Parametric Analysis Focused on Non-linear Forces in Oil-film Journal Bearings

Andrea Vania, Paolo Pennacchi and Steven Chatterton

Abstract Many investigation methods used to identify the most common faults in rotating machines do not consider the non-linear behaviour of oil-film journal bearings with an adequate care. This chapter shows the results of a parametric analysis performed to study the sensitivity of non-linear effects in the oil-film forces to changes of some parameters of the synchronous (1X) filtered orbit of the journal. This study is focused on the influence on non-linear forces caused by changes of the maximum amplitude and circularity of the journal orbit as well as by changes of the inclination angle of the major principal axis of the 1X elliptical orbit. Moreover, also the effects of the shaft rotational speed, bearing load and the average journal position have been taken into account. A procedure to perform this sensitivity analysis for different types of journal bearing is described. Then, the results obtained by the analysis of the behaviour of a two-lobe elliptical oil-film journal bearing are shown and discussed.

Keywords Oil-film journal bearings · Non-linear dynamics · Rotating machines · Diagnostics

1 Introduction

It is well known that the oil-film forces in sleeve journal bearings are considerably non-linear. The importance of this non-linearity depends on many factors like: shaft rotational speed, journal average position, amplitude and shape of the journal orbit, oil-film temperature. The effects of the non-linear component of the oil-film forces on the shaft vibration can be rather limited as they are often smoothed by the inertia forces of the shaft. However, the occurrence of very high non-linear

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oil-film forces can cause not negligible super-synchronous vibrations of the rotating machine. With regard to diagnostic purposes, this phenomenon can cause false fault identifications as the presence of shaft super-synchronous vibrations is often ascribed to dangerous faults like: rotor-to-stator rubs, shaft-crack propagations, severe machine misalignments.

In fact, many fault symptom analysis techniques do not give an adequate importance to the non-linear effects in the oil-film forces. Conversely, serious and common primary faults like, for instance, a high unbalance and a high shaft thermal bow, can cause unexpected super-synchronous harmonic components in the frequency spectrum of shaft vibrations. This can occur when large journal orbits generate considerable non-linear effects in the oil-film forces.

Some sleeve journal bearings are more sensitive to a non-linear behavior depending on their geometrical characteristics. The sensitivity of the oil-film forces of journal bearings to non-linear effects has been investigated, by means of a model-based method, by evaluating the oil-film forces caused by 1X filtered journal orbits having different amplitudes and shapes, that is by orbits caused only by synchronous vibrations. This approach makes the results of this study independent from the mechanical characteristics of the shaft and the characteristics of the rotor-system excitations.

This paper shows the results of a parametric analysis performed to study the sensitivity of the non-linear effects in the oil-film forces to changes of some parameters of the 1X orbit of the journal. More in particular, the influence on non-linear forces caused by changes of the orbit maximum amplitude and degree of circularity Orbit Shape Factor (OSF), as well as by changes of the inclination angle of the major principal axis of the elliptical orbit, has been considered in this study. Moreover, also the effects of the shaft rotational speed and the average journal position have been taken into account. A procedure to perform this sensitivity analysis for different types of journal bearings is described. Then, the results obtained by the analysis of the behaviour of a two-lobe elliptical oil-film journal bearing are shown and discussed.

2 Investigation Method

It is important to specify that the goal of this investigation is to study the sensitivity to non-linear dynamic effects in the oil-film forces of journal bearings, not to simulate the non-linear vibrations of the journal. Therefore, contrary to other usual methods [1, 2], the oil-film forces caused by only synchronous vibrations were considered. Let us denote by x and y the horizontal and vertical displacements of the journal with respect to the bearing centre. Then, the synchronous vibrations of the journal, which rotate with the angular velocity Ω, can be expressed as:

$$\begin{aligned} x(t) &= X\cos(\Omega t + \varphi) \\ y(t) &= Y\cos(\Omega t + \beta) \end{aligned} \tag{1}$$

As said above, the method used in this study to investigate the oil-film force does not require to define the time-history of the excitations that cause the 1X vibrations expressed by Eq. (1). In this way, the presence of not null super-synchronous oil-film forces is a symptom of non-linear effects.

