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Clearance measurement of a metallic rotor using electrostatic sensors

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ABSTRACT

Clearance monitoring of rotors is of vital importance for the safe operation of mechanical systems. It is essential for the system stability and early warning of faults to monitor the clearance of a rotor. This paper proposes a novel technique for the measurement of the clearance of a metallic rotor through electrostatic sensing and correlation signal processing. An electret marker is attached to the surface of the rotor as a stable charge source for the electrostatic sensors. The clearance measurement is inferred from the measured rotational speed through autocorrelation and the transit time through cross-correlation. A geometric relationship between the electrode position and the rotor axis is established. Experimental results suggest that, within the speed range of 120–3000 rpm, this technique is capable of achieving the clearance measurement of a metallic rotor with a relative error within ±8 % over the range of 2–16 mm.

1. Introduction

Rotating machinery is widely utilized across various industrial sectors, such as turbines, engines, and generators. Rotational speed is one of the crucial indicators reflecting the operational status of a rotor. Additionally, continuous operation of the rotor over a long period of time may result in changes in the clearance of the stationary part with reference to the rotor, posing a potential risk of collisions between the rotor and other components [1]. Therefore, the accurate determination of the clearance between the rotor and other components in a mechanical system is essential for maintaining operation efficiency and preventing catastrophic failures.

Well established techniques such as mechanical gauges, optical [2], ultrasonic [3] and magnetic [4] sensors have been employed for clearance or displacement measurement. These methods have weaknesses such as complex structure, high cost, and susceptibility to environmental influences. The utilization of electrostatic sensors has gained considerable attention in recent years due to their non-contact nature, high sensitivity, and low cost. Combined with correlation signal processing, electrostatic sensors have been successfully applied to measure the rotational speed of a rotating machinery in steady motion [5]. Rotational speed monitoring of a metallic rotor has been achieved by attaching a marker to the surface of the rotor [6]. However, there has been no reported research on the use of electrostatic sensors for clearance or displacement measurement. Wang et al. proposed a method for the radial vibration measurement of a non-metallic rotor based on electrostatic sensors and Hilbert-Huang transform [7]. Due to the uncertain amount of charge on the rotor surface, it cannot be used to measure the absolute displacement. In addition, the frequency domain method [8] is also used to measure the vibration of an imbalanced rotor, but the influence of the model accuracy on the measurement results is still to be studied. In this paper, a dual-electrode electrostatic sensor is used for monitoring the clearance of a metallic rotor - the clearance is defined as the distance between the rotor surface and the sensor board. With the aid of correlation signal processing algorithms, a geometric relationship between the electrode position and the rotor axis is established, thereby enabling the measurement of rotor axial position and clearance by integrating the measured rotational speed with geometric relationships. The performance of the sensor for clearance measurement of the rotor is assessed through experimentation.

2. Methodology

Fig. 1 shows the operational principle of the rotor clearance measurement system. Due to the conductivity of the metallic rotor, electrostatic charge cannot be generated and retained on its surface during rotation. Unlike an nonmetallic motor, there is no electrostatic induction between the electrode and the rotor and hence no effective signals from the electrostatic sensor. To address this problem, a film marker made of an electret material is attached to the surface of the metallic rotor. The marker provides the required source charge on the rotor for electrostatic induction. Owing to the capacity of the electret material for long-time retention of charge, the marker is negatively charged with a high voltage source. The pre-treatment of the marker helps improving the sensitivity and rangeability of electrostatic sensors. Then, the marker is further charged due to triboelectric charging effect during the rotating process. A dual-electrode electrostatic sensor is used to sense charge fluctuation on the marker. Subsequently, signals are processed in the signal processing module to determine the rotor clearance.

Each sensor signal is periodical with a period (T) representing the time taken for the rotor to make a complete revolution. The period is determined from the autocorrelation functions of the upstream and downstream signals. The time difference between the upstream and downstream signals corresponds to the transit time (τ), i.e. the time taken for the marker to move from the upstream electrode to the downstream one. The transit time is obtained from the cross-correlation

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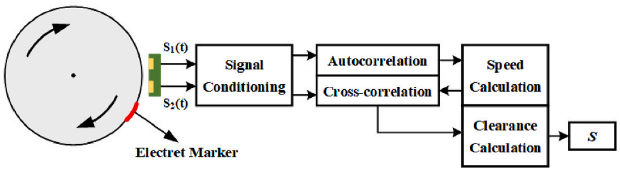


Fig. 1. Principle of the clearance measurement system.

