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Comparison of Single and Double Electrostatic Sensors for Rotational Speed Measurement

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Abstract

Accurate and reliable measurement of rotational speed is crucial in many industrial processes. Recent research provides an alternative approach to rotational speed measurement of dielectric rotors through electrostatic sensing and signal processing. This paper aims to explore the electrostatic phenomenon of rotational machineries, design considerations of the spacing between double electrostatic sensors and effect of dielectric rotors on the performance of the rotational speed measurement systems based on single and double electrostatic sensors. Through a series of experimental tests with rotors of different material types, including polytetrafluoroethylene (PTFE), polyvinyl chloride (PVC) and Nylon, different surface roughness (Ra 3.2 and Ra 6.3) and difference diameters (60 mm and 120 mm), the accuracy and reliability of the two measurement systems are assessed and compared. Experimental results suggest that more electrostatic charge is generated on the PTFE rotors with a larger diameter and coarser surface and hence better performance of the measurement systems. The single-sensor system yields a relative error of within ±1% while the double-sensor system produces an error within ±1.5% over the speed range of 500 - 3000 rpm for all tested rotors. However, the single-sensor system outperforms the double-sensor system at high rotational speeds (>2000 rpm) with a relative error less than ±0.05%.

Keywords – Rotational speed measurement; Electrostatic sensor; Correlation signal processing; Performance assessment; Surface roughness.

1. Introduction

Accurate and reliable measurement of rotational speed for rotating devices and machineries is desirable in many industries. Rotational speed is an important parameter to identify operating status, make fault diagnosis and establish an effective maintenance strategy in order to reduce downtime of an industrial process. Traditional contact-type measurement devices such as centrifugal tachometers, timing tachometers and electric-dynamic tachometers suffer from the common problems of wear, slippage and low measurement accuracy. Hence, a variety of non-contact measurement systems based on optical, electromagnetic and digital imaging techniques have been developed [1-3]. In recent years, instantaneous rotational speed has been estimated through vibration signal analysis by many researchers [4, 5]. However, photoelectric tachometers require the fitting of external illumination sources, encoders on the shaft or refection marks on the rotor surface [6]. This kind of tachometer is difficult to use in hostile environments. Stroboscopic tachometers work well under low and stable speed conditions [6]. Magnetic inductive tachometers are limited to the measurement of metallic rotors and are susceptible to electromagnetic interference [6]. Imaging based systems suffer from similar drawbacks as the photoelectric types in addition to high cost and structural complexity [3].

Electrostatic sensor arrays in conjunction with correlation signal processing algorithms have been deployed to measure rotational speed with high accuracy and good repeatability [7]. However, the mechanical structure required for the installation of the electrostatic sensor arrays is impractical to be fitted on large rotors in many cases. To solve this problem, the measurement system using a single or double electrostatic sensors has been proposed [8, 9]. Although basic electrostatic properties of some dielectric materials are well known, the effects of the material type and surface roughness of the rotor on the performance of single- and double-sensor systems are still not clear. In the present research new contributions are made in the respects of theoretical analysis and experimental investigations. Firstly, the electrostatic phenomenon of rotational machineries and design considerations of the spacing between the double sensors are discussed in detail. Secondly, comparative assessments between the single- and double-sensor systems are conducted. In addition, a high-performance data acquisition device is applied to improve the accuracy of the measurement systems. A commercial laser based tachometer with an accuracy of ±0.01% is utilized to provide reference measurements. Finally, three dielectric materials, including polytetrafluoroethylene (PTFE), polyvinyl chloride (PVC) and Nylon, with two kinds of surface roughness (Ra 3.2 and Ra 6.3), are tested over a speed range of 500-3000 rpm. The performance of the two measurement systems is assessed and compared.

2. Measurement Principle and System Design

2.1 Electrostatic phenomenon of rotational machineries

Certain materials are potential to become electrically charged after fricative contact with a different material due to triboelectric effect. There are several factors affecting the polarity and magnitude of the charge generated on the rotor surface, such as material type and surface roughness of the rotor, temperature and humidity of the environment. Work function represents the capability of a material to hold onto its free electrons [10]. In general, the material with greater work function is easier to appropriate electrons from materials with lower work functions and less likely to give up its free electrons when contacting with other materials. Meanwhile, the material with weaker work function is more likely to acquire positive charges by losing or giving up some of its free electrons. Consequently, dielectric materials have higher work functions and are hence to be electrically charged when rubbed with air which has a lower work function. Electrostatic charge is generated and accumulated on the dielectric rotor surface during the continuous process of contact, friction and separation between the rotor surface and air. Moreover, the level of electrostatic charge generated on the rotor surface is normally determined by many factors, such as physical properties (material type, size and surface roughness) of the rotor, rotational speed and ambient conditions (humidity and temperature).

With the generation of electrostatic charge, there is also a phenomenon of electrostatic discharge, which reduces the amount of electrostatic charge generated. The remaining electrostatic charge [11] on the rotor surface is determined by

$$Q = Q_0 e^{-\frac{t}{\tau}} = Q_0 e^{-\frac{t}{\varepsilon_0 \varepsilon_r \rho}} \quad (1)$$

where Q_0 and Q are respectively the initial and final levels of electrostatic charge generated on an object and τ is the relaxation time of the object, which is derived from the permittivity of free space ε_0, the relative permittivity ε_r and the resistivity ρ of the object. Equation (1) indicates that electrostatic discharge depends on the permittivity and resistivity of the material. The larger permittivity and resistivity, the longer relaxation time of electrostatic discharge and hence more electrostatic charge maintained on its surface.

2.2 Measurement principle

The structure of electrostatic sensors based the rotational speed measurement system is shown in Fig. 1. The single or double electrostatic sensors are placed in the vicinity of the rotor to sense the charge on the rotor surface. Electrostatic signals are obtained from the electrostatic sensors through electrostatic induction due to the charge generated on the moving surface of the rotor. A high-performance signal conditioning unit is utilized to condition the extremely weak signals from the sensing point. The data acquisition unit converts the analog signals to digital forms and transmits the acquired signals to a host computer. Signal processing, including auto-correlation and cross-correlation, and rotational speed calculation are realized in the host computer.

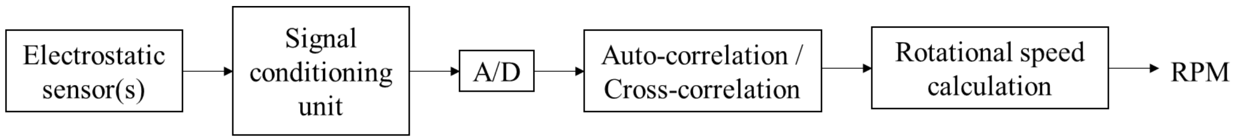


Fig. 1. Structure of electrostatic sensors based rotational speed measurement system.