The vibrations expressed by Eq. (1) cause the journal to describe an elliptical orbit having a major and minor principal axes $\bar{a}_{1X}$ and $\bar{b}_{1X}$, respectively. The parameter $\bar{a}_{1X}$ is the maximum vibration amplitude of the journal. Then, let us denote by θ the inclination angle of the major principal axis with respect to the horizontal axis x. In the case of null vibration amplitudes, the components of the journal position, x_0 and y_0, are determined by the static bearing load, W, whose horizontal and vertical components are W_x and W_y, respectively. The degree of circularity of the journal orbit, which is often elliptical, can be expressed by the ratio OSF between the minor and major principal axes of the orbit.

For each given set of values of Ω, W_x and W_y, the parameters $\bar{a}_{1X}$, OSF and θ can be varied inside suitable ranges of interest. For each given couple of the parameters OSF and θ, the changes of the maximum vibration amplitude $\bar{a}_{1X}$ cause changes of the orbit dimension without modifying the shape factor. For each couple of the parameters $\bar{a}_{1X}$ and θ, the changes of the OSF cause variations of the flatness of the elliptical orbit. In the end, for each couple of parameters $\bar{a}_{1X}$ and OSF, the changes of the angle θ cause variations of the direction along which the maximum amplitude of the journal vibration occurs.

In general, the increase of the parameter $\bar{a}_{1X}$ causes an increase of the non-linear effects in the oil-film forces. However, the importance of these effects can be highly influenced also by the orientation of the major principal axis of the orbit and by the orbit flatness.

For a given bearing load the minimum thickness $h_{\min}$ of the oil-film depends on the shaft rotational speed. Low values of $h_{\min}$ can cause a considerable increase of the non-linear effects in the oil-film forces. The lowest instantaneous value of the minimum thickness of the oil-film that occurs during a complete revolution of the shaft is affected by the parameters $\bar{a}_{1X}$, OSF and θ.

For each set of these parameters the oil-film forces were evaluated, over an entire orbit, for N samples (with $N = 256$) equally spaced in the time. For each analysis, the average position of the journal was varied by applying an iterative technique in order to obtain mean values of the horizontal and vertical oil-film forces that equilibrate the corresponding components of the bearing load. Then, the harmonic content of the oil-film forces was evaluated.

Being the journal vibration synchronous (1X), the presence of not null super-synchronous oil-film forces is a symptom of non-linear effects. In general, the amplitude of the 2X harmonic component is the highest in the super-synchronous oil-film forces.

It is important to consider that, in general, the maximum 1X and 2X oil-film forces do not occur in the same direction. Moreover, the direction of the maximum nX oil-film force does not necessarily coincide with that of the maximum vibration amplitude. Therefore, in order to make independent the results of this study from the directions along which the oil-film forces were estimated, the maximum and minimum amplitude, $\bar{F}_{a_n\mathrm{X}}$ and $\bar{F}_{b_n\mathrm{X}}$, of the nX oil-film forces were evaluated.

The oil-film forces can be obtained on the basis of the evaluation of the oil-film pressure, p (s, z), on the bearing: where s is the coordinate in the circumferential direction of the i-th bearing lobe and z is the coordinate in the axial direction. For finite length bearings, the pressure distribution $p(s, z)$ is given by the following Reynolds equation [3–5]:

$$\frac{\partial}{\partial s}\left(h^3\frac{\partial p}{\partial s}\right)+\frac{\partial}{\partial z}\left(h^3\frac{\partial p}{\partial z}\right)=6\,\mu\left(U\frac{\partial h}{\partial s}+2\frac{\partial h}{\partial t}\right) \tag{2}$$

