PAMM · Proc. Appl. Math. Mech. 17, 377 – 378 (2017) / DOI 10.1002/pamm.201710158

A Minimal Dynamic Structure Model Considering Dry Friction Energy Dissipation in Refrigerant-Lubricated Gas Foil Bearings

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In the simulation of gas foil bearing rotor systems, computational time is considered a highly critical aspect. Consequently, a great number of sophisticated foil structure models found in literature reveal to be inapplicable for a fully coupled analysis of the overall system's nonlinear dynamic response. On the other hand, most notably if considering heavily loaded bearings, phenomena such as dry friction within the foil structure cannot be neglected without introducing substantial inaccuracies. To overcome these limitations, the minimal dynamic structure model described in this contribution considers a regularized Coulomb friction law applied to a reduced spring–mass arrangement. After the successful validation against static FE results, a transient simulation is carried out, allowing for interesting insights into the mechanisms behind beneficial energy dissipation.

1 Motivation and Modeling

During the last few decades, successful applications of refrigerant-lubricated gas foil bearings (GFBs) in air cycle machines of commercial aircraft have confirmed the remarkable potential of this technology in the light of an increasing demand for energy-efficient turbomachinery. Besides excessively low wear and power loss due to the absence of solid-to-solid contact between the airborne rotor journal and the bearing structure, the use of GFBs permits to overcome yet insurmountable speed, temperature, size, mass, and cleanliness limitations of conventional rolling-element bearings. However, most GFB rotor systems are prone to undesirable self-excited vibrations with comparatively large amplitudes which occur for higher rotational speeds and may ultimately lead to machine failure [4]. As a countermeasure, the compliant and slightly movable structure inside the lubrication gap (bump foil and top foil) is supposed to dissipate a certain amount of energy via dry sliding friction mechanisms [1], thus delaying the onset of detrimental rotor vibrations or reducing at least the vibrational amplitudes [5].

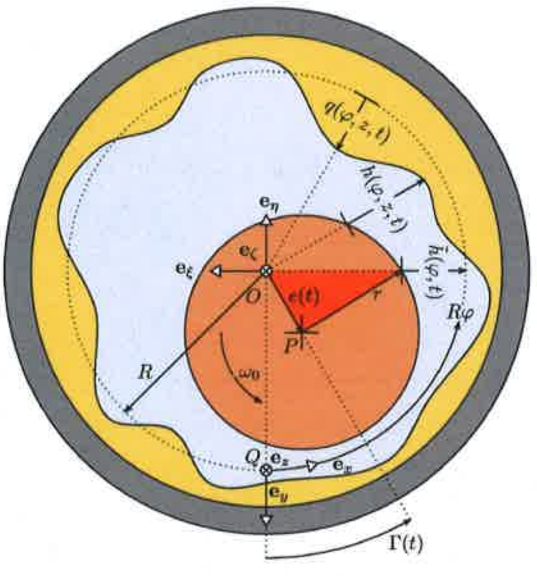

Fig. 1: Sketch of the rotor journal running inside a GFB.

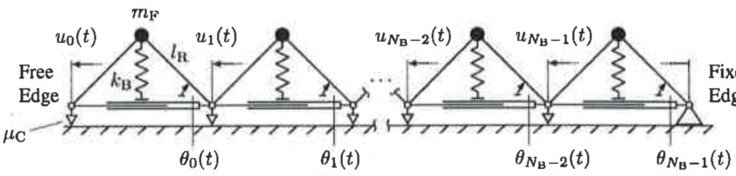

Fig. 2: Sketch of the bump foil model (with linearly interpolated top foil).

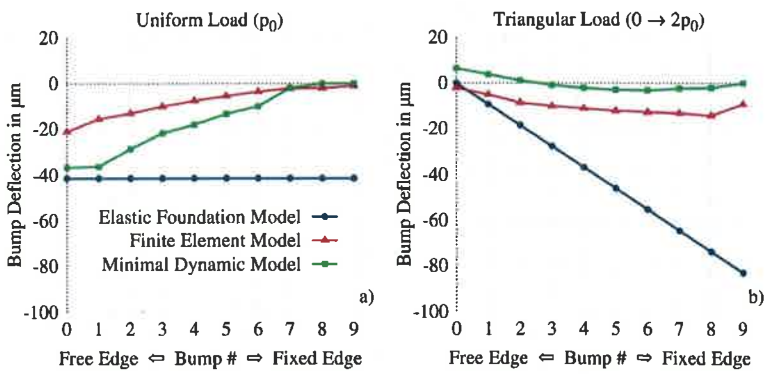

Fig. 3: Comparison of bump deflections predicted by different structure models.

Considering a fully coupled fluid–structure–rotor (FSR) interaction model as illustrated by the sketch in Fig. 1, the gas film pressure inside the lubrication gap is described by a generalized form of the classical Reynolds equation which is applicable for compressible fluids and which yields the bearing forces acting on the journal of the investigated horizontal rigid rotor [2]. Concerning the foil structure, complex FE models as discussed by many recent publications prove to be inapplicable when it comes to a transient analysis of the overall system due to excessive computational times. On the other hand, simple elastic Winkler-type foundation models do not capture any frictional effects nor any interaction mechanisms between the bumps.

