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AN ELECTROVISCOUS DAMPER[1]

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A new type of vibration damper for rotor systems has been developed and tested. The damper contains electroviscous fluid which solidifies and provides Coulomb damping when an electric voltage is imposed across the fluid. The damping capacity is controlled by the voltage. The damper has been incorporated in a flexible rotor system and found to be able to damp out high levels of unbalanced excitation. Other proven advantages include controllability, simplicity, and no requirement for oil supply. Still unconfirmed are the capabilities to eliminate critical speeds and to suppress rotor instabilities.

INTRODUCTION

Electroviscous fluids have been known for almost a century. In 1885, Koenig [1] tried unsuccessfully to demonstrate a viscosity change in a fluid due to an imposed voltage. Duff [2] and Quincke [3] succeeded in 1896-97 with glycerin and other liquids. It has since been found that a wide variety of fluids and fluid/solid mixtures (e.g. starch in silicone oil) exhibit some level of electroviscosity [4],[5]. However, the effect remained too weak for practical applications until the early 1980's when advances in polymer research led to electroviscous or EV-fluids with sufficient strength to warrant patent protection, e.g. [6].

The main effect in the modern fluids is not the viscosity change but the creation of a solid consistency with an initial shear strength which must be overcome before the "fluid" will flow. In fluid dynamics terminology, the fluid turns into a Bingham plastic when subjected to a voltage, see Fig.1. Some important characteristics of the modern fluids are as follows: the composition is roughly a 1:1 suspension of 10μ DIA polymer particles in silicone oil; the optimum thickness of the fluid layer to be sheared is 1-2 mm; the required voltage for full activation is 5,000-10,000V; the maximum current is less than 10 mA; the maximum yield strength obtainable is about 5-10 kPa; the fluid activation and deactivation time is less than 1 ms. The invention of the modern fluids led to a profusion of suggested applications in the early 1980's, e.g. [7], [8], [9]. However, to the authors' knowledge, the damper proposed in this

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paper represents the first application of EV-fluids to vibration control of rotor systems.

THE EV-DAMPER PRINCIPLE

The electroviscous, or EV-damper design is shown in principle in Fig. 2. A rotating shaft is supported by a bearing with the outer race connected to the damper housing via a so-called squirrel-cage which provides radial support flexibility. The outer bearing race also supports a non-rotating disk located inside the damper housing. The housing is filled with EV-fluid. Two annular rubber membranes seal the damper housing. The fluid films between the disk and the housing solidify when a DC voltage is applied between the disk and the housing. The solidified fluid provides Coulomb damping which impedes the radial motion of the disk, thereby attenuating the radial vibration of the shaft. The damping capacity is controlled by the applied voltage.

THE EXPERIMENTAL APPARATUS

Rig Hardware

An EV-damper with six moving disks and five stationary disks was designed and built and incorporated in a simple flexible rotor system as shown in Figs. 3 and 4. The entire apparatus is made of steel. The design configuration simulates the low pressure shaft of a gas turbine engine with the rotating disk simulating the fan stage. This configuration was chosen to demonstrate the capability of the damper to attenuate the high load excitation that follows a fan blade loss. The rotor is driven by a small air-motor through a flexible rubber coupling. A small electric pump slowly circulates the EV-fluid through the damper to prevent the polymer particles from settling out.

The multidisk damper configuration was designed to ensure that optimum system damping could be reached. The optimum equivalent viscous damping C was found by rotor analysis to be about 4000 Ns/m. The total area A for fluid shearing in the damper was then estimated from

$$C = \frac{4F_o}{\pi \omega x_o} + b \qquad (1)$$

see [10], with $F_o = pA$. F_o is the constant Coulomb damping force; p is the maximum shear strength of the EV-fluid; ω is the rotational speed; x_o is the vibration amplitude; and $b=\mu A/h$ is the viscous damping coefficient between the disks where μ is the fluid viscosity and h is the fluid-film thickness. Thus, the total required area A of fluid shearing was estimated to be roughly 4000 cm^2 with a fluid-film thickness h=1.6mm. The maximum possible radial rotor excursion at the damper location is 1 cm.