In the case of single electrostatic sensor based system, the electrostatic signal S(t) is periodic due to the continuous rotational motion of the rotor with reference to the fixed location of the sensor. The periodicity of the signal is equal to the period of the rotation motion (T), which is determined from auto-correlation function of the electrostatic signal. A normalized auto-correlation function $R_a(m)$ is defined as:

$$R_a(m) = \frac{\sum_{k=1}^{N} S(k)S(k+m)}{\sum_{k=1}^{N} S^2(k)} \tag{2}$$

where S(k) (k = 0, 1, 2, …, N) represents the digitized signal S(t), N is the number of samples in the correlation computation and m (m=0, …, N) is the number of delayed points.

The location of the dominate peak (other than the unity at m=0) on the time axis is the period T. The amplitude of the dominate peak in the auto-correlation function is the correlation coefficient, which indicates the reliability of the speed measurement through auto-correlation. The rotational speed (n) in Revolutions Per Minute (RPM) is calculated from

$$n = \frac{60}{T} \tag{3}$$

In the case of the double electrostatic sensors based system, the time delay (τ) between the two electrostatic signals $S_1(t)$ and $S_2(t)$ is equal to the time of the rotor travelling from upstream to downstream sensors and is determined through cross-correlation function $R_c(m)$:

$$R_c(m) = \frac{\sum_{k=1}^{N} S_1(k) S_2(k+m)}{\sqrt{\sum_{k=1}^{N} S_1^2(k)} \sqrt{\sum_{k=1}^{N} S_2^2(k)}} \tag{4}$$

The time corresponding to the dominant peak in the cross-correlation function $R'(m)$ is the time delay τ and thus the rotational speed (n) is determined from

$$n = \frac{30\alpha}{\pi\tau} \tag{5}$$

where α is the angular spacing in radians between the two sensors.

2.3 Sensor design

The mathematical modelling and optimal design of the single electrostatic sensor have been reported in a previous paper [12]. As suggested, the optimal width of the electrode is between 0.05 and 0.1 times of the diameter of the rotor; the length of the electrode is normally in the range of 20 mm to 50 mm in view of the practically suitable physical dimensions of the printed circuit board. The diameter of the rotors used in this study is 60 mm or 120 mm, so the width of the electrode is set to 3 mm and the length is 20 mm (See Fig. 3 (a)). The strip electrode is made of copper and embedded in a small piece of printed circuit board (PCB). The size of the PCB is designed as 42 mm × 20 mm. The charge detection and pre-amplifier circuits are mounted on the other side of the PCB. In order to avoid external electromagnetic interference, the whole circuits are enclosed by an earthed screen.

As for the design of the double electrostatic sensors, the spacing between the two electrodes is another important parameter, which mainly affects the similarity between the two signals and hence the accuracy and reliability of the rotational speed measurement system. In general, the spacing between the two electrodes should be narrow enough to keep higher signal similarity. Meanwhile, it is more accurate to fit a correlogram at the minimum transit time under the condition of highest speed. However, if the two electrodes are mounted extremely close to each other the electrical field interaction between them would become significant, resulting in reduced signal similarity and increased statistical error in the speed measurement. A mathematical model regarding to a point charge passing over the two electrodes is established and the resulting output of the double sensors is shown in Fig. 2. Due to the interaction between the two electrodes and associated insulators and the inherent asymmetry of the construction of the PCB, the two signals are not identical, but one of them is a flipped version of the other with respect to both polarity and time. Consequently, the spacing between the two electrodes should be set ranging from 2 or 4 times of the width of the electrode. So the spacing used in this study is 7 mm (See Fig. 3 (b)). In consideration of the sensor design and construction, the material and thickness of the coating between and outside the two electrodes should be made as identically as possible.

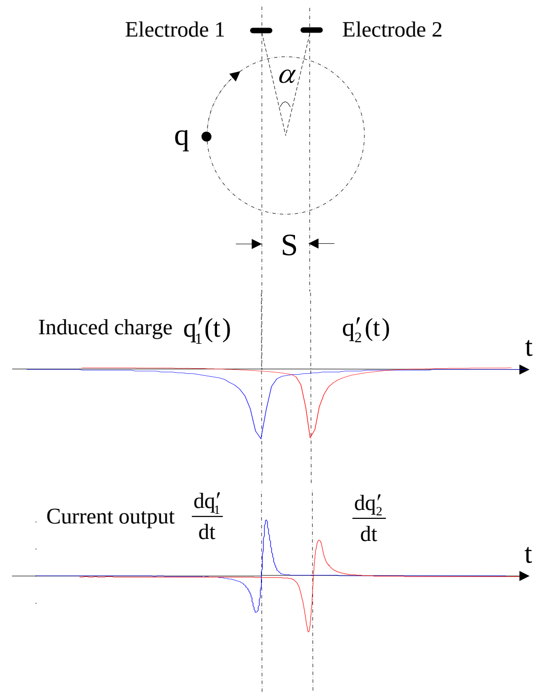


Fig. 2. A typical example of the induced charge on the double electrodes and corresponding sensor output.

(a) Structure of a single electrostatic sensor (b) Structure of double electrostatic sensors

Fig. 3. Design and construction of the electrostatic sensors.

3. Experimental Results and Discussion

3.1 Test conditions

Experimental tests were conducted on a purpose-build test rig, as shown in Fig. 4. The test rotor is driven by a three-phase asynchronous motor via a coupling. The rotor is able to provide the rotational speed ranging from 0 to 3000 rpm by adjusting the motor controller. The electrostatic sensor is placed 2 mm away from the rotor surface. The sensor outputs are sampled at a frequency of 10 kHz using a data acquisition unit (National Instruments, Data Acquisition Device USB-6351), which is sufficient to generate satisfactory measurements for the single-sensor and double-sensor systems. The signals are then transmitted to a host computer and processed through auto-correlation and cross-correlation. In order to evaluate the performance of the two measurement systems, the measured rotational speeds are compared with the reference speed acquired from a commercial laser based tachometer [13] (Monarch Instruments, PLT200). The best achievable accuracy of the commercial tachometer is ±0.01%, as stated in the operation manual. During the experimental tests the ambient temperature and relative humidity were measured to be from 20°C to 24°C and between 28% and 35%, respectively.