function of the two signals. The rotational speeds calculated using autocorrelation and cross-correlation algorithms are represented as

$$\begin{cases} RPM_{auto} = \dfrac{60}{T} \\ RPM_{cross} = \dfrac{30\alpha}{\pi\tau} \end{cases} \tag{1}$$

where α denotes the central angle between two electrodes (Fig. 2). For the proposed system in this paper, at a given sampling frequency (f_s) and data length (t_a), the minimum speed obtained from the autocorrelation algorithm is regarded as the threshold for switching between the two algorithms [6], i.e.,

$$THR = \mathrm{RPM}_{automin} = \frac{120}{t_a} \tag{2}$$

The proposed technique for clearance measurement of the rotor is also based on the principle of correlation signal processing. Under ideal conditions, both autocorrelation and cross-correlation algorithms would yield accurate speed measurement results. However, in practical experiments, the accuracy of the two algorithms is significantly influenced by the sampling frequency of the measurement system and the installation conditions of the electrostatic sensor. Previous research has demonstrated that autocorrelation algorithms have higher accuracy in speed measurement than the cross-correlation algorithm [3]. It can be observed from (1) that the error in autocorrelation speed arises solely from the error in determining the period (T), whereas the accuracy of cross-correlation speed depends on central angle (α) and transit time (τ). As shown in Fig. 2, assuming that the centers of the two electrodes are located at A and B, respectively, with a center-to-center spacing of d, and the rotor radius is R_0.

For traditional cross-correlation measurement, α is calculated based on the manually measured distance from the sensor to the rotor surface (S), which inevitably introduces the measurement error.

On the contrary, if incorporating the speed via autocorrelation into the cross-correlation algorithm, α can be derived more accurately from

$$\alpha = RPM_{auto} \cdot \frac{\pi\tau}{30} \tag{3}$$

Then, the distance from the rotor axis to the sensor board L, and the clearance between the rotor surface and the sensor S, are determined respectively, from

$$L = \frac{d}{2\tan\frac{\alpha}{2}} \tag{4}$$

$$S = L - R_0 = \frac{d}{2\tan\frac{\alpha}{2}} - R_0 \tag{5}$$

In this way, the measurement of the rotor clearance is achieved at the same time as the rotational speed measurement. It is worth noting that the premise for achieving clearance measurement is that both autocorrelation and cross-correlation algorithms yield valid measurement results, i.e., the rotational speed is higher than the threshold (THR).

3. Results and discussion

3.1. *Experimental setup*

An experimental test rig, as shown in Fig. 3, was designed and constructed. A metallic rotor with a diameter of 60 mm is connected to a servo motor, with an adjustable speed up to 3000 rpm. Following the optimization results of the electrostatic sensor in Ref. [6], the electrode length and width in this study are set to 22 mm and 4 mm, respectively, and a center-to-center distance of 7 mm between the electrodes. The adjustment of the clearance between the rotor and the sensor board is achieved by altering the height of the sensor board. In this study, the sampling frequency is set as $f_s = 100$ kHz, and the data length for a single correlation analysis is set as $t_a = 1$ s. In this case, the threshold speed is $THR = 120$ rpm. A fluorinated ethylene propylene (FEP) marker, with 22 mm in length, 2 mm in width, and 150 μm in thickness, is charged for 15 min using a grid-controlled corona discharge device with a voltage of −15 kV, and is then attached to the surface of the rotor. The reference sensor for rotational speed measurement is a high-precision optical encoder with a resolution of 2500 pulses per revolution. A laser displacement sensor is used to obtain the reference to evaluate the accuracy of the measured rotor clearance. All the tests were conducted under an ambient temperature of 18 °C and a relative humidity of 40 %.

3.2. *Rotor clearance measurement results*

A set of experiments was conducted at rotational speeds above the threshold (120 rpm) to validate the effectiveness of the electrostatic sensor for the measurement of rotor clearance. Fig. 4 illustrates the rms (root-mean-square) amplitudes of typical signals from the sensor at a rotational speed of 500 rpm for a rotor clearance of 2, 8, and 14 mm. It is evident that, as the clearance increases, the rms amplitude becomes weaker. Signal quality is one of the key factors affecting the performance of clearance measurement. Due to the triboelectric effect, the charge level on the surface of markers varies unpredictably and also depends on

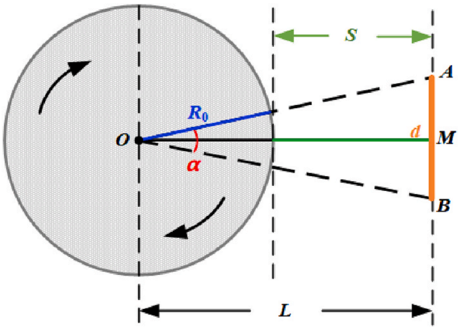


Fig. 2. Geometric schematic of the rotor and the sensor board.