The squirrel-cage consists of three outer beams and three inner beams connected via an electrically insulating disk. The beams are 120^{o} apart. Each beam is 4.8 cm long by 4.8 mm dia. The shaft is electrically insulated from the damper at the bearing outer race. The damper housing is electrically insulated from the base plate.

EV-Fluid

The EV-fluid used here has the following known characteristics:
Composition: 12 μ dia particles in silicone oil
Max. yield strength: 4 kPa at 3.5 kV/mm
Viscosity: 100 cP at $30^{o}C$ (deactivated)
Density: 1110 kg/m^3 at $25^{o}C$

Damper Power Supply

The circuit diagram of the damper power supply is shown in Fig. 5. The damping capacity is controlled manually via the variable transformer.

Instrumentation

Two perpendicular pairs of inductive proximity probes pick up the shaft displacements near midspan and near the damper as shown in Figs. 3 and 4. The DC-offsets of the probes are removed by standard op-amp summer circuits. The signals are then A/D-converted and recorded on a micro-computer in the usual fashion. The signals are also displayed live on an oscilloscope for critical speed identification and as a safety precaution. The rotational speed is derived from a photodiode facing a black and white painted stripe on the rotating disk. The speed signal is also recorded digitally and displayed live by a digital timer/counter.

RESULTS

Controllability

The rotor system shown in Figs. 3 and 4 was run up to its first critical speed (rigid body pitching mode) at about 1400 rpm and voltage was applied to the damper. The shaft whirl orbit near the damper was reduced by a factor 4 as shown in Fig. 6. Rapid voltage application resulted in slightly smaller orbits which grew to the steady-state size shown within a few seconds.

High Load Damping Capability

The rotor was run up to about 2000 rpm and an 8040 g.mm balance weight was knocked off to simulate a blade loss. The rotor was then allowed to decelerate slowly down through its critical speed. Fig. 7 shows the response, including the initial transient, with and without voltage application. The reduction of the response after voltage application is substantial. The critical speed is almost eliminated.

CRITICAL SPEED ELIMINATION

The EV-damper also has the potential capability to eliminate critical speeds as shown in Fig. 8. As the rotational speed approaches the critical speed Ω_{cr} maximum voltage is applied at Ω_1. The EV-fluid will solidify and it will remain solidified provided the yield strength of the "fluid" films exceeds the unbalance force transmitted through the damper. The effective rotor support stiffness will therefore increase so the critical speed will increase and the response curve will move to the dashed location in Fig. 8. The response at Ω_1 will then drop as shown and the rotational speed can be increased to Ω_2. The voltage is then disconnected and the response curve jumps back to its original position as the fluid relaxes. The fluid relaxation time is less than one millisecond which, for most applications, is too short for any vibrations to build up. Thus, the critical speed has virtually been eliminated. Rotor deceleration is analogous.

The minimum response that can be achieved is represented by the bottom point of the valley between the peaks. The elevation of this point depends on the sensitivity of the critical speed to changes in rotor support stiffness. It also depends on the bandwidth of the response peak which is a function of the residual damping with the EV-fluid relaxed.

With the current damper, the response peaks could not be sufficiently separated because the residual damping, due to fluid viscosity and the rubber seals, is too large. The damper will be redesigned with fewer disks and better seals to demonstrate the critical speed elimination. It is expected that a reduction of the residual damping will also result in a more dramatic rate of reduction of the unbalance response than demonstrated in this paper.

CONCLUSION

A new type of rotor-damper has been built and tested for the first time. The damper contains an electroviscous fluid which provides Coulomb damping at a variable rate controlled by a DC-voltage applied to the fluid.

Widespread industrial application of this damper is anticipated due to its simplicity, controllability, high-load damping capability and its potential capability to eliminate critical speeds.

