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Investigation about Electrorheological Squeeze Film Damper Applied to Active Control of Rotor Dynamic

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Electrorheological (ER) fluids, discovered in 1947 by W. WINSLOW, are concentrated suspensions of solid particles in an oily base liquid. Exposed to a strong electric field, their resistance to flow increases very greatly and this change is progressive, reversible and occurs very rapidly. Nowadays, ER fluids, made of lithium salt and fluorosilicon got rid of their old abrasive characteristics and are able to provide a good interface between electronics and mechanical components. A bibliographical study on ER fluids and ER technology has been carried out. The aim of this study is adapting ER technology to Squeeze Film Damper. In order to provide an active control on a flexible rotating shaft so as to command the whole shaft/bearings device in case of high rotating speed or heavy load trouble. Results of numerical computation of a shaft bearing assembly with a Squeeze Film Damper using negative ER fluid are showed in order to see the possibility of avoiding critical speeds by natural frequency shifting. A technical study of ER Squeeze Film Damper design is also presented, taking into account ER fluid properties and ER technology requirements.

Keywords: Squeeze Film Damper, Active Control, Electrorheological Technology, Non Linear Behavior

INTRODUCTION

Electrorheological fluids, says ER fluids, are types of liquid semi-conductors. They are concentrated suspensions of solid particles in an oily base liquid. Normally, they behave like a medium oil, but when they are exposed to a strong electric field, they seem to "coagulate". An increase of the frictional forces of the fluid on the wall appears. So this "coagulation" induces a change of the apparent viscosity of the fluid. This change is gradual, reversible and proportional to the applied electric field. It occurs very rapidly. The time lapse is very short, about 1 millisecond. In spite of the high tension required to obtain the ER effect, the total needed power is weak. The current never exceeds some microamps. Thus, ER fluids are able to provide a good interface between a mechanical device and an electric control system. Moreover, the speed of response could allow the realization of mechanical devices actively controlled by "electronic management".

Squeeze Film Damper is a kind of bearing damper. It has been studied for many years and its industrial applications are numerous such in aircraft gas turbine engines. The basic idea is to support a ball bearing in a fluid bearing. The rotation is insured by the ball bearing and the oil film is squeezed between the two no-rotating rings (Figure 1). For the case of a flexible shaft mounted on two bearings, one holding a Squeeze Film Damper, the numerical approach have showed that the damping of a Squeeze Film Damper could be modified by changing the viscosity of the oil.

The aim of this work is to explore the possibility of using the viscosity change of an ER fluid in a Squeeze Film Damper, in order to control the dynamic behavior of the shaft. Following this view, on has decided to study ER fluids and ER technology. The first part of this paper sums up a bibliographical research about ER fluids in order to explain how ER fluids behave. The second part is an approach of ER technology to describe the difficulties to use ER fluids in a mechanical device and to present on example of ER Squeeze Film Damper

CHRONOLOGICAL ACCOUNT

The first electrorheological effect was observed by A. W. DUFF [1896]. He was studying, at that time, the effect of electric field on liquids like glycerin, castor oil and paraffin. He observed that the viscosity of these fluids increases slightly when they are exposed to an electric field. Since this report, many research activities have been carried out, but they showed contradictory results. In 1935, Y. BJORNSTAHL, SNELLMAN and ANDRADE tried to explain electrorheological phenomena. They attributed it to an electrophoresis of ions between particles and base liquid, followed by the creation of particles clusters. The first well-marked electrorheological effect was reported by W. WINSLOW [1947]. W. WINSLOW s' suspension was made of activated silica gel particles and kerosene. With that suspension the electrorheological effect appears for an electric field of 30000 V/m. As soon as 1949, W. WINSLOW realized some electrorheological devices. The electrorheological valve and the electrorheological clutch are the most famous. Works of the same kind of W.WINSLOW's have been reported in Russia, by A. V. LIKOV, R.G. GOROKY and Z. P. SHULMAN [1968].

