ABSTRACT

Rotors supported in plain journal bearings become unstable at high speeds due to the fluid film forces. This inherent disadvantage of journal bearings has led to the development of other shapes of fluid film bearing. Squeeze film dampers have also been investigated as devices to reduce unbalanced force transmitted to the machine foundation or to increase stability of a rotor. In those applications, rolling contact bearings are mounted on retainer springs and the outer races of the bearings are allowed to move within cylindrical oil baths fixed to the engine frame constituting squeeze films. The fact that the use of viscoelastic lubricants really improves bearing performances at high shear rates, which occur within the clearance space of journal bearings, has already gained considerable experimental evidences. In squeeze film bearings, compared to a journal bearing, the viscoelastic lubricant does not undergo that high shear rate and as a result, both normal stress effect and stress relaxation effect exist; the phenomenon may be well depicted by a linear corotatoinal Maxwell's viscoelastic model. As the cost of experimental testing makes it practical to consider computer simulations for designing of rotor bearing systems, a proper technique of system modelling is of utmost importance to depict the complex dynamics of the system as closely and extensively as possible.

The present work proposes a stabilizing scheme where a squeeze film damper (termed as stabilizer in the text), unlike its general use, is connected in parallel to a circular journal bearing for supporting the rotor. With an aim to measure the influence of stabilizers on the dynamics of the rotor, the journal bearings in the system under study have been fed by Newtonian lubricants only; squeeze film stabilizers, on the other hand, are fed by both Newtonian and viscoelastic lubricants so as to compare their stabilizing influences on the rotor-bearing system.

The nonlinear fluid-film forces and their interactions play a crucial role in determining the dynamic behaviour of a rotor bearing system. Dynamics of a real system becomes further complicated when

the effects due to catch-spring compliance, stabilizer placement, gyroscopic action of rotor-inertia, rotational damping in drive-coupling etc are considered. This complex system has been modelled through bond graph technique. Maxwell's viscoelastic constitutive equation, continuity equation and equation of equilibrium are used together with a perturbation procedure to find the viscoelastic fluid film forces in stabilizers on the basis of a short bearing approximation. A Deborah number (De) perturbation scheme is used to derive viscoelastic forces which automatically returns the Newtonian solution when De becomes zero. The effect of viscoelasticity on film-forces is marked by the existence of acceleration dependent terms $\ddot{\varepsilon}$ and $\ddot{\phi}$, which are quite different from fluid inertia. Journal bearings in the system under study carry the static load while the dynamic load due to a relatively small unbalance is shared together by journal bearings and squeeze film stabilizers. Hence fluid-film forces in journal bearings are derived on the basis of π-film assumption, whereas, force derivation for squeeze film stabilizers assumes full-film condition.

As a first step of analysis stability maps are prepared for symmetric mode of vibration of the rotor. It is known that the stability of a rigid rotor supported in Newtonian bearings is governed by two nondimensional parameters, one of which is related to eccentricity while the other one is related to rotor speed (ie ε_0 and α_t). In the proposed scheme, when a stabilizer fed through a Newtonian lubricant is connected in parallel to the journal bearings, stability of the system further depends on the bearing geometry and the viscosity of the lubricants used. This influence is expressed by two nondimensional parameters, termed as bearing ratio parameters in the text (Π_1 and Π_2). When stabilizers are fed by a viscoelastic fluid the stability is influenced by still another nondimensional parameter, De (Deborah number), and consequently five nondimensional parameters (viz. $\varepsilon_0, \alpha_t, \Pi_1, \Pi_2$ and De) are involved. Study reveals that increase in Π_1 increases the high speed stability limit whereas increase in Π_2 has a negative effect towards improving rotor stability. Compared to a Newtonian lubricant when a viscoelastic lubricant is used in stabilizers it further improves the high speed stability zone with the increase in De, though an instability zone appears at the low speed range.

In a next step, a refined analysis is done through bond graph modelling which considers the effects of stabilizer mass, stabilizer placement, "catch spring" stiffness and gyroscopic action of rotor-mass, coupled parallel or conical whirl and rotational damping in the drive-coupling. Bond graph analysis reveals that the drive-coupling parameters (ie its stiffness and damping values), if suitably selected, improves system-stability at higher speeds. On the other hand, with a relatively small rotor gyroscopic-inertia, if the stabilizers are placed nearer to the rotor disc, the system tends to unstable condition.

It is known that flexibility of rotors has an adverse effect on stability at high speeds of operation. A very simple rotor system consisting of an elastic shaft fitted with a disc at its midplane is considered for theoretical study. Analysis reveals that, for a viscoelastic stabilizer, in addition to the five nondimensional parameters obtained in the rigid rotor study, rotor-flexibility influences the stability of the system through another nondimensional parameter β_t related to the natural frequency of the rotor shaft. Thus, for a flexible rotor-bearing system, stability depends on six nondimensional parameters, viz $\varepsilon_0, \alpha_t, \beta_t, \Pi_1, \Pi_2$ and De.

Though the linearized approach is a powerful tool for an initial design of the bearings a complete idea (viz effect of initial transients on rotor vibration, actual orbital motion of the journal centre, effect of sudden unbalance etc) is obtained with the help of nonlinear analysis. The nonlinear fluid-film forces in bearings and stabilizers may be easily incorporated in the bond graph by SE-elements (source of effort) related to displacement, velocity and acceleration dependent terms in the film-force expressions. The bond graph thus obtained is analysed to plot the journal orbits showing stable or unstable condition. The orbit is further investigated to observe the phenomenon of whirl through Fourier Transformation. Nonlinear analysis reveals the efficacy of the proposed scheme against sudden unbalance or impact loading on the rotor.

Experiments have been conducted on two rotors. The stiff rotor has a natural frequency of nearly 1300 Hz which is much higher than the range of rotational speeds over which the experiment has been conducted. The other rotor is a flexible one with its first natural frequency at 30 Hz. Both Newtonian and viscoelastic lubricants have been used during experiment. Newtonian lubricants of different viscosities have been prepared by mixing of kerosene oil with the commercial SAE 40 crankcase oil at different proportions whereas dilute viscoelastic lubricants of different viscosities have been prepared by mixing of polyacrylamide (molecular weight $5X10^6$) in the glycerol-water mixture at different proportions. The dynamic signals of rotor vibration are picked up through non-touching probes connected to proximitor. A real time spectrum analyzer is used to record the onset of instability, whirl frequency and variation of response obtained at different rotor speeds. There have been three significant speeds for a flexible rotor, viz critical speed, onset of instability speed and the incipient large whirl speed. Experimental observations show that an increase in Π_1 (Π_2 is constant during experiment) improves high speed stability limits of the rotors with a simultaneous decrease in vibration amplitudes. When a flexible rotor system is aided by a viscoelastic stabilizer, it is observed that instability persists almost throughout the entire range of operation which is in agreement with the theoretical study; but experimental results further shows that viscoelastic stabilizing samples postpone the growth of large incipient whirl (though instability onset has started quite early) to very high speeds.

KEYWORDS

Whirl, Critical speed of rotor, Rigid rotor, Flexible rotor, Rotor-dynamics, Viscoelastic lubricant, Deborah number, Weissenberg effect (Normal stress effect), Stress relaxation effect, Maxwell's constitutive equation, relaxation time, Squeeze film stabilizer, parallel configuration, Bond graph, Causality, Bearing ratio parameter, Stability parameter, Apparent inertia coefficients, Catch-spring, Laminar flow, Preloading, Rattling.