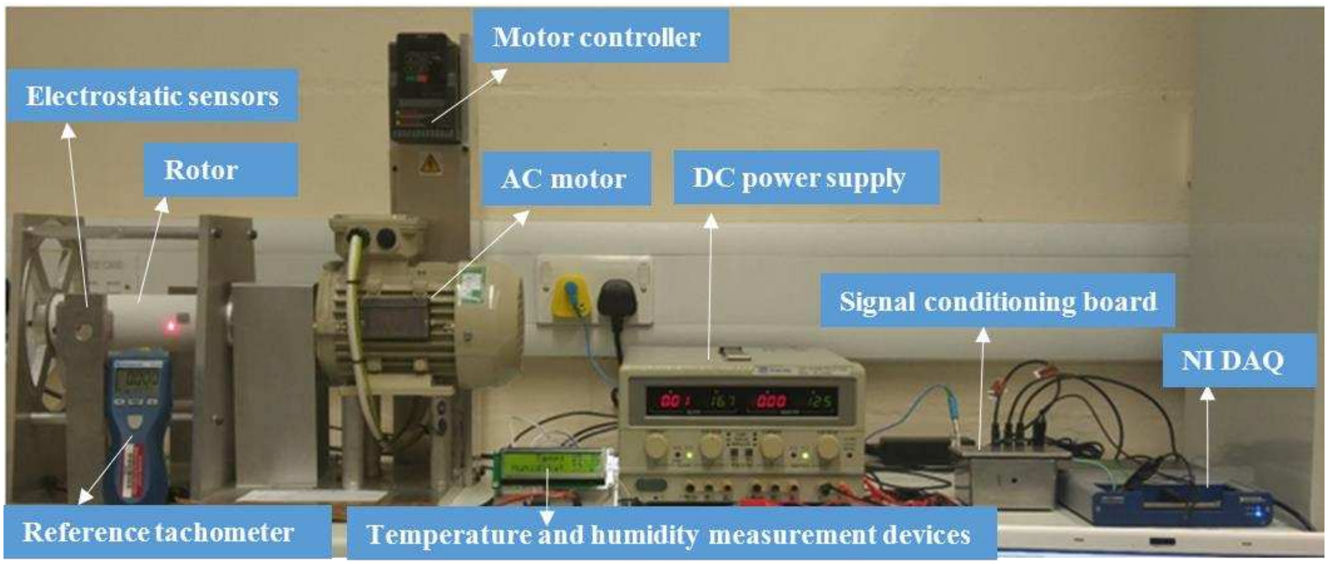


Fig. 4. Rotational speed measurement system.

A series of experiments were conducted on the test rig under different test conditions which are summarized in Table 1. In order to investigate the effect of material type on the performance of the single or double electrostatic sensors based rotational speed measurement systems, test rotors are made of three common dielectric materials (PTFE, PVC and Nylon). The surface roughness of each rotor is set to Ra 3.2 and Ra 6.3, respectively, where Ra (roughness average) is the most commonly used one-dimensional roughness parameter (i.e., arithmetic mean deviation of the surface profile) in the manufacturing industry [14]. The higher the value of Ra, the coarser the surface texture. The rotors with a diameter of 60 mm have surface roughness of Ra 3.2 and Ra 6.3, respectively whilst the larger rotor (120 mm diameter) has a surface roughness of Ra 6.3. The surface roughness was achieved using a computerized numerical control (CNC) machine with a lathe tool and verified with a set of surface roughness comparators (reference plates). The axial length of the rotors is set to 152 mm.

Table 1. Test programme.

Electrostatic sensor	**Rotor**			
	Material type	**Surface roughness**	**Rotor diameter (mm)**	**Rotational speed (rpm)**
Single / Double	PTFE	Ra=3.2, 6.3	D=60	n: 0-3000
		Ra=6.3	D=120	
	PVC	Ra=3.2, 6.3	D=60	
		Ra=6.3	D=120	
	Nylon	Ra=3.2, 6.3	D=60	
		Ra=6.3	D=120	

3.2 Material characteristics

The likely electrostatic charging trend of common materials is shown in Fig. 5 under certain conditions [15]. A material on the right-hand side of the series will always charge positively when brought into contact with a material on the left (i.e. the latter will charge negatively). This is because a material on the right side of the series has a lower work function than those on the left and thus tends to lose electrons and accumulate positive charge. In general, materials with higher work functions tend to appropriate electrons from materials with lower work functions. According to the physical characteristics of PTFE, PVC and Nylon outlined in Table 2 [16-20], PVC and PTFE with higher work functions are easier to charge negatively when they rub with the air with a lower work function. Disagreements between the charging series (Figure 5) and the work functions (Table 2) are noted and commented by other researchers [16].

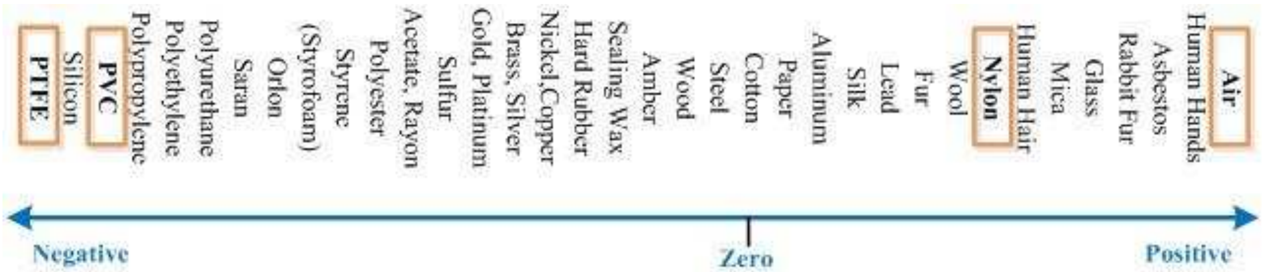


Fig. 5. Triboelectric series [13].

