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A Study of Stiffness and Damping Characteristics of Conventional Fluid and Smart Fluid Applied to Squeeze Film Damper

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Abstract— Turbo machinery and other high speed engines play a vital role in industries worldwide. These high speed engines received considerable attention from the scientific and industrial community in order to extract better performance and higher reliability. Due to competitiveness and rapid technological advancement, the dynamic behavior of these machines is greatly dependent on the fluid film bearings. These fluid film bearings are used for its long life, low power consumption and versatile dynamic behavior. Despite of significant advancement in lubrication technology and advent of meticulous design procedures, bearings do fail in operation. Accordingly tribologists and practicing lubrication experts around the world are nowadays involved in design of general bearing system using entirely a design approach based on electrorheological fluids instead of conventional fluids to suit the requirement of high speed and heavy load operation. 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 which cannot be carried out in case of conventional fluids. This paper presents a comparative study of stiffness and damping characteristics of conventional fluids (damper oil) and electro rheological fluids (functional fluids) of external damper becomes a essential part of analysis. Calculations are carried out for different parameters like clearances, oil film thickness, fluid film width, different eccentric ratios etc. Thus the use of electro-rheological 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. This reduces the amplitude considerable and safe operation for high accuracy and efficiency.

Index Terms— High speed engines, fluid film bearings, conventional fluids, electro-rheological fluids, stiffness and damping, vibration.

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-efficient. 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-efficient assuming short bearing approximations and are;

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

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

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”. Theroto-dynamic instabilities have become more and more common as the speed and horse power of turbo machinery have increased. These instabilities can be erratic, seemingly increasing vibration amplitude for no apparent reasons **[3].** Equations (1) and (2) for stiffness and damping are derived on the basis of Reynolds’s equation, 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 instantaneously 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, ie, 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.

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Thee lectro-rheological fluids are continued to be explored and implemented with the advent of new technology, like nanotechnology.

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.

A hydrodynamic squeeze film damper (SFD) is essentially a bearing within a bearing. In general, a SFD is often considered to be a bearing system that accommodates both advantages of journal and ball bearing (see fig 1). In squeeze film damper rotor shaft rotates with the inner race of a supporting ball bearing, whereas its stationary outer race, which acts as the journal of SFD, whirls within the housing of the SFD. Whereas, the outer race is usually prevented from rotating and the squeezing action from the oil action from the cavity gives rise to damping forces.

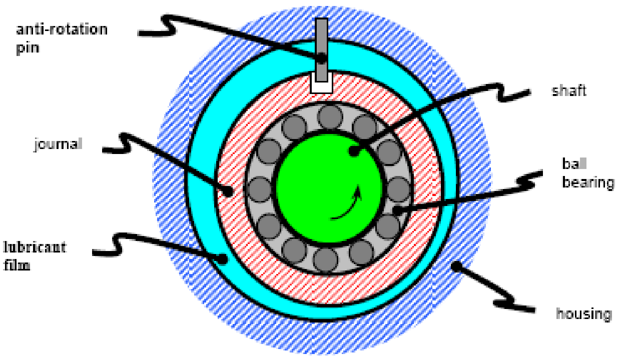

Fig: 1 - Typical squeeze film damper

A squeeze film damper(SFD) installed at a outer race of a ball bearing support shaft adds externally additional damping to the flexible rotor system for improving damping capacity, vibration and stability**.** 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).

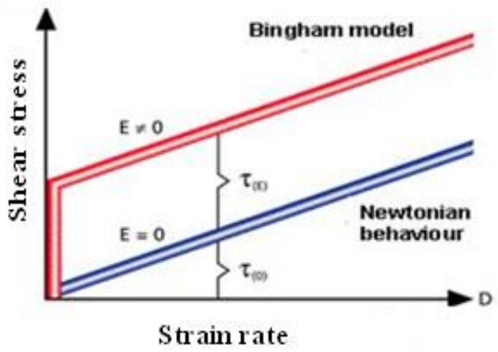

Fig: 2- Simplified Bingham model

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

$$\tau = \tau_y \, Sgn(\dot{\gamma}) + \mu \dot{\gamma} \quad (3)$$

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.