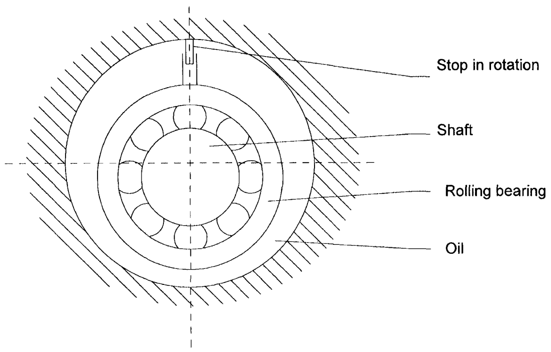

FIGURE 1 Squeeze Film Damper.

The potential value of WINSLOW's fluids aroused many interests from industrial people. Vibration actuator and electrically controllable damper were considered. Unfortunately, their strong abrasive nature reduce their utilization in commercial applications to nothing. So, research moved towards explanation of the ER effect, in order to improve electrorheological fluids. KLASS and MARTINEK [1966], reported observations about rheological and electrical behaviors of WINSLOW's fluids. They, also, presented a theory of ER effect. It supposed that clusters of particles developed because of induced polarization of particles. In 1974, OKAWAGA suggested that particles in the fluid underwent a spin due to electric field which modified the apparent viscosity of the suspension. Another theory, named "water bridges" was presented. It suggested that particles held together, in clusters, by means of water links due to interfacial tension between water and base liquid. Nowadays J. E. STANGROOM [1983] has developped electrorheological technology to provide industrial uses of electrorheological fluid.

NATURE AND BEHAVIOR

Electrorheological fluids are suspensions of high dielectric particles in an insulating liquid. The particles are spherical and have an average size between 5 and 10 micrometers, in order to act lightly on the suspension viscosity. The particle density must be close to the liquid density to avoid sedimentation. A lot of suspensions present an electrorheological activity. Hence, it's difficult to define precisely the components of an electrorheological suspensions. WINSLOW's fluids were made of activated silica gel powder into a kerosene fraction for a concentration of about 50 percent by volume. They showed electrorheological effects for a field about 30000 V/m. Current fluids are different. They are suspensions of porous particles of lithium polymer salt in a fluorosilicon oil. These arrangements allowed to reduce abrasion and sedimentation risks. But they are done to the detriment of good conducting particle's properties. The fluorosilicon oil is one of the rare liquids to combine high boiling point, low freezing point, low viscosity and a density close to solid particle density. Moreover, it is biologically inert and non aggressive against common engineering materials including natural and synthetic rubber. A large number of criteria interfere in ER fluid manufacturing: insulation, conductivity, working temperature, electric field, corrosive properties of base liquid, abrasive properties of particles, chemical stability of the mix, size of the particles. The list is non exhaustive. This high number of criteria makes the ER fluid specifications complex. An expensive study is often required to design a new ER fluid.

Out of any electric field, the ER fluid behavior could be assigned as a Newtonian fluid. The viscosity of the suspension is given is this case by Einstein formula (Figure 2).

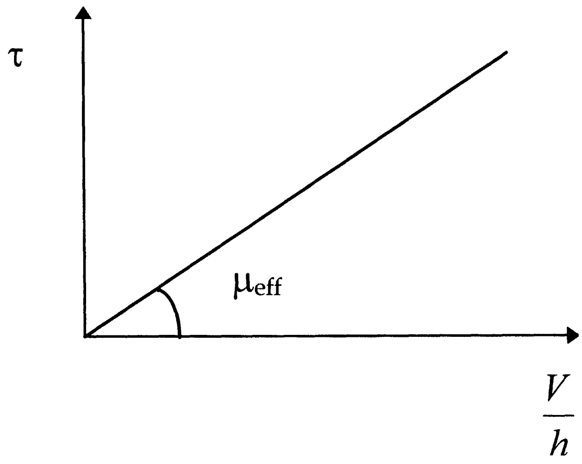

FIGURE 2 ER fluid without electric field.

$$\mu_{eff} = \mu \cdot \left(1 = \frac{5}{2} \cdot \varphi\right)$$

Where μ is the viscosity of the base liquid and is the volume of particles up to the total volume of the suspension. When an electric field is applied to the fluid, it behaves like a "Bingham solid". Figure 3 shows the representation of the fluid behavior. The fluid behaves like a solid until the shear stress τ exceeds the yield stress τ'. When the shear stress is up to the yield stress, the fluid could be assimiled to a Newtonian fluid whose Newtonian viscosity is μ_{pl}, say "plastic viscosity".