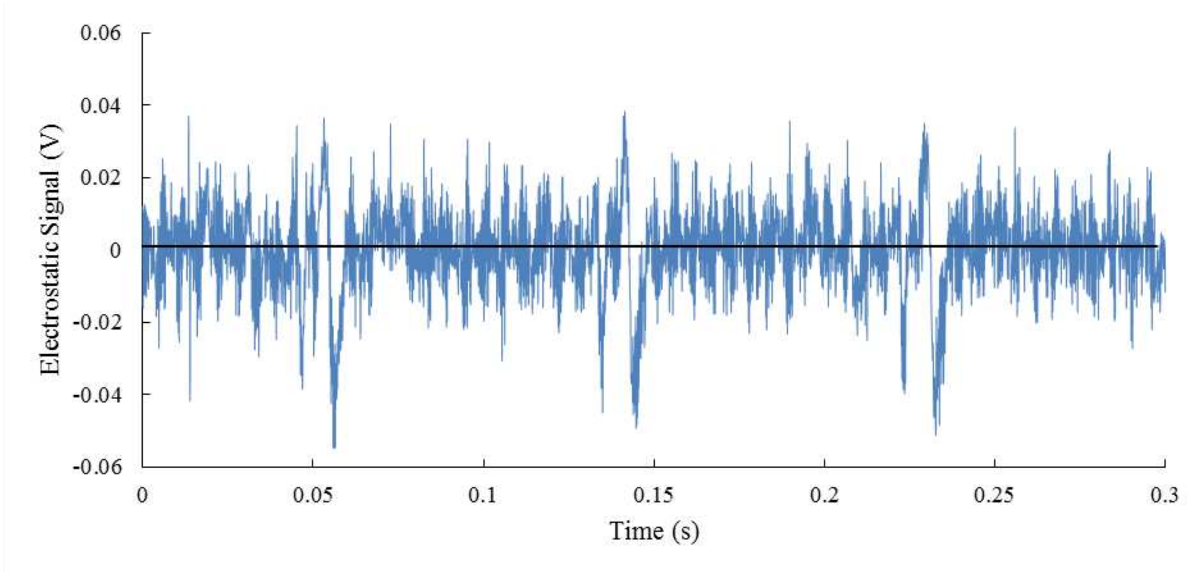
Table 2. Physical characteristics of different material [10, 16-19].

Material	Work function (eV)	Permittivity	Resistivity (Ωm)
PTFE	4.26	2.10	10^{16}
PVC	4.85	3.18	10^{16}
Nylon	4.08	3.50	10^{12}

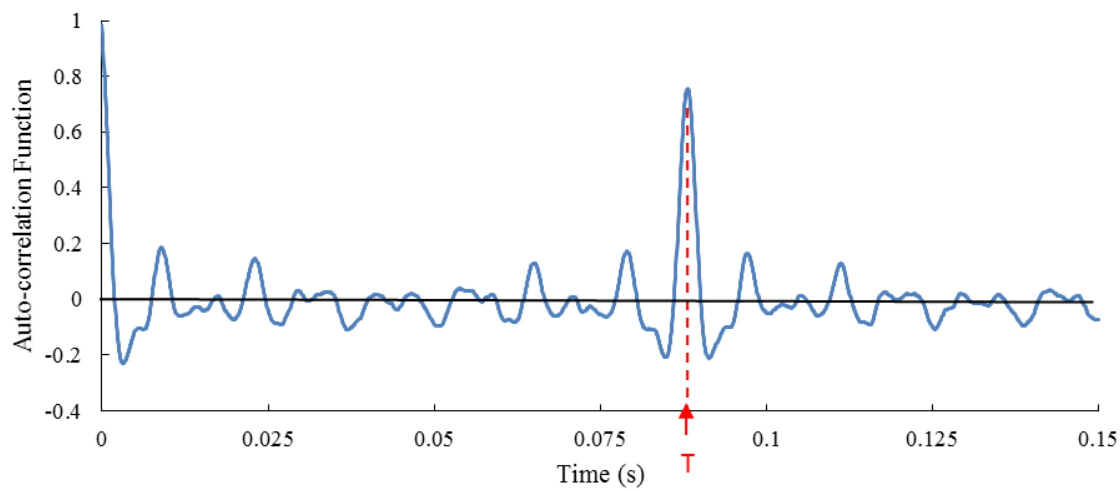
Surface roughness is one of the important factors affecting the level and the distribution of the electrostatic charge generated through friction. It is typically considered to be the high-frequency and short-wavelength component of a surface. The rough surface usually have higher friction coefficients than smooth surface. In addition, the peaks on the surface may have substantial charge that generates a large electric field in a very small area resulting in corona discharge or the breaking down of the air molecules [18].

3.3 Sensor signals

A typical signal waveform from the single electrostatic sensor and resulting auto-correlation function are plotted in Fig. 6 (a) and (b). When the rotor is rotating continuously, electrostatic charge is generated on its surface and a dynamic balance is reached between the natural discharge and recharge. The period (T) of the signal, determined from the location of the dominant peak in the auto-correlation function is shown in Fig. 6 (b). The signal waveforms from the double electrostatic sensors and resulting cross-correlation function are plotted in Fig. 7 (a) and (b). The two signals are similar but there is a time delay between them. The time delay (τ) is determined from the location of the first dominant peak in the cross-correlation function.

