$ is estimated. The estimated values of ratio as a function of E is plotted in figure (6).

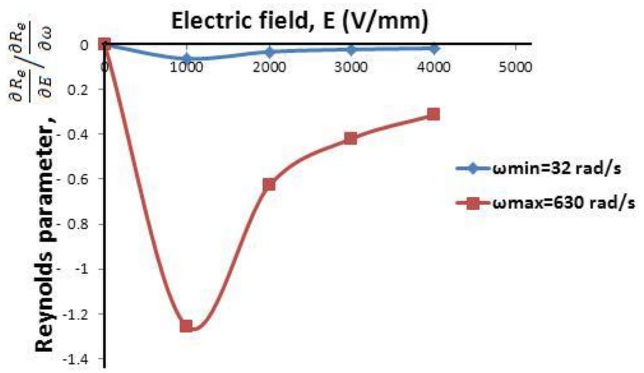

Figure-6 Variation of Reynolds parameter as a function of electric field for different angular velocities

The estimated ratio is not much dependent on 'E' at low speed of 32rad/sec. At high speeds of 630 rad/sec, the ratio is reaching a peak value of magnitude 1.3 at 1000V/mm and stabilizes to magnitude of 0.4 after 3000V/mm.

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Dependence of Reynolds number on E which is shown in figure (5) and the ratio shown in figure (6) suggests that Reynolds number influences the mechanical response of smart fluids.
The direct stiffness (K_d) and direct damping (C_d) using equation (13) are expressed in terms of Reynolds number to evaluate the influence of Reynolds number on direct stiffness (K_d) and direct damping (C_d).

The equations are;

$$K_d = \frac{\rho\,\omega^2 D^2 L^2 (L/D)\epsilon}{c(1-\epsilon^2)^2 R_e} = \frac{A}{R_e} \tag{15}$$

Where $A = \dfrac{\rho\,\omega^2 D^2 L^2 (L/D)\epsilon}{c(1-\epsilon^2)^2}$

$$C_d = \frac{\rho\,\omega D^2 L^2 (L/D)\pi}{4c(1-\epsilon^2)^{3/2} R_e} = \frac{B}{R_e} \tag{16}$$

Where $B = \dfrac{\rho\,\omega D^2 L^2 (L/D)\pi}{4c(1-\epsilon^2)^{3/2}}$

Equation (15) and (16) describes the direct stiffness and damping co-efficients as a function of Reynolds number.
The constant A and B represents the direct stiffness and damping co-efficients of the damper operating at unit Reynolds number and is a function of damper configuration, excitation frequency and the type of fluid used.
The ER fluid data and damper specification with reference to figure (1) used in estimating direct stiffness (K_d) and direct damping (C_d) are tabulated in the table 1and 2.

Table 1: ER Fluid Specifications

Type	Manufacturer	Density, Kg/m^3	Viscosity mPa
Lid 3354	Lord Corporation	1.46X10^3	110

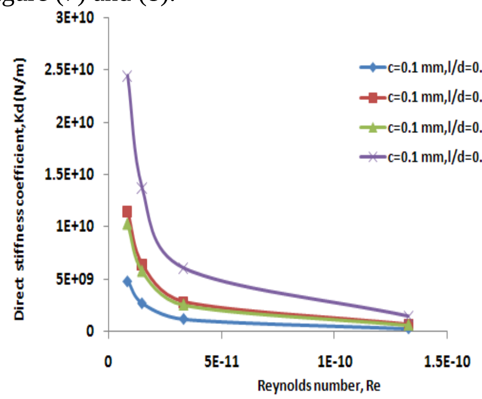
Table 2: **ER Squeeze Film Damper/Journal Bearing**

Description		
Clearance c, mm	0.1	0.2
ength L, mm	30	40
Diameter, D mm	100	100
L/D Ratio	0.3	0.4
Excitation Frequency,(ω , rad/s)	100	100
Eccentricity ratio,(n)	0.1	0.1