In fact, the fluid follows a model of rheopexy, namely a hysteresis in the fluid behavior next to the yield stress (Figure 4). Another particularity of ER effect is that, like most materials, the "sticking" friction is greater than the "sliding" friction. In other words, the force required to initiate a flow or a shearing is greater than the force needed to maintain it. So it can be considered that there are 2 types of yield stress, a "static" one and a "dynamic" one.

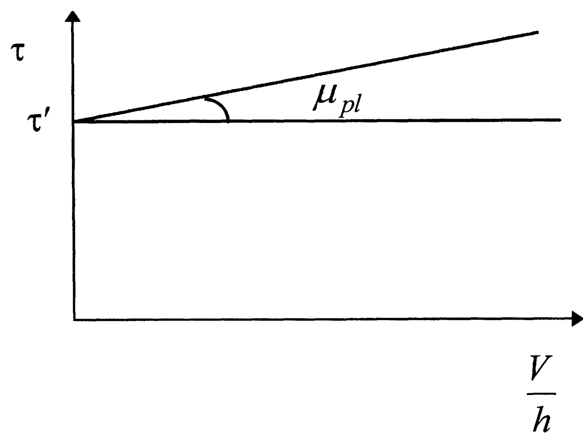

FIGURE 3 ER fluid with electric field.

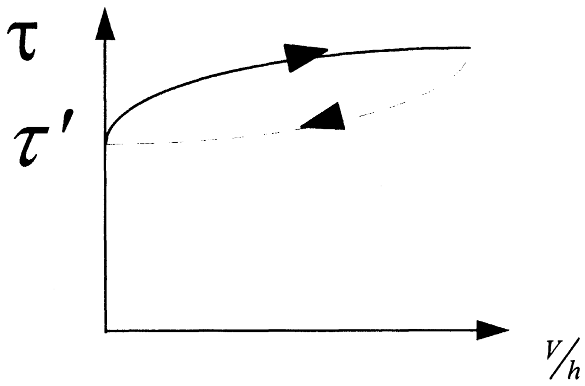

FIGURE 4 Rheopexy.

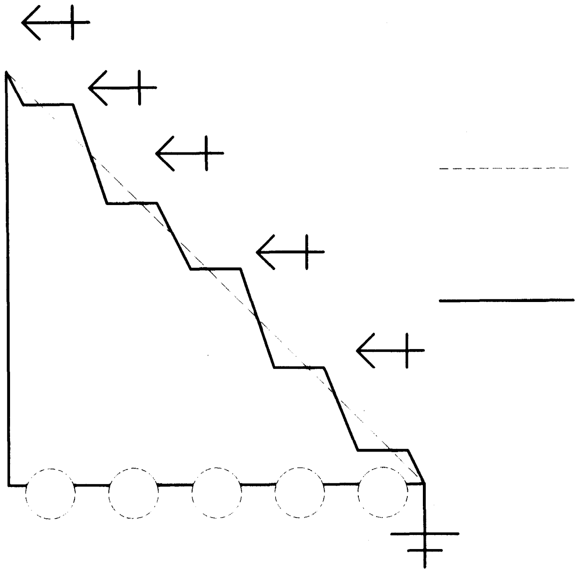

FIGURE 5 Theory of induced dipole.

THEORIES OF THE ELECTRORHEOLOGICAL ACTIVITY

In a microscopic view of the ER effect, the application of an electric field induces the formation of particles' chains. These particles' chains are organised in fiber roughly parallel to the direction of the field. The fluid flow or the fluid shearing can only take place if the chain structure is destroyed. But the presence of the electric field tends to continually reform these chains. There is then a destruction/construction equilibrium. This constant confrontation provides a supplementary mean of dispersing energy.