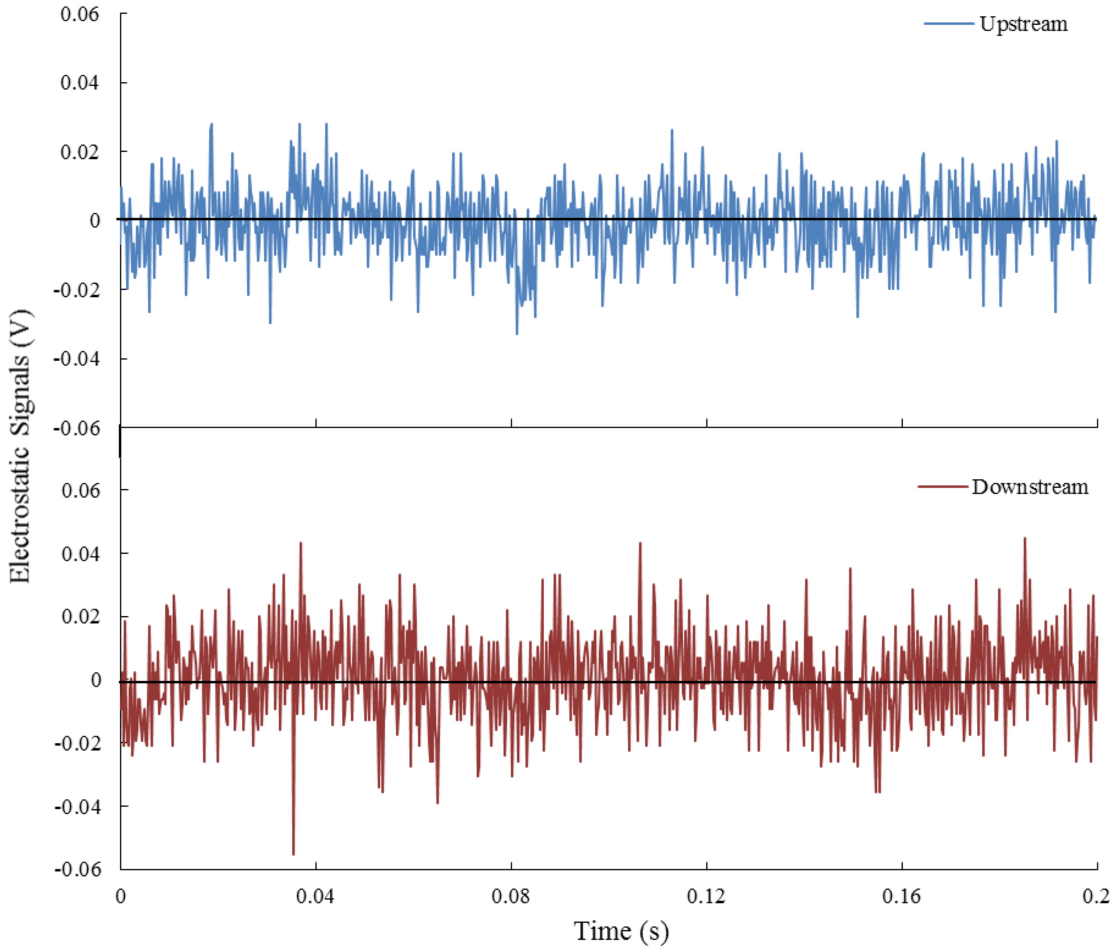


(a) Signal waveform

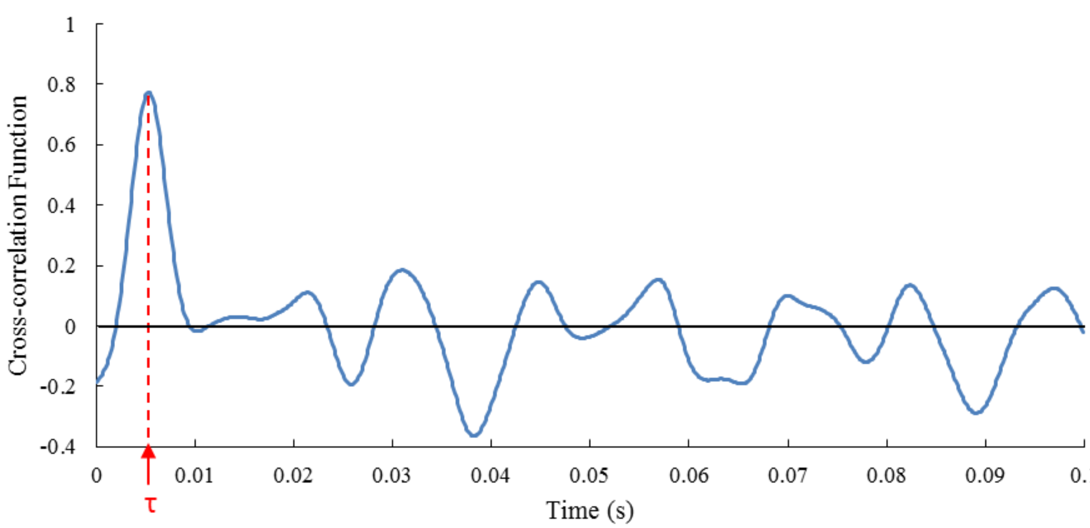


(b) Autocorrelation function of the signal

Fig. 6. Typical signal waveform from the single-sensor system and resulting auto-correlation function.



(**a**) Signal waveforms

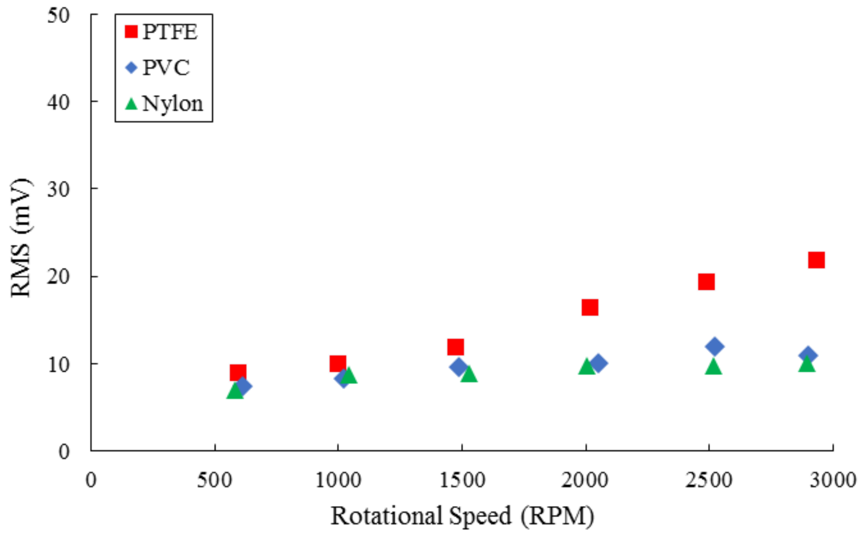


(b) Cross-correlation function of the two signals

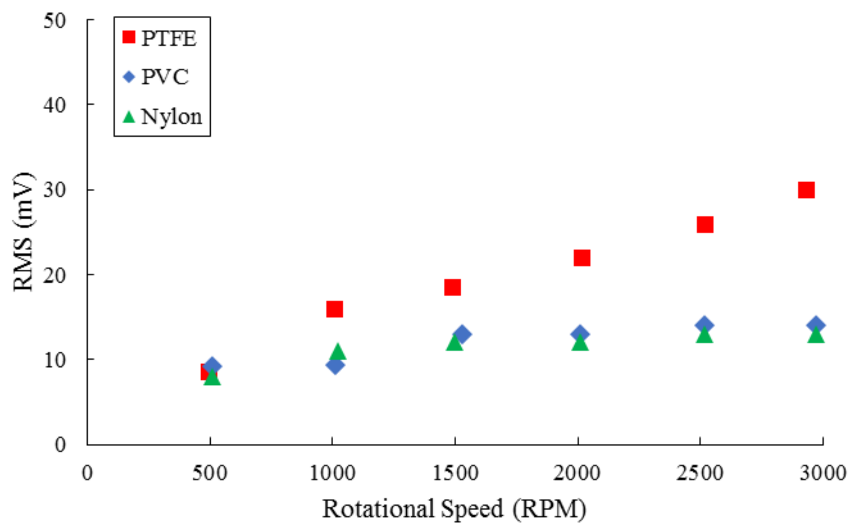
Fig. 7. Typical signal waveforms from the double-sensor system and resulting cross-correlation function.