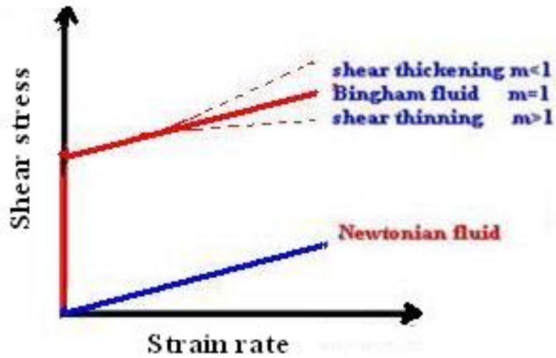

Fig: 3 -Visco-plasticityHersche**l**-Bulkley model

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;

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

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;

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

Eqn. (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,

$$\mu_e = K \, .$$

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;

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

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

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

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,

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

(10)

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

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

$\mu_t = \mu(E)\,(1+E^2)$ (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 eta l **[12]** takes 1.100x10^{-7} Pa-s for $\mu_{(0)}$ (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 $\mu_t(E)$ is plotted as a function of E and this is shown in the figure (4).

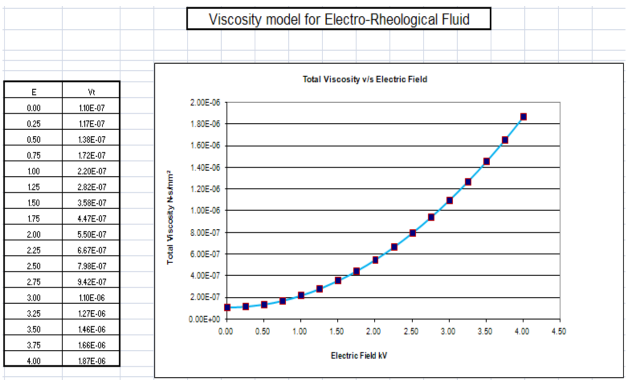

Fig: 4 - viscosity model for ER fluid

II. ANALYSIS OF SHORT BEARING LUBRICATED WITH CONVENTIONAL AND SMART FLUIDS

The Conventional/Electro-rheological 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. A separate graph is drawn for stiffness and damping.

Table – 1 Conventional/Electro-rheological Fluid Data

Type	Manufacturer	Density, Kg/m^3	Viscosity mPa
Lid 3354	Lord Corporation	1.46X10^3	110
Conventional fluid		835	480

Table – 2 ER Squeeze Film Damper/Journal Bearing Specifications

Description	Parameters	
Clearance c, mm	0.1	0.2
Fluid film Length L, mm	30	40
Fluid film Diameter D, mm	100	100
L/D Ratio	0.3	0.4
Excitation Frequency, (ω, rad/s)	100	100
Eccentricity ratios, e	0.25, 0.5	0.25, 0.5