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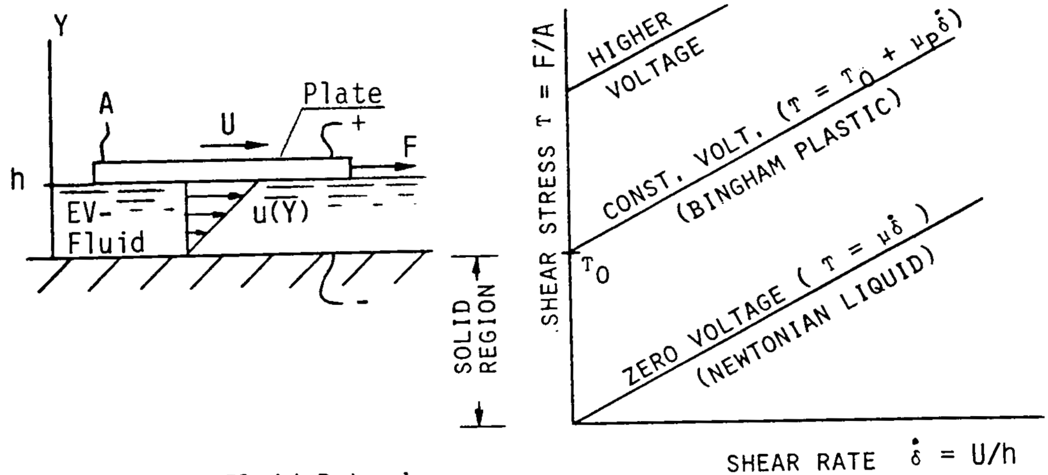