There is no general theory on the mechanism of ER fluids. A lot of questions are still pending. and theories are needed to explain the ER activity. In this paragraph, we will present the three major theories: the theory of induced dipole, the theory of water joining and the theory of the opposite spins. All these theories give a reliable explanation of the ER effect but each of them fails to explain some experimental behavior.

The first one, the theory of induced dipole supposes that, due to the high dielectric constant, the particles become induced dipoles when they are put in an electric field. A diagram shows this effect in figure 5. When the fluid is placed between two electrodes, the field is uniform for pure oil, but for high dielectric constant particles in the liquid, the field gradient is reduced in the particles. Then, particles behave like independent electric dipoles. These dipoles can also interact and form chains along the field direction. Some authors try to improve this theory by considering particles geometry, but the fundamental features remain unchanged.

The second theory is the water joining's one. It considers that ER fluid is a suspension of hydrophilic and porous particles in a hydrophobic base liquid. The particles contain a certain amount of water, the absorbed water influences greatly the performance of the ER fluid. The water is hold by mobile ions M_+ which can move between the pores of the particles as seen on Figure 6. When the field is applied, the mobile ions move to one end of the particle, carrying water molecules with them. Thus, this end of the particle becomes overtly wet and water joining can also form between particles. The water joining holds the particles together by interfacial tension. This effect is often compared to dry flour added with water. This theory fails to explain the activity of ER fluid without water.

The third theory considers that the particles are spherical. If the ER fluid is placed in a flow or between two shearing plates, the particles spin due to the velocity gradient (1) as seen on Figure 7. The particles have a high dielectric constant so they be-

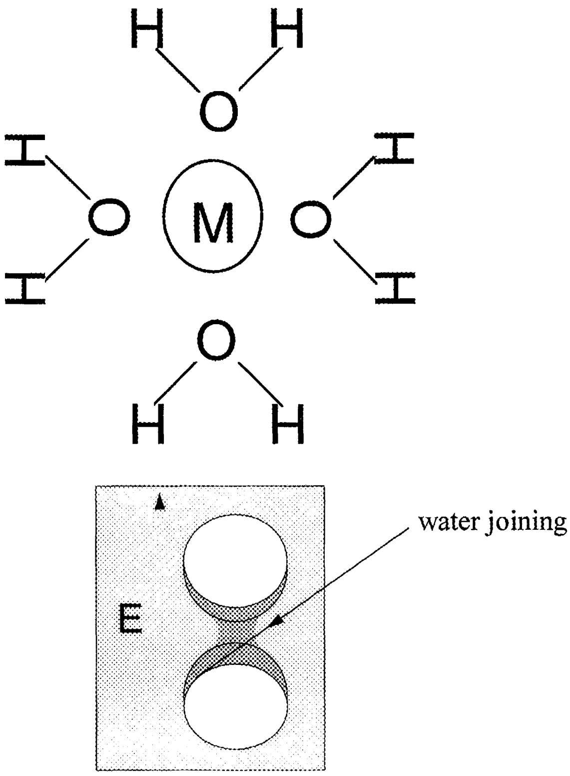

FIGURE 6 Theory of water joining.

come induced dipoles. These dipoles in particles are expected to carry out an alignment with the field. Therefore the particle presents a couple (2) opposing the spin and also opposing the flow. This couple is dependent on the electrical resistance of the particles. The apparent viscosity is then increased. The quantitative importance of this activity is not known. Moreover, this theory fail to explain the strong stiffness of ER fluid in presence of an electric field, when it is squeezed between two plates.

