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Numerical determination of the mechanical stiffness of a force measurement device based on capacitive probes: Application to roller bearings

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Abstract

Bearings allow external loadings to be transferred from one raceway to the other through rolling elements, which induces strains in the bearing constituents. In order to measure the radial component of these forces, the fixed ring is inserted within a housing equipped with capacitive probes able to measure displacements with very high sensitivity. This work mainly focuses on determining the optimal housing shape using FE simulations and their influence on the global stress state undergone by the structure. Finally, an averaged global stiffness is computed, allowing proper calculation of the contact forces involved in the bearing.

Keywords: Roller bearings; Local mechanical stiffness; Capacitive probe; Nanometric displacement measurement; Radial forces measurement; FEM

1. Introduction

The purpose of this work, which follows previous papers [1–3], is to use FEM simulations as a means of getting additional information regarding displacement measurements given by capacitive probes; i.e. the stiffness of the structure. Using the theory detailed in Section 2, the structure stiffness could help compute directly the forces transmitted by each rolling element of the bearing. The presence of capacitive probes placed in a specific ring, a bearing housing with grooves, added to the initial bearing setup, can affect the overall stiffness of the mechanism and interfere with proper operation of the bearing. The objective of this work is manifold; (a) determine the optimal shape of the sensor housing, (b) ensure that machining a groove in the bearing housing does not alter proper operation of the bearing; and finally (c) build a methodology able to define an average stiffness of the outer ring induced by the presence of the probe housing, yielding an estimation of the force applied to each rolling element. This methodology can thus be adapted to each type of bearing assembly and each operating configuration, highlighting the relevance of capacitive probes technology in the field of force measurement.

The shafts of rotating machines are held in position in housings using ball or roller bearings, basically constituted of two raceways with rolling elements in-between. Balls as well as rollers therefore ensure proper transmission of external loadings thanks to localized contact zones [4–6]. In order to measure the loads transferred from rolling elements to the fixed ring, we equip the latter with a specific housing in which capacitive probes housings have been machined [2,1,7,8]. Capacitive probes display a certain number of advantages, among which:

- Nanometric displacement measurement
- Contact-free measurement, granting very high robustness
- Excellent repeatability
- Negligible influence of thermal gradients
- Small size allowing convenient placement in the vicinity of the target zone ($S < 3\ \text{mm}^2$).

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- Static and dynamic modes
- Large bandwidth (0–100 kHz)
- Easy manufacturing

Loads transmitted by rolling elements are responsible for micrometric displacements of the bearing raceways. Under nominal operating regime, rotating machines undergo stresses low enough to assume that the employed materials remain in the linear elasticity field: the relation between the force applied to the bearing and the resulting displacement is therefore linear [9–11]. As a matter of fact, the displacement field of the raceway enables calculation of the forces transmitted by the rolling elements. These displacements are related to the local stiffness of the device as well as the amplitude of the applied radial load F_r. Various parameters have a noteworthy effect on the locale stiffness, such as:

- Young's moduli of the materials in use
- Geometry of the outer ring
- Geometry of the bearing housing
- Geometry of the probe housing
- Angular position θ of rolling elements at the apex of the corresponding housings

In this paper, a device aiming at measuring the radial loads transmitted by rolling elements to the fixed ring is described. We will first briefly introduce the operating principle of capacitive probes. Next, a Finite Element (FE) numerical study is addressed, which purpose is to evaluate the local mechanical stiffness of the structure as a function of intrinsic parameters of the device. To this end, after reviewing the associated 2D FE model, the effect of the presence of probe grooves machined in the bearing housing is investigated, leading to the calculation of a numerical average stiffness of each probe housing. Being directly bonded to intrinsic characteristics of the bearing, the stiffness will enable proper computation of the loads transmitted by each roller, using experimental displacement measurements supplied by the capacitive probe.

2. Displacement measurement using capacitive probes

The fundamental of the method is to measure the average displacement on a target surface lying on the outer ring, as a rolling element passes beneath. The target surface is electrically connected to ground and stands for the movable end of a condensator with varying spacing. The fixed probe stands for the second end (see Fig. 1).

All capacitive probes in the device are enclosed inside the bearing housing, ensuring protection against environmental perturbations [12]. They also feature a guard ring [1,2]. Probes are powered by a constant electric current source using a Howland power source (see Fig. 2).

Impedance capacitor Z_{C0}, capacitance C_0, module impedance $|Z_{C0}|$ and voltage amplitude V_0 are defined as follows:

$$Z_{C0} = \frac{1}{jC_0\omega}; \quad C_0 = \varepsilon\frac{A_{\text{probe}}}{D_0}$$
$$\left|Z_{C0}\right| = X_{C0} = \frac{1}{C_0\omega} = \frac{1}{\varepsilon\omega A_{\text{probe}}}D_0;$$
$$V_0 = \frac{1}{C_0\omega}I_{\text{probe}} = \frac{I_{\text{probe}}}{\varepsilon\omega A_{\text{probe}}}D_0 \tag{1}$$

The parameters remain constant during measurements and can therefore be substituted by a constant

$$K_{\text{probe}} = \frac{I_{\text{probe}}}{2\pi f\varepsilon A_{\text{probe}}} \tag{2}$$

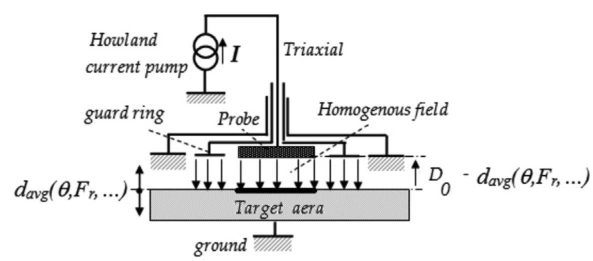

Fig. 2. Measurement principle.

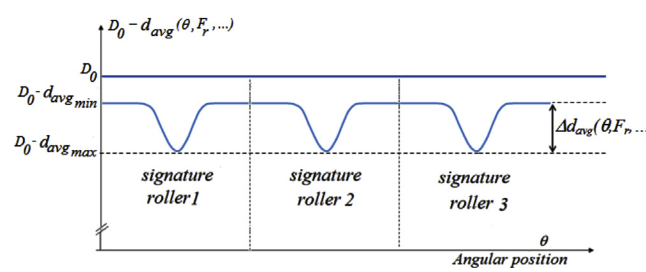

Fig. 3. Rolling elements signatures during bearing rotation.

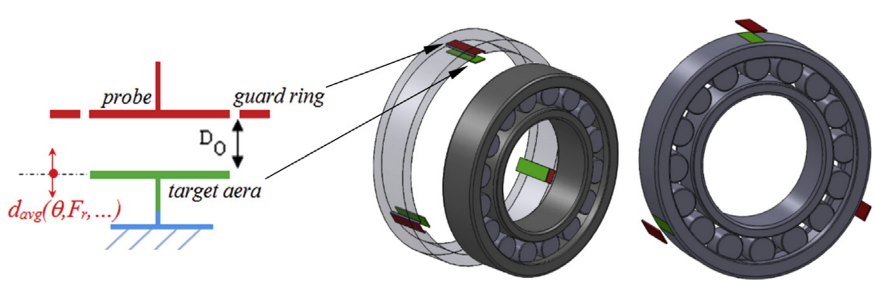

Fig. 1. Capacitive probes.