Figure 1 EV-Fluid Behavior

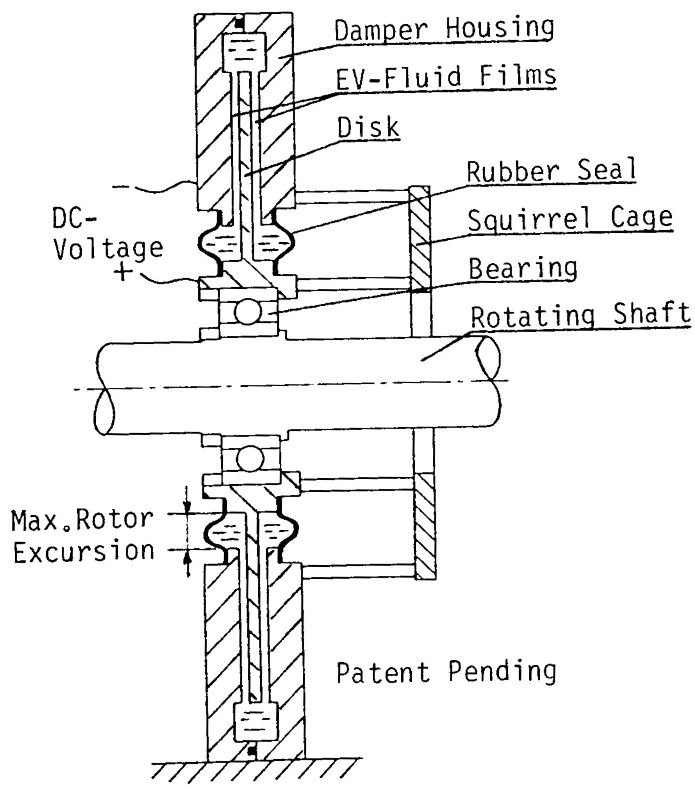

Figure 2 EV-Damper Principle

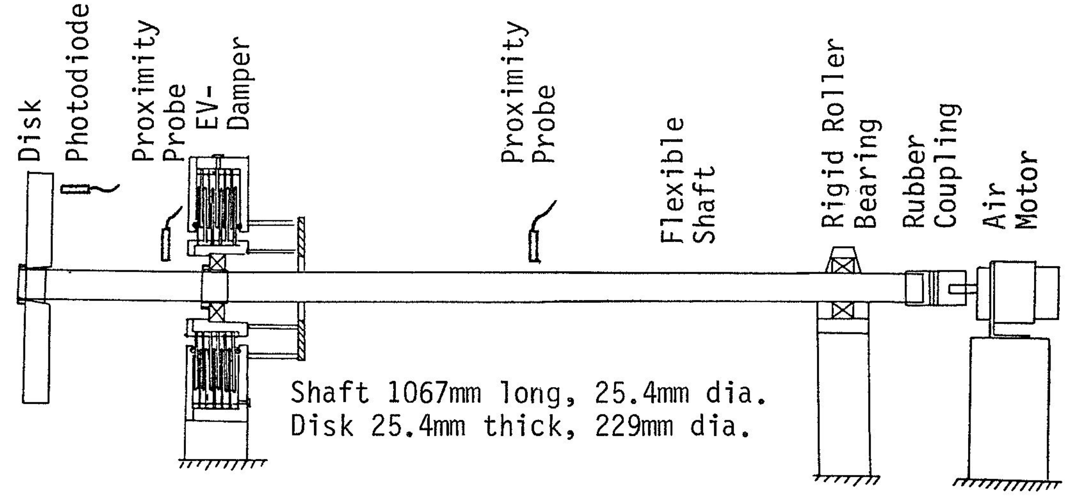

Figure 3 EV-Damper Test Rig (Schematic)