GRAPH FOR STIFFNESS - Kd

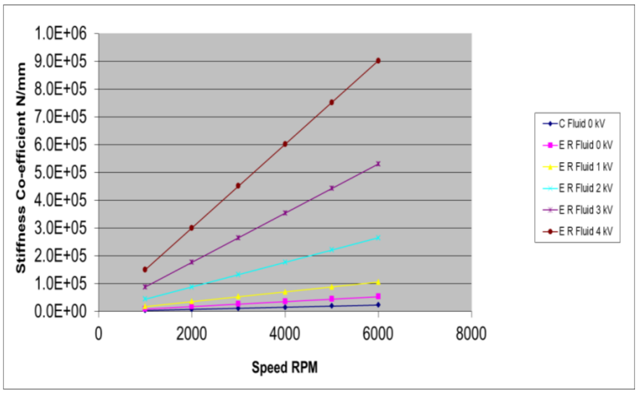

Fig: 5 Speed Vs Stiffness for e=0.25, L/D=0.3

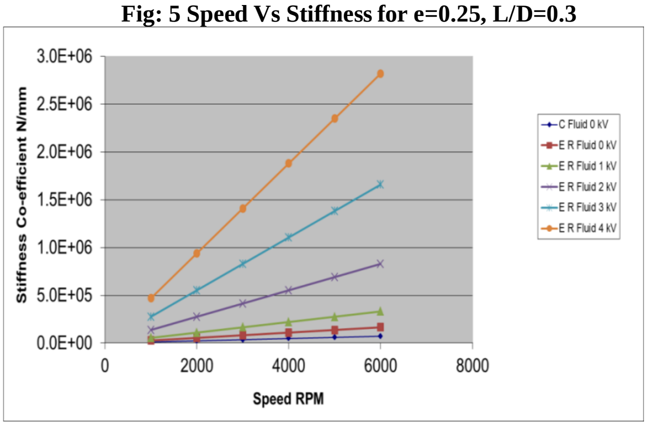

Fig: 6 Speed Vs Stiffness for e=0.5, L/D=0.3

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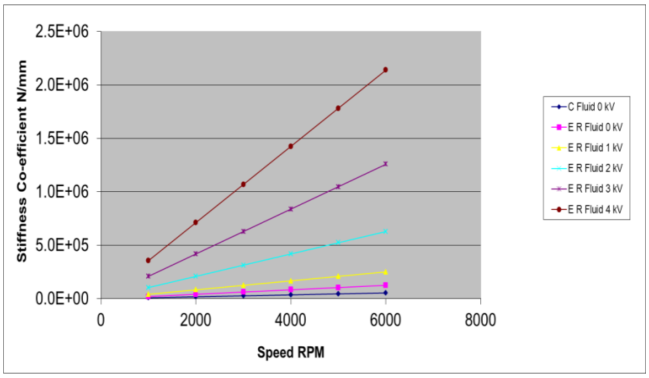


Fig: 7 Speed Vs Stiffness for e=0.25, L/D=0.4

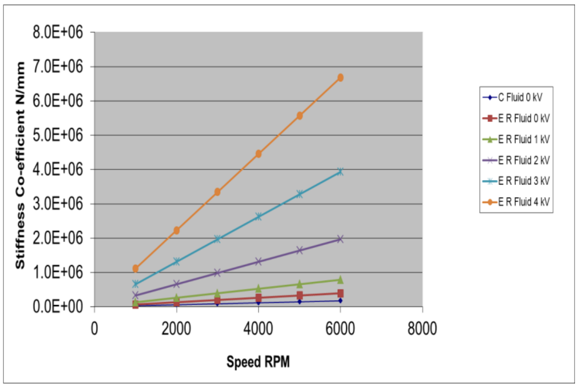
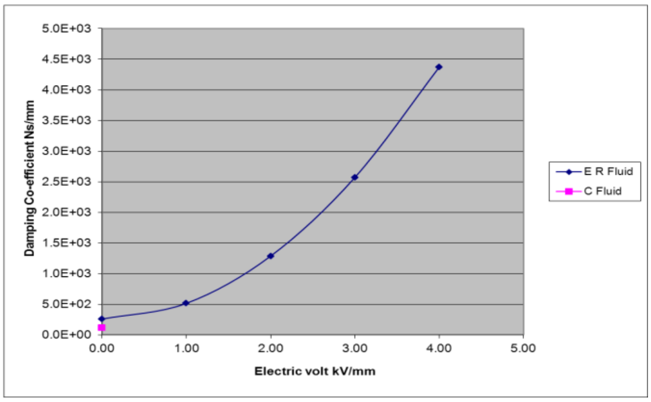


