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Numerical and experimental investigation of bump foil mechanical behaviour

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Corrugated foils are utilised in air foil bearings to introduce compliance and damping thus accurate mathematical predictions are important. A corrugated foil behaviour is investigated experimentally as well as theoretically. The experimental investigation is performed by compressing the foil, between two parallel surfaces, both statically and dynamically to obtain hysteresis curves. The theoretical analysis is based on a two dimensional quasi static FE model, including geometrical non-linearities and Coulomb friction in the contact points and neglects the foil mass. A method for implementing the friction is suggested. Hysteresis curves obtained via the FE model are compared to the experimental results obtained. Good agreement is observed in the low frequency range and discrepancies for higher frequencies are thoroughly discussed.

1. Introduction

The static and dynamic characteristics of compliant foil bearings are determined by the behaviour of the fluid film and a flexible element underneath the bearing surface altering its compliance. Several configurations are possible to obtain compliance, being the usage of corrugated bump foils one of the most widely used. The addition of these compliant elements into the design enables to introduce additional damping to the one generated in the fluid film. The increase of the energy dissipation is obtained due to the sliding friction forces, generated as the bearing surface deforms and induces displacements in the foil layers. However, the mechanism for obtaining the additional damping characteristics exhibits highly non-linear behaviour, which introduces significant complexities considering the obtention of an acceptable level of predictability for this bearing design.

The challenges related to the technology have generated a significant number of publications, dealing with the theoretical modelling and experimental testing of bump foil bearings. The presentation given here tries to follow a chronological progression, and focusses on the ones that have influenced the development of the work presented in this paper. Namely, the isolated static and dynamic characterisation of the corrugated foil structure by neglecting the fluid film effects.

Ku and Heshmat [1–3] presented an analytical mathematical bump foil model based on the work of Walowit and Anno [4]. The model considered a circular bearing and took into account the effect of the pad location. The model provided predictions for stiffness, hysteresis and equivalent viscous damping. Non-linear stiffness behaviour was attributed to the geometrical effects of having a circular journal loading the foils. They predicted that the dynamic coefficients were anisotropic and highly non-linear and that the stiffness and damping were dependant on the pad angle. Bump stiffness under different load distributions along the bump strip was also investigated [1] and the theoretical prediction followed the trend of earlier experimental data, regarding the higher stiffness of the bumps located at the fixed end compared to those closer to the free end. Lower friction coefficients were found to make bumps softer, whereas an increment in friction increased the stiffness and could result in pinned bump ends for the bumps close to the fixed end.

Experimental results of hysteresis curves for bump strips deformed between two straight surfaces were presented in [5]. One of the surfaces featured a pivot to enable tilting motion, in order to obtain different load distributions over the foils. The effect of pivot location and different surface coatings was investigated and the bump deflections were recorded using an optical tracking system. ‘Local’ stiffness and damping were identified and found to be dependant on amplitude and load.

Peng and Carpino [6] were among the first ones to couple the bump structure with the fluid film in a mathematical model. Coulomb friction forces and bump flexibility were included by means of an equivalent continuous friction force and a spring

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Nomenclature

A	area
E	modulus of elasticity of foil
F_n	normal force in contact point
F_μ	friction force in contact point
K	foil stiffness
L_0	initial length
L_1	current length
N^e	element force
Q	foil flexibility
S	bump foil pitch
V	volume
W	vertical load on foil strip
$\tilde{w}_0$	dimensionless foil deflection
e	element
h_0	bump foil height
k	spring stiffness
l_0	bump half length
t_b	thickness of bump foil
u, v	nodal deformations
w_b	width of bump foil
x, y	Cartesian coordinates
x_r	relative deflection
ΔL	$L_1 - L_0$
Δu	$u_j - u_i$
Δu_s	shift
Δx	$x_j - x_i$
δ	variation
μ	coefficient of friction
ν	Poisson's ratio of foil
σ	stress
θ_0	bump angular extend
ε	strain
ε_s	smoothing factor
$\{B_0\}$	independent strain displacement vector
$\{D\}$	global displacement vector
$\{F\}$	surface traction vector
$\{P\}$	global load vector
$\{R_{ext}\}$	external residual vector
$\{R_{int}\}$	internal residual vector
$\{R\}$	residual vector
$\{\Phi\}$	body force vector
$\{\overline{B}\}$	strain displacement vector
$\{\sigma\}$	stress vector
$\{\mathbf{u}\}$	nodal displacements
$\{\varepsilon\}$	strain vector
$\{d\}$	local displacement vector
$\{p\}$	nodal load vector
$[K_t]$	tangential matrix