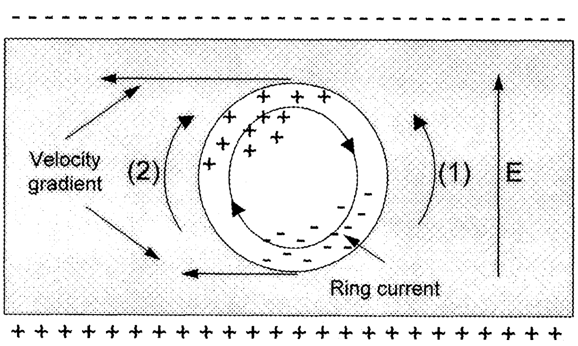

FIGURE 7 Theory of opposite spins.

NEGATIVE ELECTRORHEOLOGICAL FLUIDS

In general it is observed that the electric field is responsible for the sticking of high dielectric constant particles in chains for a low electric constant liquid. Negative ER fluids are suspensions of insulating particles in a high dielectric constant liquid. The effect of an electric field on these fluids is a decrease of the apparent viscosity. The advantage of this change is that the behavior remains Newtonian. The decrease can be explained by the following principle. Without an electric field, the insulating particles form chains in the liquid by their own attractions. These chains caused the suspension viscosity to be higher than the base liquid viscosity. If an electric field is applied, repelling between close spheres appears. Then the apparent viscosity of the suspension becomes lower than the initial viscosity. The major problem of this fluid is that, when removing the field, the viscosity retains its low value for a long time. This problem is due to a slow electrophoresis between particles and base liquid.

ELECTRORHEOLOGICAL FLUID PROPERTIES

This phenomenon appears for an electric field about 500 V/mm. As shown on Figure 4, the yield stress increases linearly with the field, contrary to the "plastic viscosity" which decreases linearly with the field. In extreme cases, the plastic viscosity could become negative (Figure 8).

The response speed of an ER fluid is high. The characteristic frequency is just under 1 kHz. Some ER fluids respond more slowly than this but rapidly enough in mechanical terms. The current through an

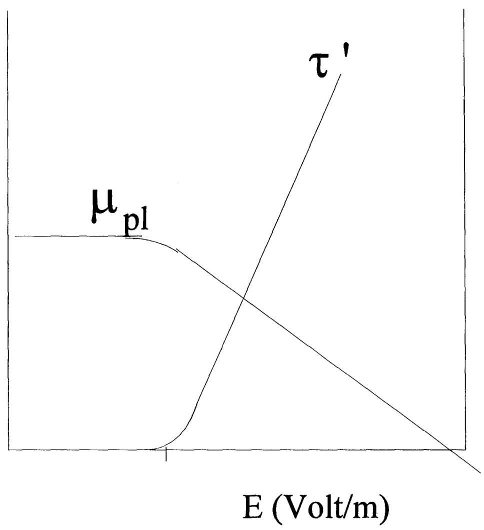

FIGURE 8 ER behavior versus field.

ER fluid is weak about 0,02 μA. It ensues a quadratic law. The current density can be written in function of the electric field E following the rule:

$$I = P(\cdot)E + Q(\cdot)E^2$$

where P can usually be ignored in estimation. Q varies with the temperature and follows a typical Boltzmann law:

$$Q = Q_0(\cdot)e^{\frac{-\Gamma}{kT}}$$

Q_0 and Γ are constants of the particular ER fluid. The temperature influences greatly the current density through the fluid. It can be assumed that the current doubles for each 6 or 12°C increase. This is the main problem of ER fluid. With such an increase of current tension arcing can occur and destroy fluid and device, and even can be potentially lethal. Consequently, good insulation has to be provided and power units must have a security device.