where μ is the lubricant viscosity, h (s, z) is the oil-film thickness, and U is the circumferential velocity of the journal. The oil-film forces were evaluated by solving the Reynolds Eq. (2), numerically, by means of a finite difference method [3–5]. With regards to this, classical boundary conditions were used: that is null pressure in the inlet and outlet grooves, as well as null lateral pressure. Moreover, the following classical Reynolds conditions were used in the cavitation regions:

$$\frac{\partial p}{\partial s}=0 \quad p=0 \tag{3}$$

3 Case Study

This chapter shows the results obtained by the analysis of the behaviour of an elliptical oil-film journal bearing (Fig. 1). The main geometrical characteristics of this bearing are reported in Table 1. Owing to the short length of the chapter only some of the results obtained for a shaft rotational speed of 1,000 rpm are shown.

In order to consider dimensionless quantities the amplitude of the major and minor elliptical orbits were divided by the assembled radial clearance C_b of the bearing. That is:

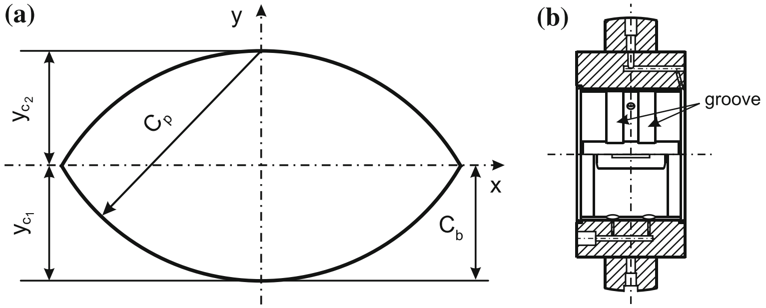


Fig. 1 **a** Configuration of an elliptical oil-film journal bearing. **b** Section view of a real bearing

Table 1 Bearing characteristics

	Symbols	
Diameter	D	457 mm
Length	L	254 mm
Machined clearance	C_p	0.608 mm
Assembled clearance	C_b	0.304 mm
Lower lobe width	$\Delta\theta$	160°
Pre-load factor	m_p	0.5
Oil viscosity	μ	26.57 cSt
Bearing load (vertical)	W	200 kN

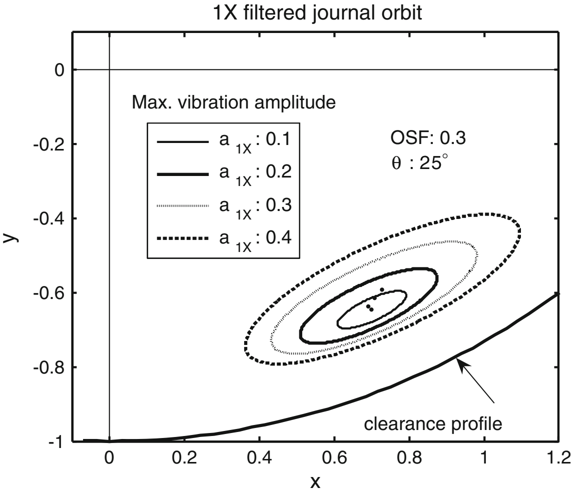
$$a_{1X} = \bar{a}_{1X}/C_b \, b_{1X} = \bar{b}_{1X}/C_b \tag{4}$$

A vertical bearing load of 200 kN was considered in this study. The amplitude of the parameter a_{1X} was varied from 0.05 to 0.4 while the OSF was varied from 0.1 to 0.5. In the end, the inclination angle θ of the major principal axis a_{1X} was varied from 5° to 55°.

For each case study, the oil-film forces were evaluated over a complete shaft revolution. Then, the harmonic content of these forces was computed. Afterwards, the maximum amplitude of the 1X and 2X oil-film forces generated during a complete orbit, $\bar{F}_{a_{1X}}$ and $\bar{F}_{a_{2X}}$, were evaluated.