3.4 Signal amplitude

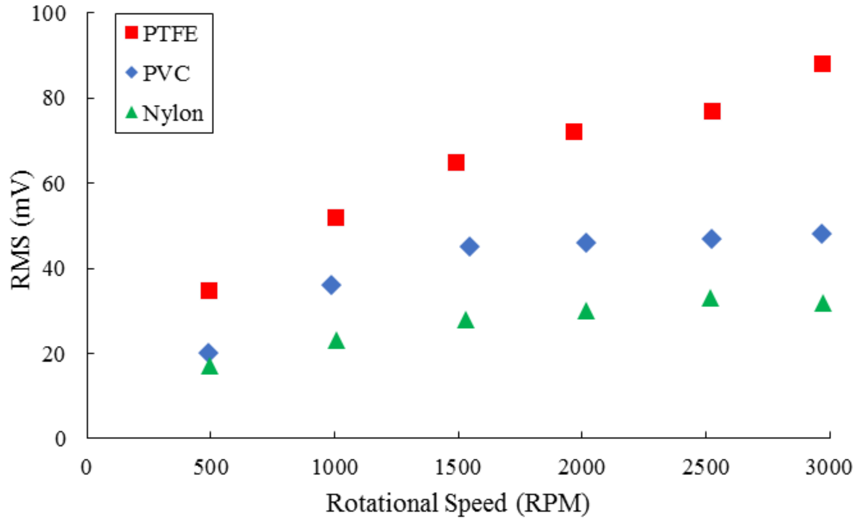
Apart from environmental factors (ambient temperature and relative humidity), the amplitude of electrostatic signal also depends on operating conditions, such as material type, surface roughness, rotor size and rotational speed. In this study, the ambient temperature and relative humidity were set within a narrow range (Section 3.1) while the effects of rotors and operating speed on the measurement systems are investigated. Fig. 8 depicts the signal amplitude collected from the same electrostatic sensor along with corresponding signal conditioning unit for different test rotors. Each data point in Fig.8 is a time averaged value with a standard deviation of less than 1%. The PTFE rotor generates higher electrostatic signal amplitude than the PVC and Nylon rotors for the same geometric dimension and surface roughness due to its better triboelectric characteristics and larger permittivity and resistivity. Through testing on the rotors with the same material and size, more electrostatic charge is generated on the rotors with the surface roughness of Ra 6.3. The signal amplitude of the 120 mm rotor in Fig. 8 (c) is higher than that of the 60 mm rotor in Fig. 8 (b) with the same material and surface roughness. This is due to the larger surface area and faster surface speed generating more electrostatic charge on the rotor surface. It can be obviously seen from Fig. 8 (a)-(c) that the RMS (Root-Mean-Square) signal amplitude for a certain rotor increases with the rotational speed because of the increased electrostatic charge on the rotor surface.



(a) D=60 mm and Ra=3.2



(b) D=60 mm and Ra 6.3



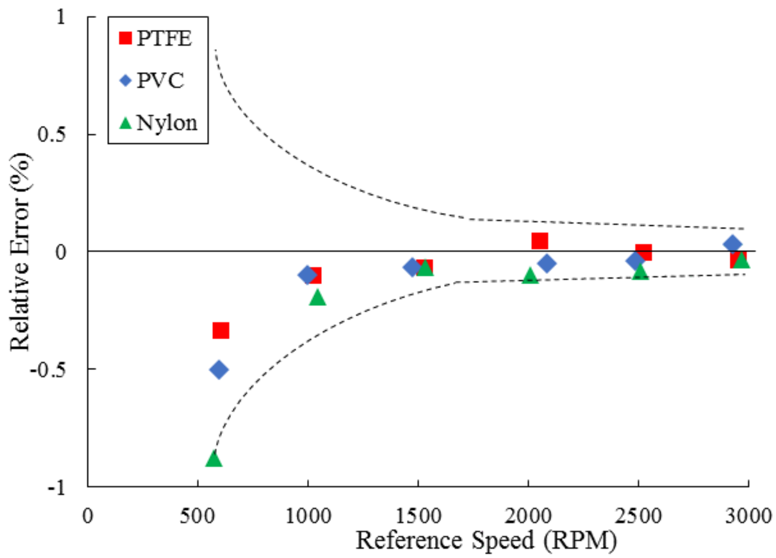
(c) D=120 mm and Ra=6.3

Fig. 8. Signal amplitude of different rotors.

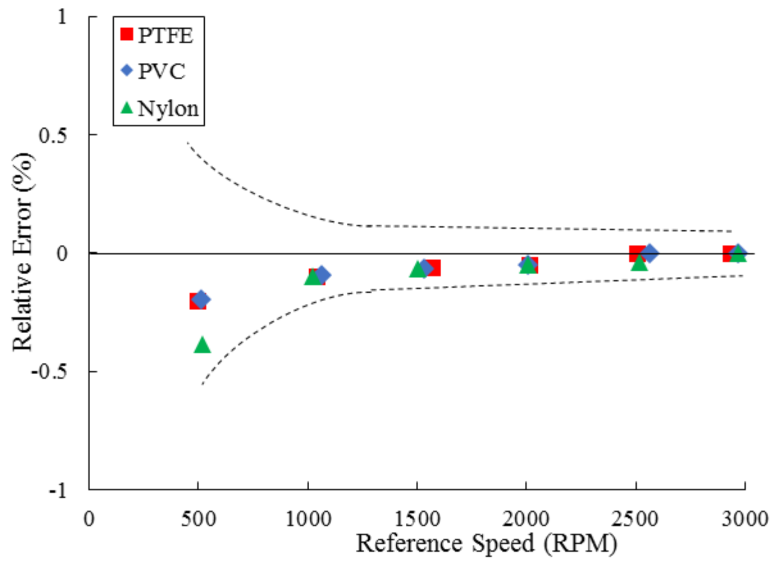
3.5 Accuracy

The accuracy of the electrostatic sensor based measurement systems depends on the signal –to-noise ratio of the electrostatic signals and their sampling frequency. When the rotor speed is lower than 500 rpm, limited electrostatic charge is generated on the rotor surface and discharges quickly over one revolution. In this case it is difficult to obtain valid rotational speed measurements using the single-sensor system. However, additional measures can be taken to increase electrostatic charge on the rotor. For example, a marker with better triboelectric property or even permanent charge on its surface (e.g. electret) may be used.