ELECTRORHEOLOGICAL TECHNOLOGY

In a previous work [Bonneau 1989] an elastic rotor mounted in a squeeze film damper was studied. A numerical and experimental comparison was carried out with good agreement. The conclusion of that work was the following: the influence of the squeeze film damper is very important and this effect is very different according to the rotor speed. When the rotational speed is close to a critical speed, the squeeze film damper has to dissipate a lot of energy and consequently the squeeze film damper must be flexible. On the other hand a high stiffness is better when the speed is very different from the critical speed. In [Bonneau and Frêne 1990] a squeeze film damper with an axial controlled flow was studied, the results were interesting but the obtained regulation was not effective enough. To realise a better control, an active squeeze film damper has been modelled [Bonneau and Frêne 1994]. The idea is to regulate the radial clearance by a parameter x corresponding to the position of a conical squeeze film damper in its housing. This control is completely mechanical and it is interesting now to develop a new approach using ER fluid. A numerical study to simulate the dynamical behavior of a flexible shaft has been performed. The theory of that simulation is developped in [Bonneau 1989, 1990, 1994]. It is a step by step non linear simulation of the Reynolds equation which governs the film pressure and of the equations of the shaft motion (obtained by a finite element approach with modal technique). The idea is to feed the SFD with a negative ER Fluid and to apply an electric field between two electrodes. Figure 9 presents a scheme of this SFD. A negative ER Fluid was chosen in spite of

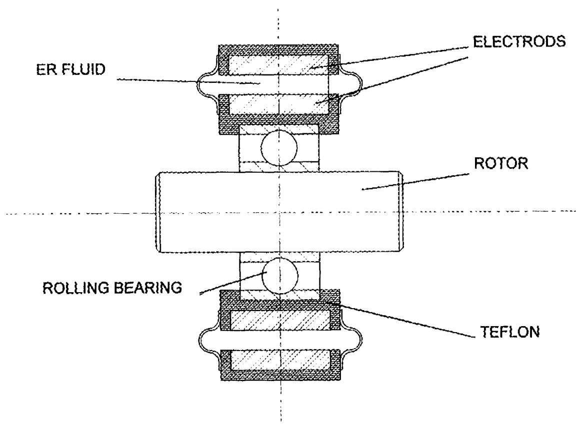

FIGURE 9 Electrorheological Squeeze film damper.

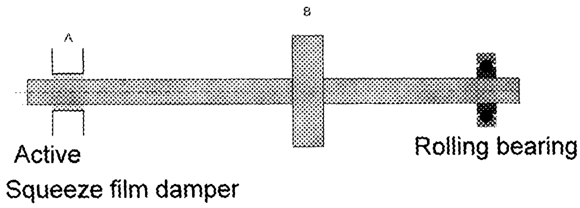

FIGURE 10 Shaft representation.

its newtonian behavior (assuming that the response time is large enough for that application). The rotating shaft is supported at one end by a ball bearing and at the other one by an active squeeze film damper without centralizing spring (Figure 10). Numerical results are obtained for a linear rotation speed variation from 6000 to 20000 rpm. The shaft and bearing characteristics are the following: bearing span: 0.8 m, rotor diameter 0.06 m, bearing length: 0.015m, diameter: 0.09 m, radial clearance 0.07 mm.

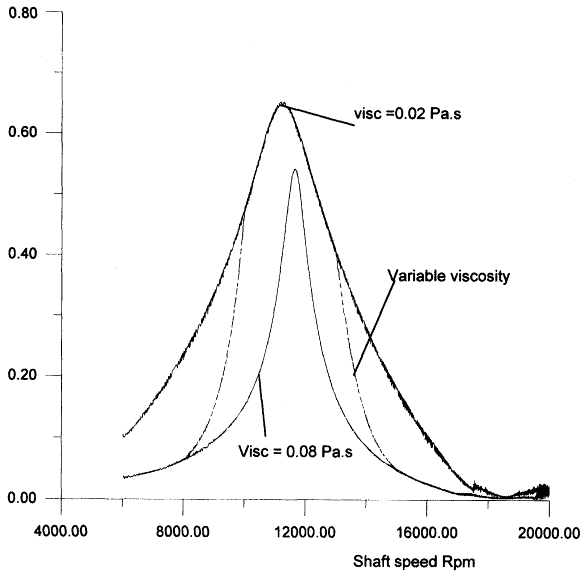

FIGURE 12 Amplitude in the SFD (point A) versus Rotational Speed.