Figure 2 shows some 1X elliptical orbits that have been obtained by changing only the maximum vibration amplitude a_{1X}. The clearance profile shown in Fig. 2 delimits the area of the bearing inside which the journal position can be contained without causing any contacts between shaft and Babbit metal. These orbits do not have the same centre because the increase of the orbit dimension causes changes also of the mean value of the horizontal and vertical oil-film forces that must

Fig. 2 Variations of the maximum amplitude of the 1X journal orbits (OSF = 0.3, θ = 25°)



equilibrate the assigned bearing load. However, all these orbits have the same shape factor and the same orientation.

Figure 3 shows some 1X elliptical orbits that have been obtained, for a given couple of values of the parameters a_{1X} and θ, by changing the OSF.

Also in this case, the journal orbits do not have the same centre, owing to the above mentioned reasons. In the end, Fig. 4 shows some 1X elliptical orbits that have been obtained, for a given couple of values of the parameters a_{1X} and OSF, by changing the inclination θ of the major principal axis.

In order to manage dimensionless quantities, the maximum amplitude of the 1X and 2X oil-film forces was divided by that of the bearing load W. That is:

Fig. 3 Variations of the shape factor of the 1X journal orbits $(a_{1X} = 0.3,\ q = 25^{\circ})$

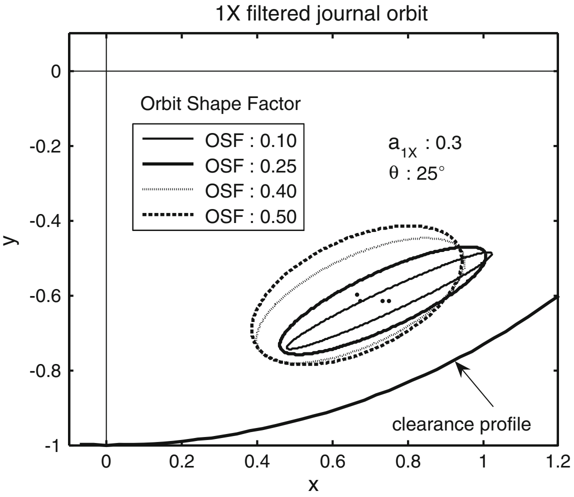
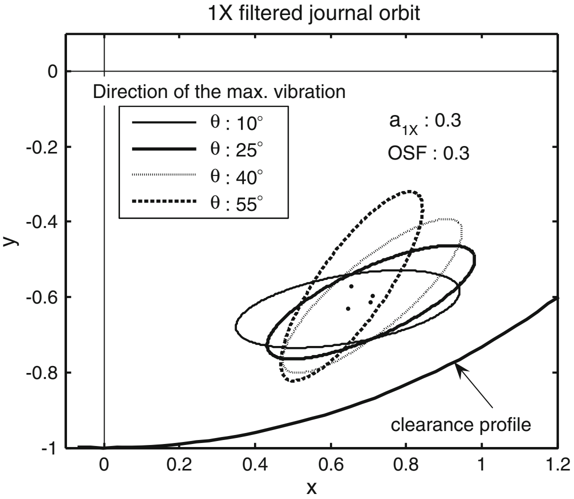


Fig. 4 Variations of the inclination θ of the 1X journal orbits $(a_{1X} = 0.3,\ \mathrm{OSF} = 0.3)$



$$F_{a_{1X}} = \bar{F}_{a_{1X}}/W \quad F_{a_{2X}} = \bar{F}_{a_{2X}}/W \tag{5}$$

Figures 5 and 6 show the influence of the parameters a_{1X} and OSF on the amplitude of the 1X and 2X oil-film forces, $F_{a_{1X}}$ and $F_{a_{2X}}$, respectively.