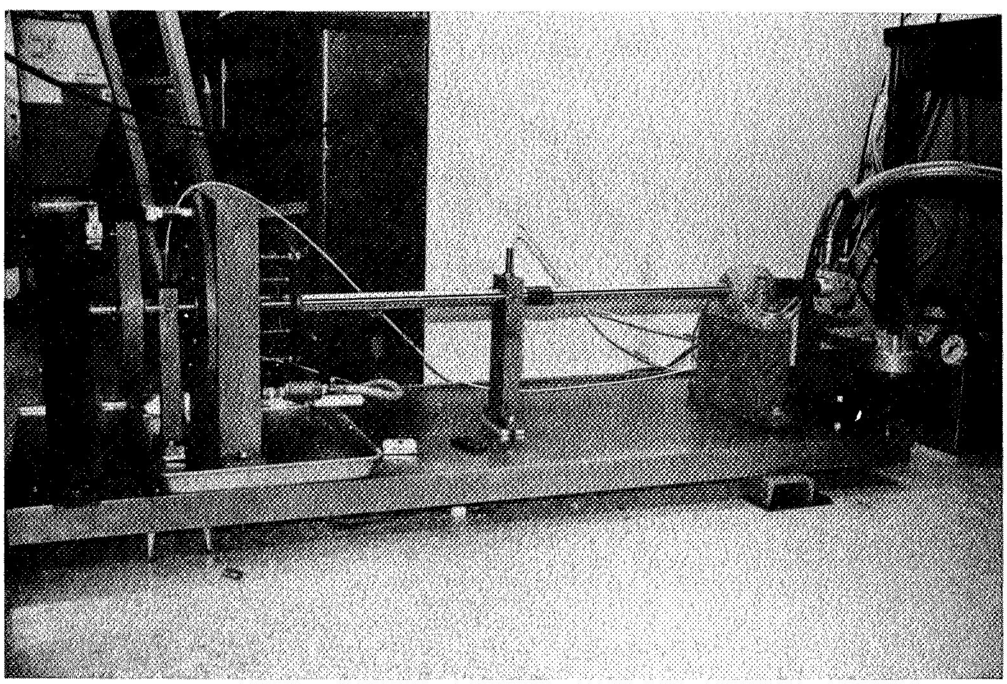

Figure 4 EV-Damper Test Rig

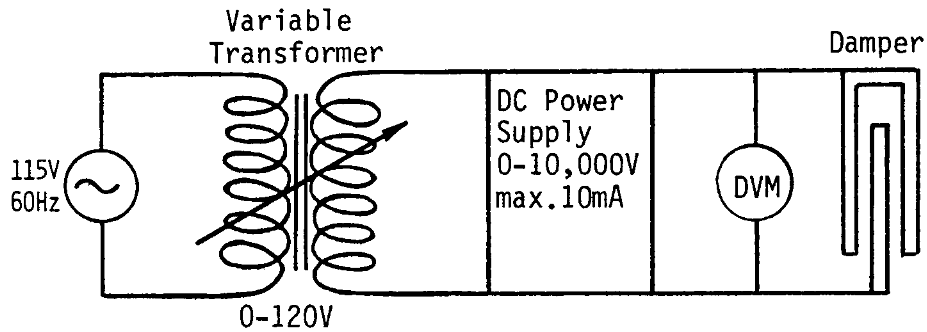

Figure 5 Damper Power Supply

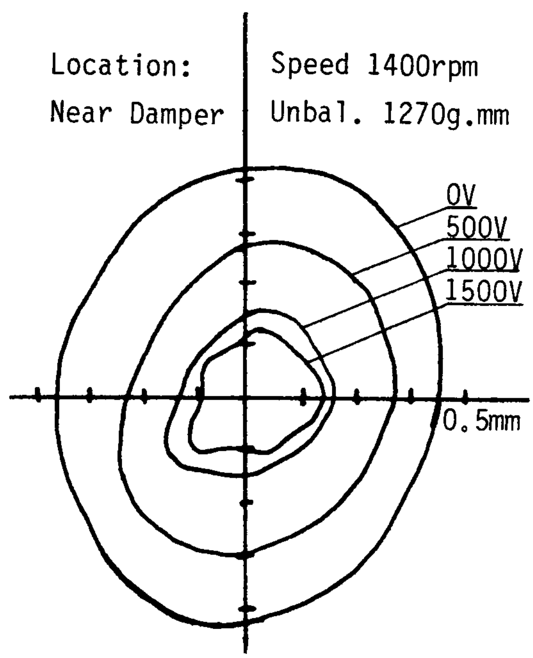

Figure 6 Trace of Shaft Whirl