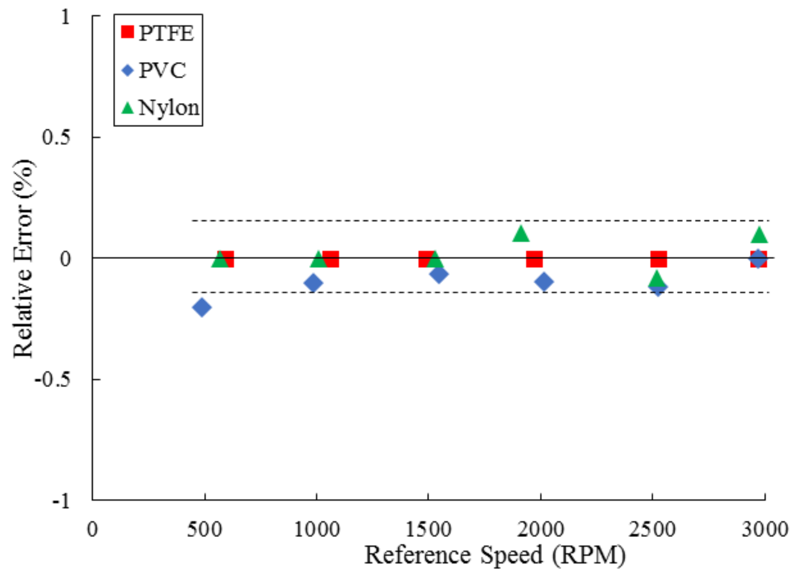
The relative errors of the measured rotational speed, as shown in Fig. 9 and Fig. 10, are average values with a standard deviation of less than 0.05%. The dashed lines in Fig. 9 and Fig. 10 depict the error range. It is evident that the measured speed from the single-sensor based measurement system is very close to the reference reading with a maximum error of less than ±1.5%. It can be seen from Fig. 9 that the measurement system performs better on the larger rotor and high rotational speed as more electrostatic charge generated on the rotating surface and hence high quality of signal. Moreover, the PTFE rotor outperforms the PVC and Nylon rotors in terms of accuracy. For PTFE rotors, the relative errors are always within ±0.5% over the range of 500 rpm to 3000 rpm. This outcome agrees well with the triboelectric charging series as shown in Fig. 5.



(a) D=60 mm and Ra=3.2



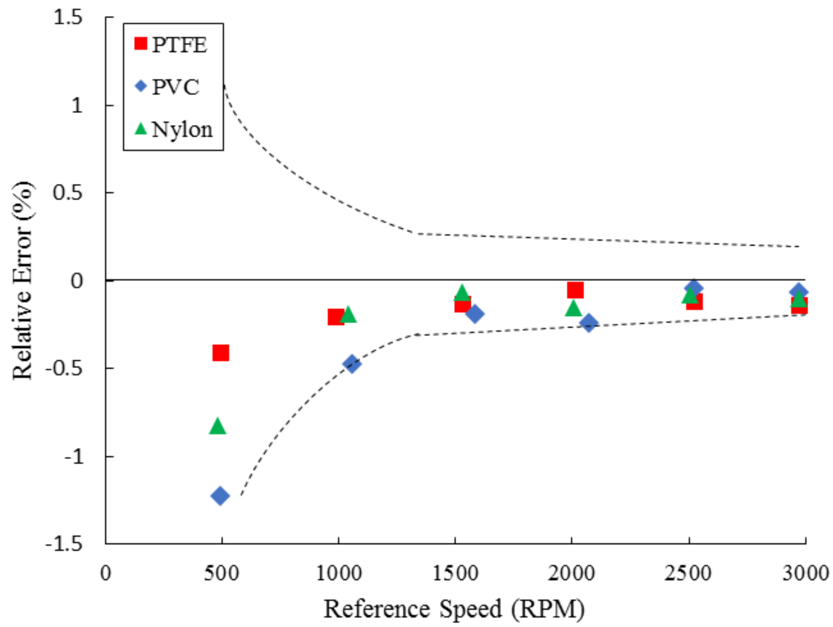
(b) D=60 mm and Ra=6.3



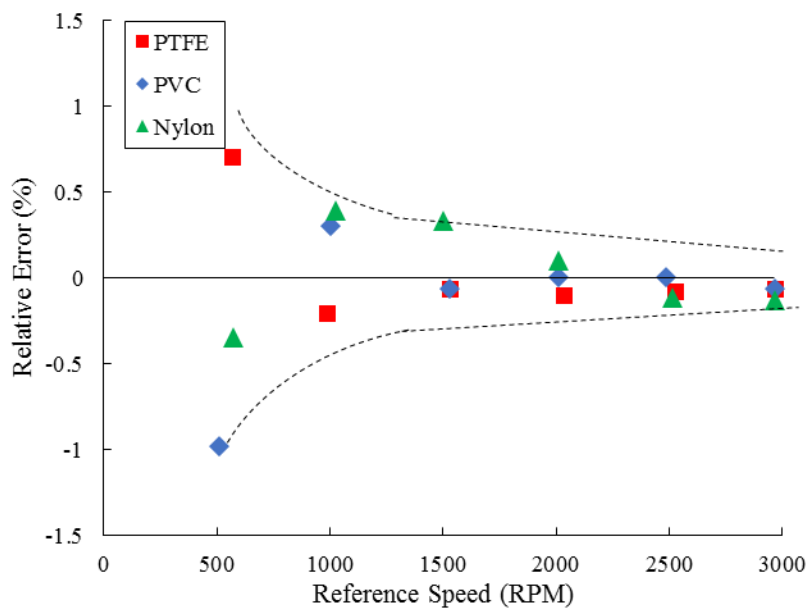
(c) D=120 mm and Ra=6.3

Fig. 9. Relative errors from the single-sensor system.

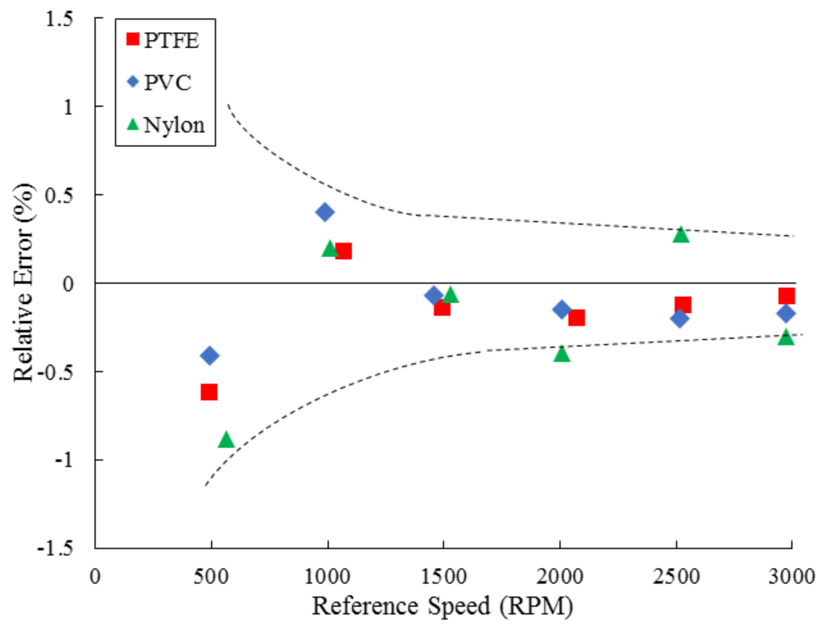
Fig. 10 shows the experimental results of comparative tests on the double-sensor system. As the rotational speed increases, more electrostatic charge is generated on the rotor surface and hence smaller relative errors. The relative error from the double-sensor system is within ±1.5% when the rotational speed ranging from 500 rpm to 3000 rpm. However, the errors are relatively larger than those from the single sensor system, because the spacing between the two electrodes yields a short time delay between the two signals, which is relatively difficult to measure accurately, compared to the single-sensor system. It can be seen from Fig. 10 that the PTFE rotors yield more accurate measurement results than the PVC and Nylon rotors.



