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Subcritical vibrations of a large flexible rotor efficiently reduced by modifying the bearing inner ring roundness profile

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ABSTRACT

Undesired vibration of a rotor is harmful for industrial processes and decreases the machine lifetime. In industrial processes, large rotors are commonly operated below the critical speed.

In the subcritical speed range, the bearings are an important excitation source of vibration. The bearing inner ring based excitation is observed at a frequency, which is the rotor rotating frequency multiplied by the number of undulations in the roundness profile of the roller race of the bearing inner ring. Subcritical resonance occurs, when the bearing excitation frequency equals the natural frequency of the rotor system.

The present study investigates the effect of the bearing inner ring roundness profile on the subcritical vibrations of a flexible rotor. The roundness profile of the bearing inner ring was measured, while installed on the rotor shaft. The roundness profile was modified to five different geometries to investigate different excitation cases. Finally, the roundness error of the inner ring was minimized.

The rotor subcritical vibration was measured with each bearing inner ring geometry in the horizontal and vertical directions. The analysis was focused on the 2nd, 3rd and 4th harmonic vibration components, occurring at 1/2, 1/3 and 1/4 of the critical rotational speed.

The results clearly suggest that the roundness profile of the roller race of the bearing inner ring affects the rotor subcritical vibration significantly. The increased waviness components of the bearing inner ring roundness profile increased the corresponding subcritical vibration amplitude. Minimizing the roundness error decreased the subcritical vibration substantially.

1. Introduction

Rotor running accuracy is a critical factor in a rotor system. The vibration levels exhibited by the rotor and transmitted to the bearings and other suspending components of the rotor foundation can reduce the lifetime of the apparatus and can increase the production downtime, with both leading to avoidable costs. Rotor balancing is a commonly used method in the industry for reducing vibration derived from static and dynamic unbalance [1]. Furthermore, optimizing the bearing inner ring geometry may also improve the vibrational situation by reducing the excitation from the rotor bearings.

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Nomenclature

c.	circa, approximately
CNC	Computer Numeric Control
DAQ	Data Acquisition
f	frequency [Hz]
f_i	inner ring excitation frequency [Hz]
FEM	Finite Element Method
FFT	Fast Fourier Transform
H	harmonic
k	waviness component/lobe number
LPF	Low Pass Filter
N	positive integer, $N \geq 2$
p	positive integer
PCI	Peripheral Component Interconnect
q	positive integer
RC	resistor-capacitor
$S_1 \ldots S_4$	four-point method sensors
TTL	transistor-transistor logic
u	number of rolling elements
U	uncertainty
ω_i	angular frequency of the inner ring [Hz]
ω_c	angular frequency of the cage [Hz]

The flexible rotor subcritical behaviour is important, e.g., in industry fields using electric motors and generators and turbines. The rotor assemblies are typically designed to operate on a certain speed range. The excitation from the bearing inner ring is dependent on the rotating frequency of the rotor and the waviness number (number of undulations) of the roller raceway surface. One undulation per revolution excites the rotor at its own rotating frequency; resonance and thus increased vibration is apparent when the rotor speed approaches its natural frequency. Moreover, two undulations per revolution excite the rotor at twice the frequency of the rotor itself, which leads to resonance at a rotor speed half the natural frequency. These superharmonic bearing excitations produce resonance peaks also on the subcritical (below natural frequency) speed range and are likely to occur when the ratio between the natural frequency and the running frequency is a positive integer.

The actual rotor run-out during operation is relevant in certain fields of industry such as papermaking, which utilizes the rotor (roll) surface to form the end product. The roll surface movement towards the paper web direction (run-out) is critical considering the product quality. The roll surface movement is transferred to the product and observed as undesired, periodic thickness variation. Roll surface geometry can be optimized using, for example, a roll surface measurement and grinding method proposed by Kuosmanen [2]. In addition, improving the bearing assembly may also have a significant effect on the roll run-out in operationally important directions, such as nip direction.

The design speed for a large, flexible rotor is usually below the critical speed, i.e., natural frequency of the rotor. Some rotors are designed to operate in a wide speed range covering the frequencies 1/2, 1/3, 1/4 ... 1/N times the natural frequency. In this range, the bearing inner ring raceway profile is one of the reasons for superharmonic excitation causing subharmonic vibrations.

The early studies concerning the waviness of the bearing inner ring was conducted by Gustafsson et al. [3] and Yhland [4]. They found in their experimental studies that the lobe number (number of waves) multiplied by the inner ring angular velocity dominates the vibration spectrum as proposed also by Slocum [5]. Aktürk [6] confirmed similar results with his mathematical model of waviness in bearing elements with balls as the rolling elements. Excitation caused by a defected inner ring (small crack) was analysed with a similar model by Arslan and Aktürk [7].

The connection between the waviness of the inner ring and the radial vibrations is expressed with the following connection [3,4,6]: the inner ring waviness of the orders

$$k = q \cdot u \pm p \tag{1}$$

causes vibration at frequencies

$$f = q \cdot u(\omega_i - \omega_c) \pm p \cdot \omega_i, \tag{2}$$

where $q \geq 0$ and $p \geq 1$ are positive integers, u is the number of rolling elements, ω_i is the angular frequency of the inner ring and ω_c is the angular frequency of the cage holding the rolling elements. When q is set to zero, the rotor angular frequencies producing harmonic resonance vibration are found, when the Eq. (2) gives the natural frequency of the rotor.

A dynamic bearing excitation model including Hertzian contact forces between the bearing elements has been proposed by Changqing et al. [8]. However, the investigated waviness number was as high as 18. Harsha et al. [9–13] have developed a