Orbits Near Damper

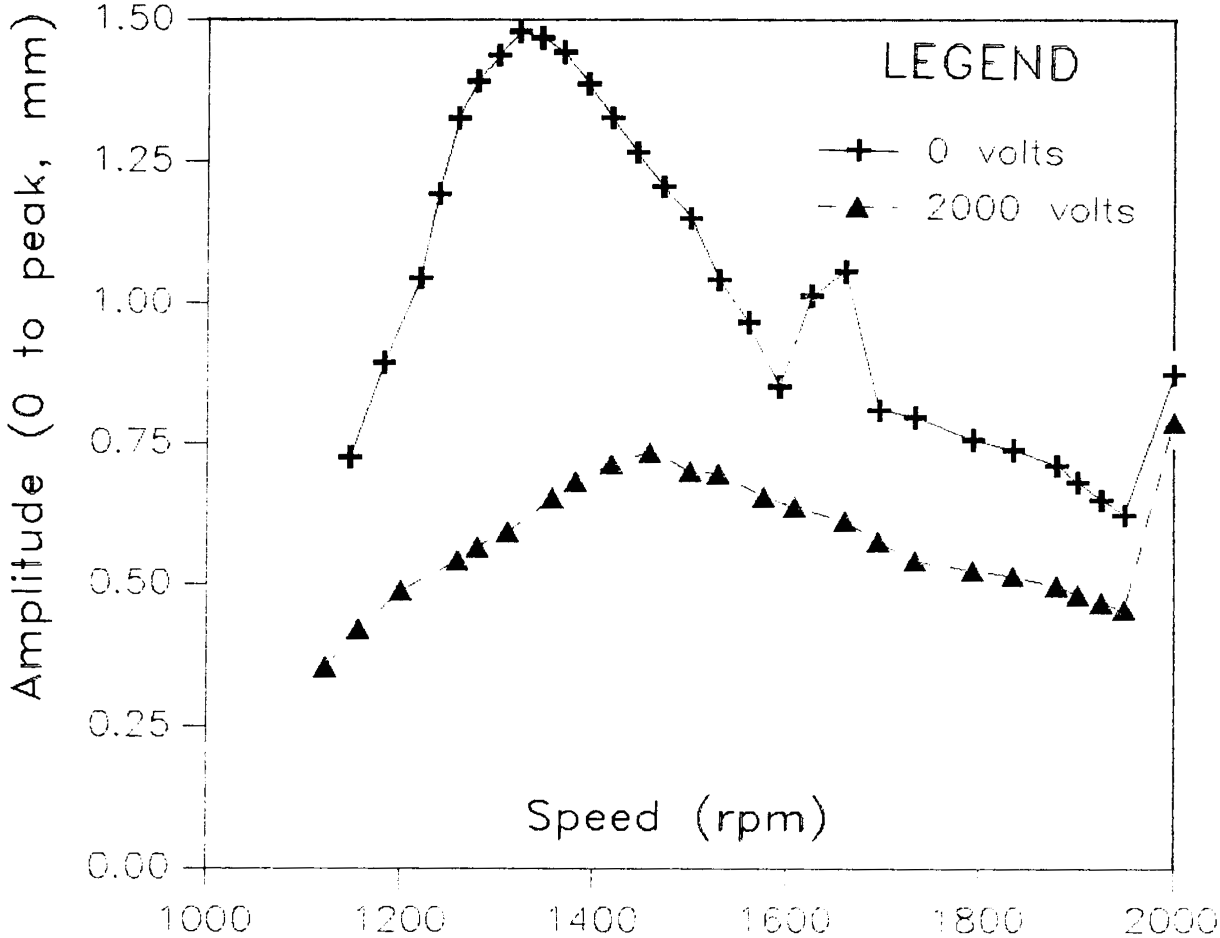

Figure 7 Simulated Blade Loss Response as a Function of Voltage

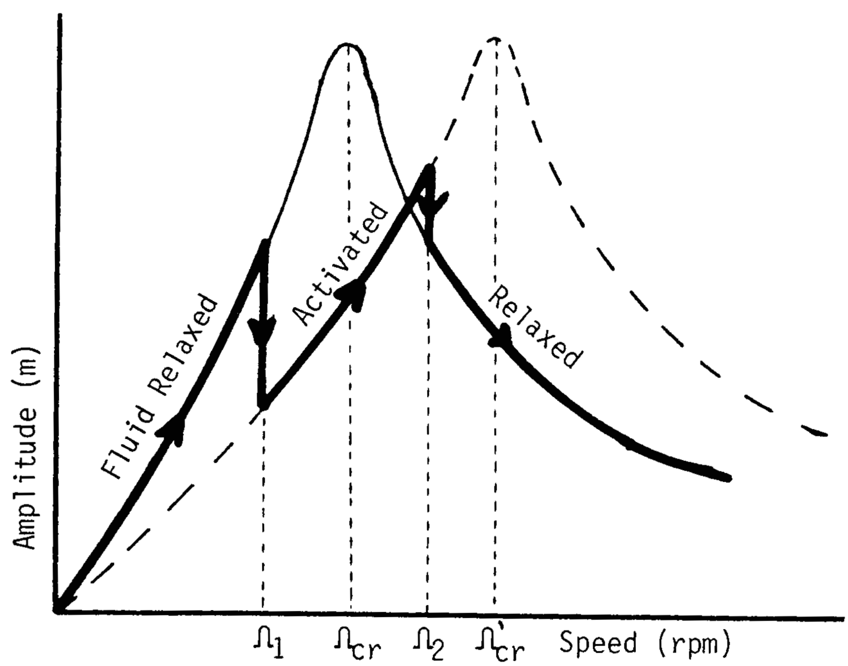

Figure 8 Critical Speed Elimination (Schematic)