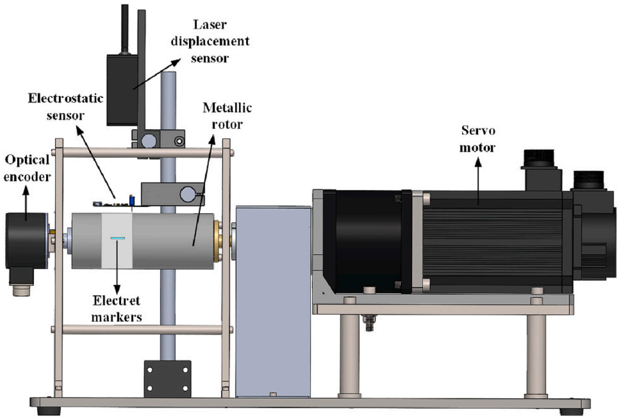
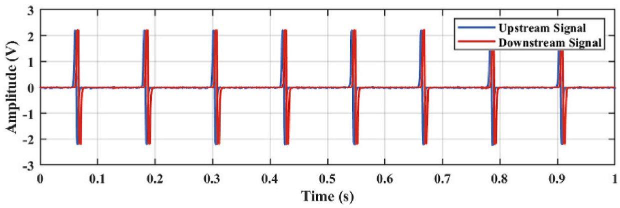
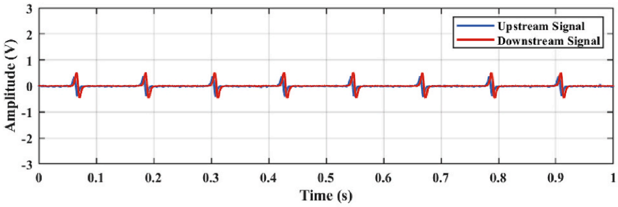


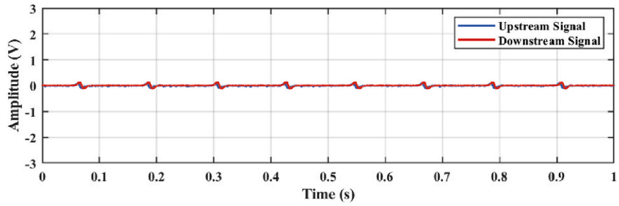
Fig. 3. Test rig.



(a) 2 mm



(b) 8 mm



(c) 14 mm

Fig. 4. Amplitude (rms) of typical signals from the electrostatic sensor for three different rotor clearance cases.

environmental factors especially at low speeds. For this reason, the clearance cannot be quantified reliably from the signal amplitude.

The period (T) and transit time (τ) of the signals at different speeds are determined using autocorrelation and cross-correlation algorithms. Then, the autocorrelation speed is calculated and integrated into (4) to derive the central angle between the two electrodes (α). Finally, the clearance (S) between the sensor board and the rotor surface is obtained.

Fig. 5 shows a direct comparison between the measured clearance and the reference value within the range from 2 to 16 mm at speeds of 120, 1000, 2000, and 3000 rpm. The measured values demonstrate a better agreement with the reference values at smaller clearances, while with increasing clearance, slight deviations between the two are observed.

Fig. 6 illustrates the relative error of the rotor clearance measurement. The dashed lines delineate the range of the relative error. It can be observed that, as the clearance increases at the constant speed, the deviation between the measured and reference values increases gradually. This is attributed to the sensitivity of the electrostatic sensor to sensing distance, where the quality and strength of signals decrease sharply with clearance, resulting in an increase in relative error. Furthermore, at a given rotational speed, an increase in clearance results in a reduction in the central angle, leading to a shorter transit time τ. For a given data sampling frequency, the number of sampling points within the transit time decreases, resulting in an increased error. This is another reason for the increase in the measurement error. As the speed increases, the overall error in clearance measurement also increases due to the fact that the transit time of the marker passing through the two electrode regions decreases with the speed, leading to an increased relative error in the determination of the transit time. Therefore, the measurement accuracy of the rotor clearance is higher at lower speeds. The relative error in the clearance measurement is within ±8 % over the range of 2–16 mm.

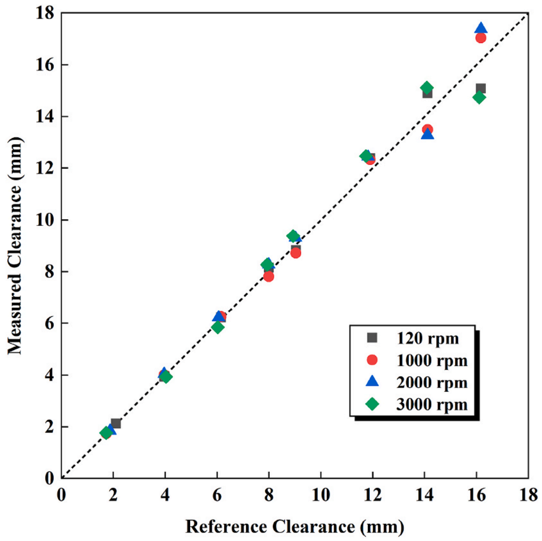


Fig. 5. Comparison between measured and reference clearance.