These results were obtained for a value of the angle θ equal to 20°. The results illustrated in Fig. 5 show that, especially for the highest values of a_{1X}, the decrease of the orbit flatness causes an important increase of the 1X oil-film forces.

The results illustrated in Fig. 6 show that increasing values of a_{1X} cause an increase of the sensitivity of the 2X oil-film forces to the OSF.

Moreover, it is possible to find a limited range of values of the OSF parameter inside which the 2X oil-film forces, that is the non-linear effects, are minimised. Figures 7 and 8 show the influence of the parameters OSF and θ on the amplitude of the 1X and 2X oil-film forces, $F_{a_{1X}}$ and $F_{a_{2X}}$, respectively.

These results were obtained for a value of the parameter a_{1X} equal to 0.3. The results illustrated in Figs. 7 and 8 show that the direction of the maximum

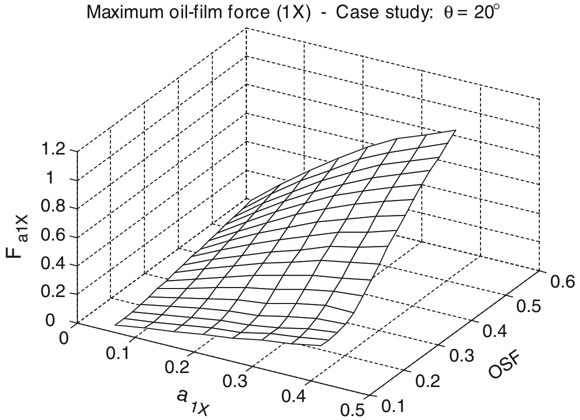


Fig. 5 Influence of the parameters a_{1X} and OSF on the maximum magnitude of the 1X oil-film force (case study: $\theta = 20°$)

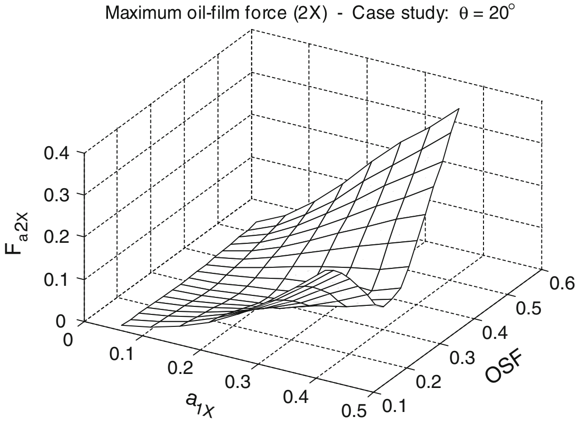


Fig. 6 Influence of the parameters a_{1X} and OSF on the maximum magnitude of the 2X oil-film force (case study: $\theta = 20°$)

Fig. 7 Influence of the parameters OSF and θ on the maximum magnitude of the 1X oil-film force (case study: a_{1X}= 0.3)

