Enhancing the performance of a rotational speed measurement system through data fusion

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Abstract. Electrostatic sensors with a single electrode or double electrodes have been applied for rotational speed measurement. In order to improve the performance of the rotational speed measurement system based on double electrostatic sensors, a data fusion algorithm is incorporated in the system. Two independent signals are accessible from the electrostatic sensor with double electrodes. From these signals two independent rotational speed measurements are obtained through auto-correlation processing of each signal and the third rotational speed measurement is also achieved by cross-correlating the two signals. A data fusion algorithm is then applied to optimally combine the three measurements. The system with the data fusion algorithm is capable of producing more accurate and more robust measurements than previous double-sensor system with a wider measurement range. Experimental results suggest that the relative error of the improved system is mostly within ±0.5% over the speed range of 200 rpm - 3000 rpm.

1. Introduction
Rotational speed is one of the most important variables to be measured for condition monitoring of rotating machineries. Over the past few decades a variety of tachometers based on mechanical, electrical, electromagnetic and optical principles have been developed [1-3]. These tachometers are generally classified into two types according to their sensing mode: contact and non-contact. The non-contact tachometers are superior to the contact ones due to the relief of mechanical wear and improvement in measurement accuracy. In recent years, as one of the most promising sensors for industrial applications, electrostatic sensors with single, double or quadruple electrodes have been proposed to measure rotational speed in recognition of the advantages of low-cost and suitability for a hostile industrial environment [4,5]. The single or double-electrode design is preferable over the quadruple design for practical applications due to the simpler installation of sensors [5]. However, previous experimental investigations suggest that the double-electrode system using cross-correlation between the two signals generates an error within ±1.5% in rotational speed measurement over a speed range of 500 rpm - 3000 rpm [5]. In order to improve the performance of the double-electrode system in terms of measurement accuracy, uncertainty and robustness, data fusion techniques are applied to combine the independent measurements from the individual sensors. This paper presents the principle of the proposed data fusion method along with experimental results.

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2. Measurement principle

Figure 1 shows the block diagram of the rotational speed measurement system based on a double-electrode electrostatic sensor with a data fusion algorithm. When a non-metallic rotor is in rotational motion, its surface becomes electrostatically charged due to the friction between the rotor surface and air. The double-electrode sensor is placed adjacent to the rotor surface to sense the motion of the rotor. Electrostatic charge on the rotor surface is detected by the two electrodes through electrostatic induction. After the signal conditioning unit, the amplified and filtered signals, \( S_1 \) and \( S_2 \), are converted to digital signals, \( S_1(k) \) and \( S_2(k) \), and processed using correlation techniques.

![Figure 1. Block diagram of the measurement system with data fusion.](image)

Through auto-correlation signal processing of \( S_1 \) and \( S_2 \), respectively, two independent rotational speeds, \( RPM_1 \) and \( RPM_2 \), are obtained,

\[
RPM_1 = \frac{60}{\tau_1} \quad (1)
\]

\[
RPM_2 = \frac{60}{\tau_2} \quad (2)
\]

where \( \tau_1 \) and \( \tau_2 \) are the periods of the rotational motion, which are determined from the auto-correlation functions of \( S_1 \) and \( S_2 \), respectively,

\[
R_1(m) = \frac{\sum_{k=1}^{N} S_1(k)S_1(k+m)}{\sum_{k=1}^{N} S_1^2(k)} \quad (3)
\]

\[
R_2(m) = \frac{\sum_{k=1}^{N} S_2(k)S_2(k+m)}{\sum_{k=1}^{N} S_2^2(k)} \quad (4)
\]

where \( R_1(m) \) and \( R_2(m) \) are the resulting auto-correlation functions of the two signals, respectively, and \( N \) is the total number of data points in the sampled signal during each measurement cycle. The location of the dominate peak on the time axis of each auto-correlation function is the period of the rotational motion, \( \tau_1 \) or \( \tau_2 \).