constant. Stiffness and damping coefficients were calculated using the coupled model. No isolated validation of the foil structural model was included in this work.

Ku and Heshmat [7,8] performed an experimental investigation of the dynamic behaviour of a compliant foil bearing and compared the results to the mathematical model presented in [1–3]. Agreement between the theoretical and experimental results was reasonably good. The results showed that the cross coupling stiffness and damping are negligible and that the direct terms decrease with increasing dynamic amplitude. An increase of the excitation frequency was found to decrease the equivalent viscous damping and to increase the stiffness.

Similar experiments were performed by Rubio and San Andres [9,10]. These authors compared the experimental results to the ones obtained using a simplified mathematical model, in which the bump foil contribution was represented by simple elastic springs. The stiffness of these springs was calculated by the analytical expression of Iordanoff [11]. Furthermore, the equivalent damping was determined experimentally, for a given bump geometry, by assuming a one DOF system to which the experimental data was fitted [12,13]. This method is based on the assumption of harmonic oscillations which can be hard to obtain in an experimental set-up. Temperature effects were also investigated [12] and found to be negligible. The dry friction coefficient was found to be nearly constant with the excitation frequency but dependent on the load amplitudes. The obtained friction coefficient values varied between 0.05 and 0.2.

An NDOF discrete bump formulation model including the effect of Coulomb friction was presented by Le Lez et al. [14,15]. The foil structural model was composed of simple spring elements with elementary stiffness given by analytical expressions. The results were compared to a detailed finite element (FE) model based on a commercial software as well as experimental data [14] with good agreement. Furthermore, the calculated stiffness was compared to the simple foil flexibility given by Walowit and Anno [4] and implemented in the simple elastic foundation model by Heshmat et al. [16,17]. The updated results were found to be significantly stiffer than the reference ones, due to the inclusion of the dry friction effect.

Lee et al. [18] presented a mathematical model incorporating both the fluid film pressure field described by the Reynolds equation and the structural dynamics of the foil structure. The solution was based on FEM analysis, and it was performed using a time domain integration routine. An algorithm to deal with the stick slip phenomenon related to friction forces was incorporated as well. A parametric study was performed and hysteresis loops were presented for the bearings running under steady state conditions. The dissipated energy for the individual bumps was calculated at a given unbalance. The study indicated that optimum values of bump stiffness and friction coefficients exist with regard to minimising the resonance vibration response of a rotor mounted on foil bearings.

Zywica [19,20] simulated the top foil structure using commercial FE programs and compared to results previously published in [10]. This structural model was applied in a complex model [21] taking into account the fluid film pressure by solving the Reynolds equation. The study was of purely theoretical nature.

Considering the literature background given here, this paper is focussed on the global, quasi-static and dynamic behaviour of a bump foil strip and the local behaviour in its individual sliding contact points. This is achieved through mathematical modelling and experimental observations. The study focusses on a bump foil strip, pressed between two parallel surfaces. This original approach enables a direct comparison between experimental and theoretical results. The structural mathematical model is based on the finite element method (FEM) and the virtual work principle, applied to the studied foil geometry. Hence, the entire bump foil strip is modelled explicitly, using non-linear large deformation theory. The Coulomb friction forces are modelled using an original approach, based on equivalent non-linear springs located in the contact points between the bump foils and the mating surfaces, acting in the direction of the bump longitudinal displacement. The model is set up so that the correct direction of the friction force at each contact point is directly obtained, eliminating the need for updating the forcing term. It was implemented in a dedicated computer program and the theoretical