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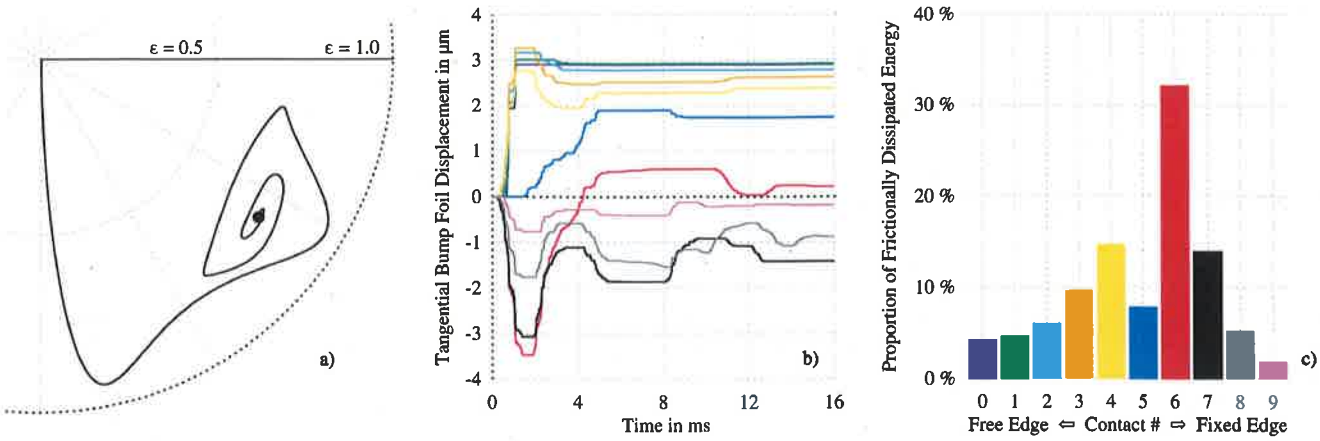

Fig. 4: Simulation results obtained for a transient rotor drop under vertical load: a) rotor journal orbit, b) tangential bump foil displacements, and c) proportions of frictionally dissipated energy. Each color is associated to a specific contact between bump foil and bearing sleeve.

Aiming at accurate simulation results at reasonable computational cost, the minimal dynamic structure model described hereafter considers energy dissipation assuming Coulomb friction applied to a reduced spring–mass arrangement. As shown by the sketch in Fig. 2, this plane model exhibits one free and one fixed edge and consists of N_B bumps, each of them represented by two massless rods (length l_R) and a connecting sliding collar. Moreover, N_B discrete particles (equivalent foil mass m_F) and springs (equivalent bump stiffness k_B) are associated to the structure. Depending on the normal force $[N_n(t)+N_\mathrm{Mounting}]$, mostly due to the pressurized gas film, the friction force $F_n(t)$ acting upon the bump foil in the n-th contact zone is stated by

$$F_n(t) = \mu_\mathrm{C}\,[N_n(t) + N_\mathrm{Mounting}]\,\mathrm{sgn}\,\dot{u}_n(t), \qquad \dot{u}_n(t) = -2l_\mathrm{R}\sum_{i=n}^{N_\mathrm{B}-1}\left[\dot{\theta}_i(t)\sin\theta_i(t)\right]. \tag{1}$$

For the computational analysis, the discontinuity of Eq. (1) with respect to the contact sliding velocity $\dot{u}_n(t)$ is regularized by means of $\mathrm{sgn}\,\dot{u}_n(t) \approx \tanh[\Xi\dot{u}_n(t)]$ with an appropriately chosen large parameter $\Xi \gg 1$. After spatial discretization of the Reynolds equation using a finite difference scheme, a fully coupled FSR state-space representation $\dot{\mathbf{s}}(t) = \mathbf{k}(\mathbf{s}(t))$ is deduced.

2 Results and Conclusion

The minimal dynamic structure model is firstly compared to a simple elastic foundation and validated against FE results from the literature [3] for two characteristic static load cases. Assuming a uniform load p_0 in Fig. 3a) and a triangular load $0 \to 2p_0$ in Fig. 3b) applied to a bump foil ($N_\mathrm{B} = 10$), the elastic foundation predicts strictly proportional deformations. However, the considered FE results suggest that realistic bump deflections are significantly smaller as a consequence of friction, bump–bump interaction and because of the fixed edge, which is found very similarly using the proposed minimal dynamic structure model.

For the dynamic analysis, a rotor drop under vertical load is simulated, resulting in the transient orbit depicted in Fig. 4a). Prior to reaching a stationary operating point, tangential bump foil displacements as shown in Fig. 4b) are observed in the different contact zones, each being associated to a specific proportion of frictionally dissipated energy. According to Fig. 4c), this correlation appears to be scarcely predictable and exhibits a strong dependence on the occurring bump–bump interaction. For instance, surprisingly few energy is dissipated in contact # 5 as a result of opposite displacements in contacts # 4 and # 6.

In summary, the present study proves the feasibility of integrating dry friction into a fully coupled fluid–structure–rotor interaction model, thus allowing for runtime-efficient computational rotor dynamics. Moreover, the transient simulation results underline the importance of bump–bump interaction when investigating frictional energy dissipation. With regard to future work, stick–slip effects will be integrated into the model and a systematic study of frictional stabilization is to be conducted.

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