Fig: 8 Speed Vs Stiffness for e=0.5, L/D=0.4



GRAPH FOR DAMPING - Cd

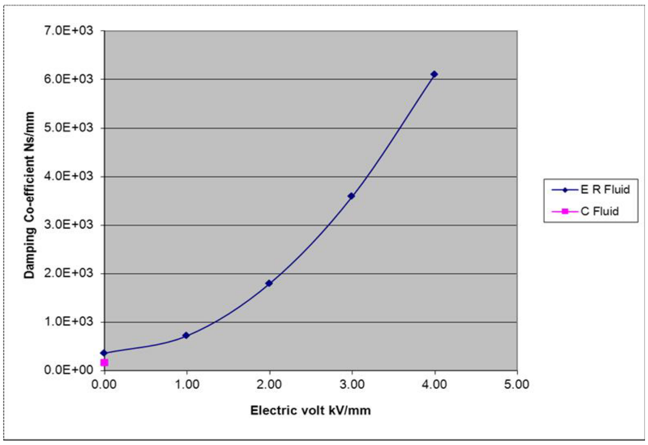


Fig: 9 Electric Current Vs Damping for e=0.25, L/D=0.3

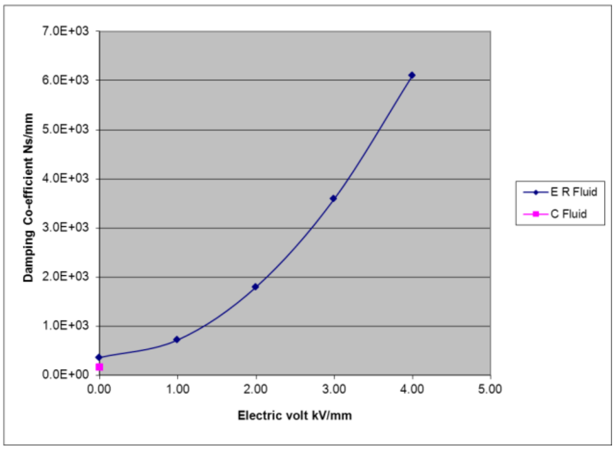


Fig: 10 Electric Current Vs Damping for e=0.5, L/D=0.3

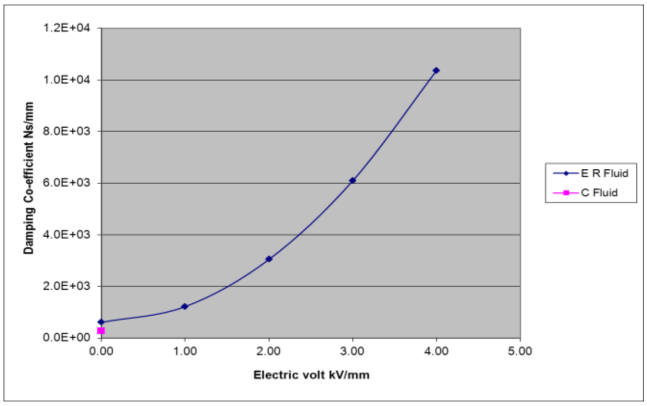


Fig: 11 Electric Current Vs Damping for e=0.25, L/D=0.4

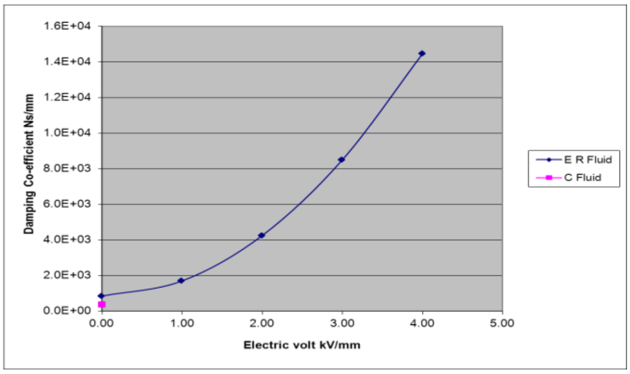


Fig: 12 Electric Current Vs Damping for e=0.5, L/D=0.4

III. RESULTS AND DISCUSSIONS

The theoretical investigation reveals that

- For the range of speeds the stiffness offered by the electro-rheological fluid is higher than that of the conventional fluid at zero volts.
- For the same range of speeds the stiffness offered by the electro rheological fluid is much higher than that of conventional fluid as the voltage varies from 1kV/mm to 4kV/mm for the ER Fluids.
- For zero volts the damping offered by the electro rheological fluid is higher than that of conventional fluid.

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- As the voltage varies (1kV/mm to 4kV/mm) the damping offered by the ER fluid is much higher than that of conventional fluid. These are automatic feedback control systems or devices in which the rheological property (Viscosity) varies in accordance with the field, thereby influencing the stiffness and damping coefficients. The rotor amplitude thus lays the safe levels prescribed by the designer.

IV. CONCLUSION

This paper has been concerned with an assessment of the comparative study of the conventional fluid (damper oil) and the electro-rheological fluid (functional oil). These fluids were seen to behave very differently and the analysis confirms the advantage to be gained by employing electro-rheological fluids. Ultimately it is intended to incorporate the result of study of the stiffness and damping characteristics using the viscosity model developed. This enables or aids the designer to obtain the stiffness and damping characteristics using the squeeze film damper. The study results are shown in the graphs. An attempt is made here to link the flow characteristics of the fluid to the damping and stiffness characteristics of the electro-rheological fluid squeeze film damper. Also this coefficient can be controlled by the intensity of electric field, thus paving the way for active squeeze film damper.
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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