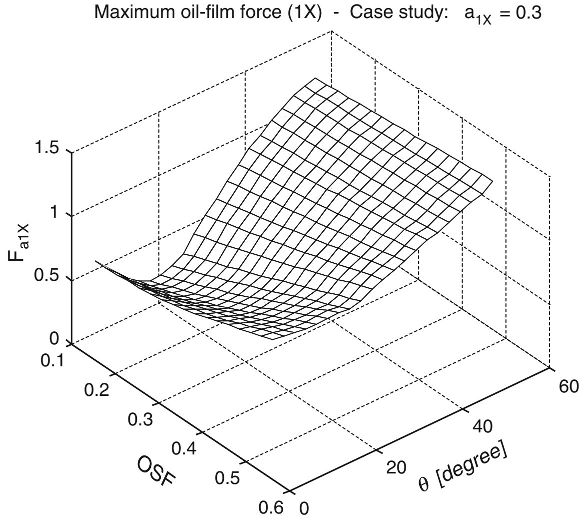
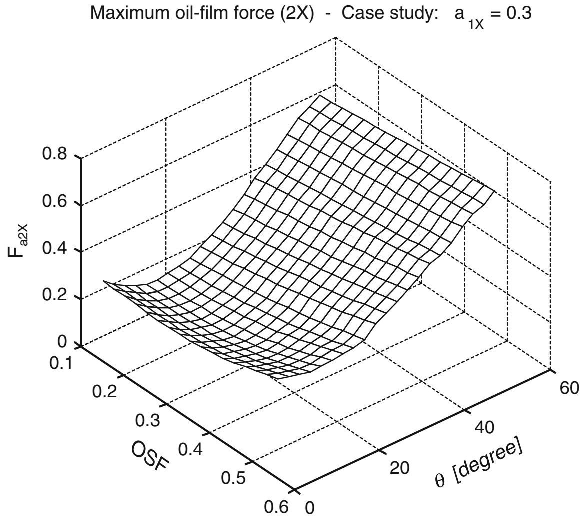


Fig. 8 Influence of the parameters OSF and θ on the maximum magnitude of the 2X oil-film force (case study: $a_{1X} = 0.3$)



vibration amplitude affects significantly both 1X and 2X oil-film forces associated with given values of the parameters a_{1X} and OSF.

Figure 9 summarizes the results provided by the parametric analysis about the maximum 2X oil-film forces. The effect of the maximum vibration amplitude is really evident. If the excitations acting on the shaft cause large journal orbits whose maximum amplitude occurs in a direction that forms an angle θ higher than about 35° the non-linearity in the oil film forces considerably increases.

Figure 10 shows the influence of the parameters a_{1X} and OSF on the direction, $\beta F_{a_{1X}}$, of the maximum 1X oil-film forces. These results were obtained for a direction of the maximum vibration amplitude $\theta = 30°$. Although the amplitude of

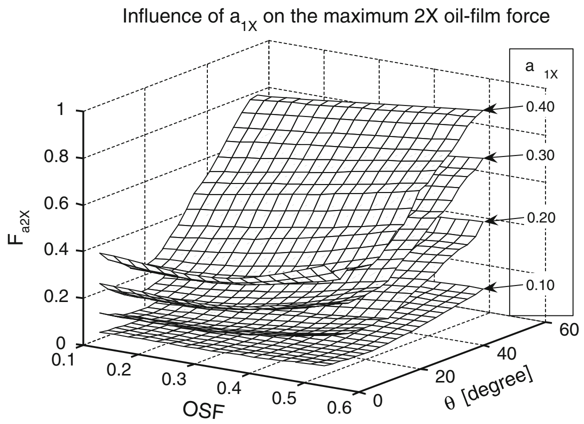


Fig. 9 Influence of the parameters a_{1X}, OSF and θ on the maximum magnitude of the 2X oil-film force

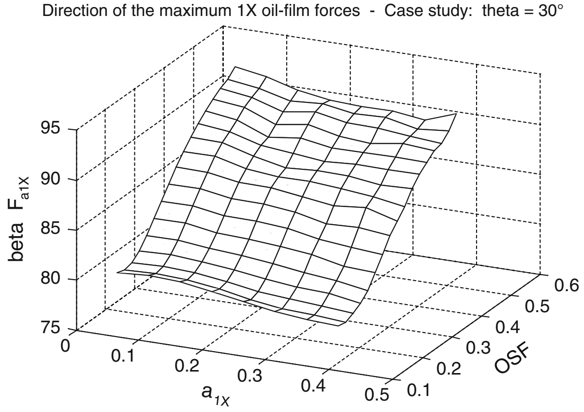


Fig. 10 Influence of the parameters a_{1X} and OSF on the direction of the maximum magnitude of the 1X oil-film force (case study: $\theta = 30°$)

the horizontal 1X vibration of the journal is higher than the corresponding vertical one, the direction of the maximum magnitude of the 1X oil-film forces is nearly vertical. This is a consequence of the considerable anisotropy of the oil-film stiffness that characterized the elliptical journal bearings.