The third rotational speed, \( RPM_{12} \), is determined from,

\[
RPM_{12} = \frac{30\alpha}{\pi \tau_{12}} \quad (5)
\]

where \( \alpha \) is the angular spacing in radians between the two electrodes, \( \tau_{12} \) is the transit time taken for the rotor moving from the upstream electrode to the downstream one, which is determined from the cross-correlation function between \( S_1 \) and \( S_2 \).
The time corresponding to the dominant peak in the cross-correlation function $R_{12}(m)$ is the transit time $\tau_{12}$.

The final rotational speed, $RPM$, through data fusion, is given by,

$$RPM = \frac{c_1 \times RPM_1 + c_2 \times RPM_2 + c_{12} \times RPM_{12}}{c_1 + c_2 + c_{12}}$$

where $c_1$ and $c_2$ are correlation coefficients of the auto-correlation functions ($R_1(m)$ and $R_2(m)$) respectively, which represent the degree of periodicity of the signals due to the rotational motion, and $c_{12}$ is the correlation coefficient of the cross-correlation function ($R_{12}(m)$) which represents the similarity between the two signals.

3. Experimental results and discussion

3.1. Test rig

As shown in figure 2, an experimental system based on the measurement principle was designed and implemented. The test rotor is made of PTFE with a diameter of 60 mm. The rotor, driven by an AC motor, provides a rotational speed up to 3000 rpm. The electrostatic sensor consists of two identical strip-type electrodes with a centre-to-centre spacing of 7 mm. Each electrode is 3 mm in width and 20 mm in length. In order to evaluate the performance of the measurement system with data fusion, a commercial laser tachometer (Monarch Instruments, PLT200 [6]) was used to provide reference speeds. During the experimental tests the ambient temperature and relative humidity were measured to be from 20 °C to 23 °C and between 30% to 35%, respectively.

![Figure 2. Rotational speed measurement system](image)

3.2. Experimental results

Experimental tests were conducted on the test rig over the speed range of 200 rpm to 3000 rpm. For each speed, 30 measurements were recorded. The relative error of the measurement system is plotted in figure 3. The data points in figure 3 represent the average speed. The error bars indicate the maximum and minimum relative errors of the 30 measurements at each speed. Rotational speed $RPM_{12}$ is directly obtained through cross-correlation between the two signals, while $RPM$ is the final average speed through data fusion. As shown in figure 3, the average speed of $RPM_{12}$ is very close to the averaged $RPM$. Both of the average speeds are no greater than 0.1%. In terms of maximum and
minimum relative errors, the variation of $RPM$ is less than $RPM_{12}$ under all test conditions. The relative error of $RPM$ is mostly within ±0.5%, which suggests the measurement results with data fusion have low uncertainty. The relatively more significant fluctuation at a lower speed is due to low signal-to-noise ratio because less electrostatic charge is generated on the rotor surface. For this reason, the system is unable to provide reliable rotational speed measurement lower than 200 rpm. As the speed increases, the relative error becomes smaller or much smaller because of the increased charge on the rotor surface. In addition, the measurement system with data fusion has better robustness. For instance, if one of the sensing channel failed, the system with sensor fusion would still be able to produce measurements through auto-correlation of the signal from the working sensor.

![Figure 3. Relative error of the measured rotational speed](image)

4. Conclusions
Data fusion techniques have been applied to improve and enhance the performance of the rotational speed measurement system based on a double-electrode electrostatic sensor. Experimental results have demonstrated that the measurement error has been reduced from ±1.5% to ± 0.5% due to the use of the data fusion algorithm. In addition, for this level of measurement error, the lower end of the measurement range has been extended from the previous 500 rpm to 200 rpm with reduced measurement uncertainty. Meanwhile, the robustness of the system is enhanced as the system would still be able to produce valid measurements in the case of a malfunctioning signal channel. More investigations into the effects of environmental factors (i.e. ambient temperature and relative humidity) on the measurement system and industrial trials will be conducted.

5. References
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