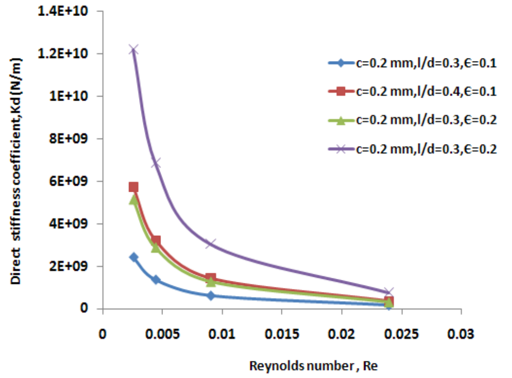
Specifications

IV. RESULTS AND DISCUSSIONS

The estimated values of direct stiffness (K_d) and direct damping (C_d) as a function of Reynolds number is plotted in the figure (7) and (8).



(a)

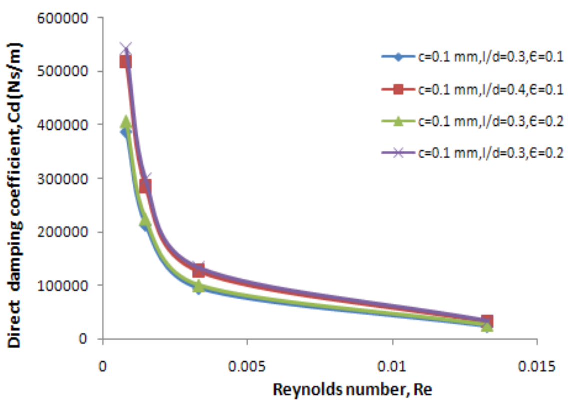


(b)

Fig. 7: Direct Stiffness coefficient (N/m) vs. Reynolds number for clearances (a) c=0.1 mm (b) c=0.2

The maximum and minimum values of the stiffness coefficient are attained with different damper configurations as shown in the figure (7). Thus the stiffness coefficient is enhanced by smaller clearance, higher L\D ratio and eccentricity. The direct stiffness (K_d) approaches infinity as Reynolds number approaches zero, on the other hand, the direct stiffness (K_d) approaches zero as the Reynolds number approaches infinity. This variation in the values of direct stiffness (K_d) is due to the response of smart fluids with the change in the applied field 'E'. The smart fluid offer higher viscosity at higher voltage rendering the fluid to bear longer load and hence larger value of direct stiffness (K_d). Thus the damper cannot be operated in the lower range of Reynolds number as the rotor becomes too rigid movement to generate the required damping forces. Similarly, the damper cannot operate at higher Reynolds number as it yields a highly flexible rotor, incapable of generating the required pressure forces to support the load. Thus the damper has to operate at an optimum Reynolds number for its satisfactory performance.

The values of direct damping (C_d) decreases with increasing in Reynolds number as shown in figure (8).



(a)

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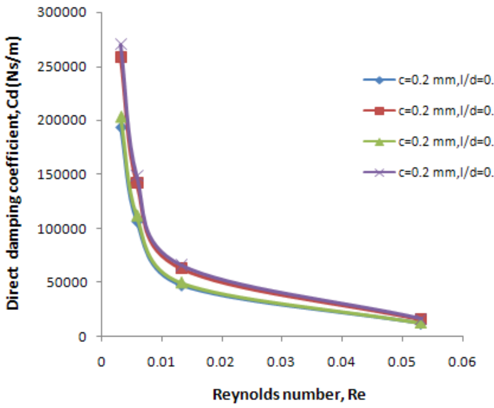

(b)

Fig. 8: Direct Damping coefficient (Ns/m) vs. Reynolds number for clearances (c) c=0.1 mm (d)c=0.2 mm

The maximum and minimum values of the damping coefficient are found to depend on Reynolds number with different damper configurations. The direct damping (C_d) is found to be independent of damper configuration unlike the direct stiffness (K_d) which depends on the damper parameters.

V. CONCLUSION

The above analysis indicates that the electro-rheological fluids can be successfully applied in the squeeze film dampers to provide variable stiffness and damping in accordance with the requirement of the rotor dynamic system.

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