Results with Two Constant Viscosities

Figure 11 and Figure 12 show the displacement amplitude of the middle of the rotor (point B) and of the rotor in the squeeze film damper (point A) versus rotational speed. Results with two constant viscosities are presented ($\mu = 0.02$ and $\mu = 0.08$ Pa.s) Figure 11 shows that a deacrease of the viscosity gives an increase of damping (amplitudes are lower around the critical speed). In fact a low viscosity leads to larger displacement in the squeeze film damper and leads to higher dissipated energy: that is shown on Figure 12 where the amplitude in the SFD increases with a decrease of viscosity.

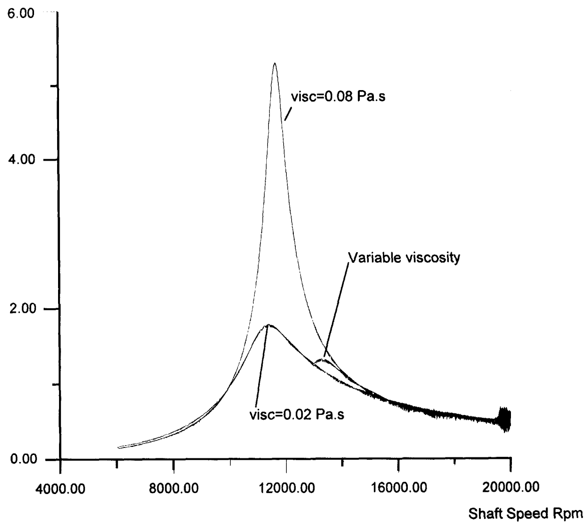

FIGURE 11 Amplitude in the middle of the rotor (point B).

Results for Electrorheological Fluid

The idea is to monitor the viscosity at the rotational speed with a trapezoïdal variation of the viscosity (from 0.08 Pa.s to 0.02 Pa.s).(Figure 13) The curve in

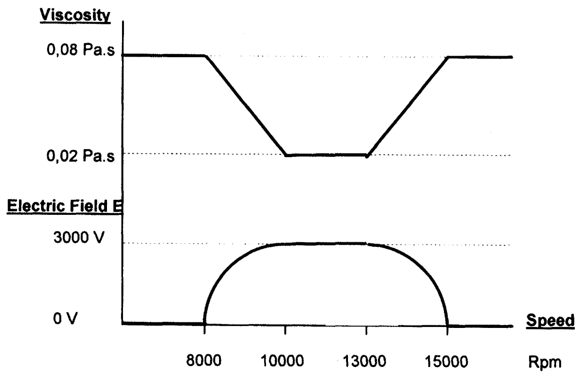

FIGURE 13 Viscosity variation versus rotational speed.

dashed line on Figure 11 and 12 presents the variable viscosity effect: the amplitude passes successively from one curve (0.08 Pa.s) to the other (0.02 Pa.s) near the critical speed, and then returns to the 0.08 Pa.s curve. This control allows to take advantage of the two behaviors: high dissipated energy near a critical speed and low displacements in the SFD when the rotational speed is far below or above the critical speed.

CONCLUSION

An investigation about electrorheological fluid applied in lubrication has been carried out. The electrorheological effect has been detailed. Simulation shows that it could be possible to monitor the damping of a squeeze film damper. The calculation carried out on flexible shaft shows the importance of this approach.

Nevertheless ER Fluid lubrication applications presently encounter some difficulties. The main reasons are the low performances with temperature and the presence of solid particles. Some chemical progress must be achieved to produce a fluid with good lubricant properties and with effective electrorheological behavior, technical outlets of that fluid could be very important.

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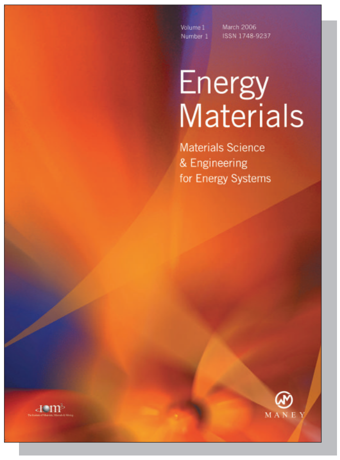

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