Similarly, Fig. 11 shows the influence of the parameters a_{1X} and OSF on the direction, $\beta F_{a_{2X}}$, of the maximum 2X oil-film forces. Also in this case study, these results were obtained for a direction of the maximum vibration amplitude $\theta = 30°$. Owing to the shape and mechanical characteristics of the oil-film that is generated when the journal moves along the lower arc of the orbit, the direction of the maximum magnitude of the 2X oil-film forces, caused by the non-linear effects, is nearly vertical.

These results show that the most important non-linear effects, here represented by the maximum magnitude of the 2X oil-film forces, not necessarily occur in the same direction along which the highest journal vibration occurs. This is the reason for which, in this investigation, the authors decided to take into account both shape and amplitude of the 1X journal orbit to evaluate the harmonic content of the oil-

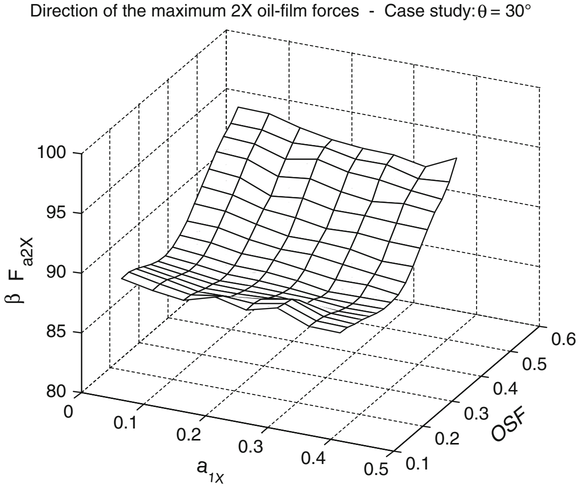


Fig. 11 Influence of the parameters a_{1X} and OSF on the direction of the maximum magnitude of the 2X oil-film force (case study: $\theta = 30°$)

film forces rather than considering the maximum vibration level evaluated in a single pre-established direction.

4 Conclusion

A model-based method aimed to study the sensitivity of sleeve journal bearings to non-linear phenomena in the oil-film forces has been shown in the chapter. The results obtained by means of a parametric analysis have been shown and discussed.

The proposed method evaluates the oil-film forces caused only by synchronous vibrations, that is by 1X elliptical orbits. The influence of the basic parameters that define these orbits on the synchronous and super-synchronous oil-film forces have been investigated. The results of this parametric analysis have been shown and discussed.

The method proposed by the authors to evaluate the sensitivity of a fluid-film journal bearing to give rise to non-linear effects in the lubricant forces has shown to be able to point out the contribution of single factors to the non-linear phenomena. The results provided by this investigation method can be very useful for diagnostic purposes and for an optimization of the bearing design aimed at improving its performances.

References

1. Vania A, Pennacchi P, Chatterton S (2012) Analysis of the sensitivity to non-linear effects in the oil-film forces of journal bearings. In: Proceedings of 10th IMECHE international conference on vibrations in rotating machinery, London, UK, C1326-037
2. Bachschmid N, Pizzigoni B, Tanzi E (2000) On the 2xrev—vibration components in rotating machinery excited by journal ovalization and oil-film non-linearity. In: Proceedings of 7th IMECHE international conference on vibrations in rotating machinery, University of Notthingam, Nottingham, UK, C576-083, pp 449–458
3. Hori Y (2006) Hydrodynamic lubrication. Springer, Tokyo
4. Stachowiak GW, Batchelor AW (2005) Engineering tribology. Butterworth Heinermann, Burington, USA
5. Szeri AZ (1998) Fluid film lubrication—theory and design. Cambridge University Press, Cambridge