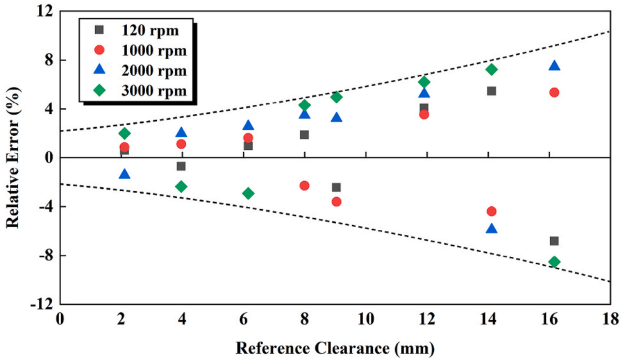


Fig. 6. Relative error of the measured clearance.

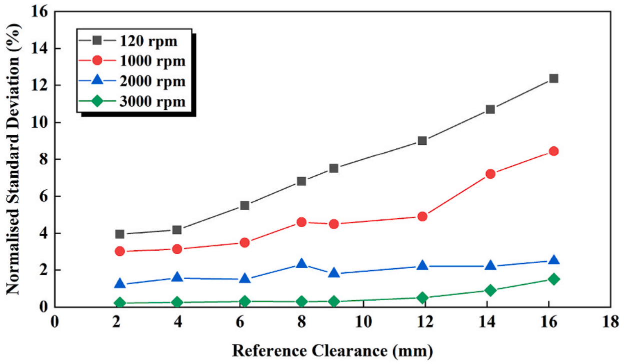


Fig. 7. Normalised standard deviation of the measured clearance.

The repeatability of the measurement system is assessed using the normalised standard deviation. Fig. 7 shows that the normalised standard deviation is no greater than 13 % within the clearance range of 2–16 mm. Due to the reduction in signal quality when the sensor is further away from the rotor, the repeatability of the system deteriorates with the rotor clearance. When the clearance exceeds 16 mm, due to the extremely low signal quality, the correlation algorithms are unable to obtain the signal period and transit time, rendering the clearance measurement results unreliable. Additionally, a higher rotational speed leads to more accumulation of surface charge on the marker, resulting in an improved repeatability of the system.

4. Conclusions

The measurement of the clearance between the metallic rotor and the sensor board has been implemented using an electrostatic sensor with an electret marker assisted. The measurement method proposed in this paper has also been validated through experimental evaluations. The preliminary experimental results indicate good performance of the measurement system for the measurement of rotor clearance. Additionally, the measurement of clearance between the rotor and the sensor has a relative error within ±8 % over the range of 2–16 mm and this is accomplished simultaneously with the speed measurement. Future research will be conducted to explore the performance of the electrostatic sensor in clearance measurement under different operation conditions of the rotor. Additionally, the rangeability of electrostatic sensors used for clearance measurements will also be assessed.

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References

[1] V.R. Patil, P.V. Jadhav, Dynamic response analysis of unbalanced rotor-bearing system with internal radial clearance, SN Appl. Sci. 2 (2020) 1–13.

[2] Y. Ren, P. Zhang, B. Shao, X. Liu, X. Lei, et al., Correlation-changed-EMD algorithm for single frequency-sweep interferometry signal of high-speed rotating structure clearance measurement, IEEE Sensor. J. 23 (23) (2023) 29366–29375.

[3] A. Ermolaev, B. Gordeev, S. Okhulkov, G. Panovko, A. Plekhov, Measuring of rotating shafts angular deformation by means of ultrasonic vibration meter, J. Meas. Eng. 11 (1) (2022) 51–61.

[4] N. Meier, A. Georgiadis, Automatic assembling of bearings including clearance measurement, Procedia CIRP 41 (2016) 242–246.

[5] L. Wang, Y. Yan, Y. Hu, X. Qian, Rotational speed measurement through electrostatic sensing and correlation signal processing, IEEE Trans. Instrum. Meas. 63 (2014) 1190–1199.

[6] X. Liu, Y. Yan, Y. Hu, L. Wang, Optimization of electrostatic sensors for rotational speed measurement of a metallic rotor, IEEE Trans. Instrum. Meas. 73 (2024) 9501811.

[7] L. Wang, Y. Yan, Y. Hu, X. Qian, Radial vibration measurement of rotary shafts through electrostatic sensing and Hilbert-Huang Transform, in: 2016 IEEE International Instrumentation and Measurement Technology Conference, Taipei, China, 23-26 May 2016, pp. 1–5.

[8] K. Reda, Y. Yan, Vibration measurement of an unbalanced metallic shaft using electrostatic sensors, IEEE Trans. Instrum. Meas. 68 (2018) 1467–1476.

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