(a) D=60 mm and Ra=3.2



(b) D=60 mm and Ra=6.3

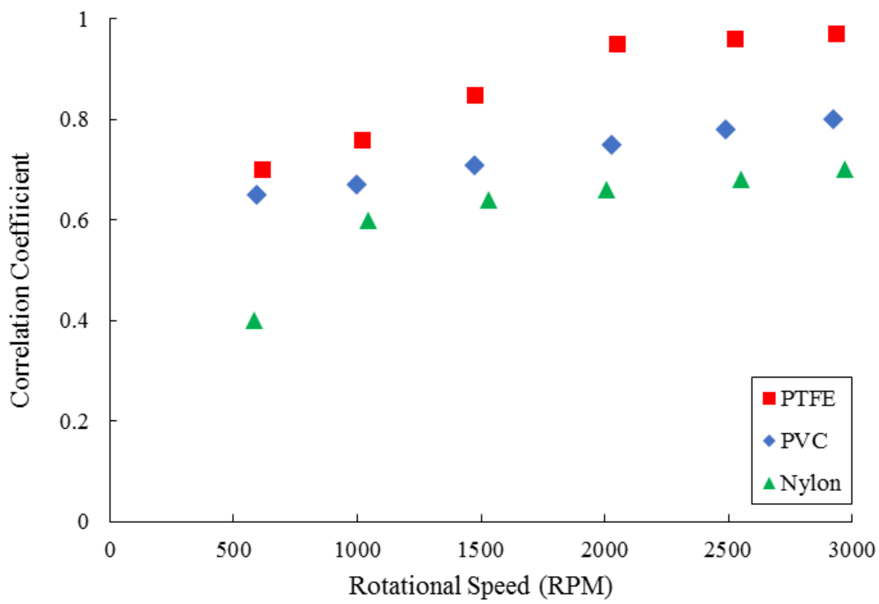


(c) D=120 mm and Ra=6.3

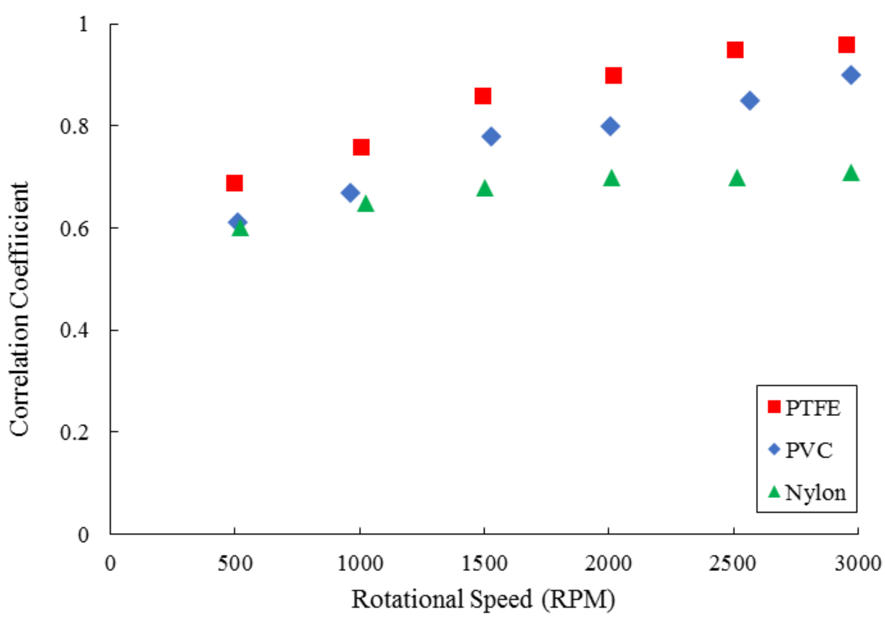
Fig. 10. Relative errors from the double-sensor system.

3.6 Correlation coefficient

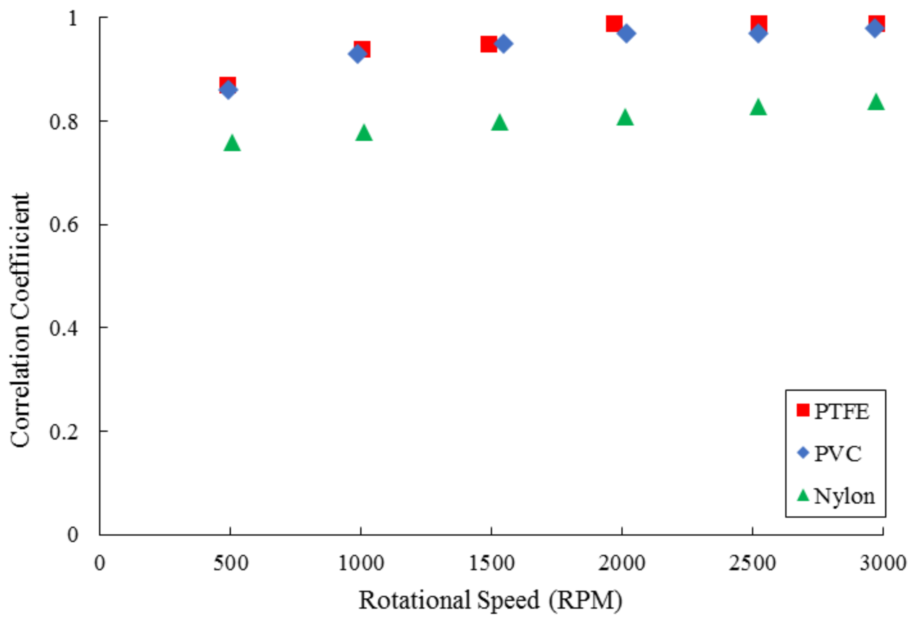
Correlation coefficient normally represents the similarity between two signals [6] as those in the double-sensor system. In the case of the single-sensor system, the correlation coefficient represents the degree of repetitiveness or periodicity of the sensor signal due to the rotational motion. As shown in Fig. 11, the correlation coefficient obtained from the single sensor system tends to increase with the rotor speed. As expected, less electrostatic charge is generated on the Nylon rotor, resulting in lower correlation coefficient (0.4 to 0.8). However, the correlation coefficient of the PTFE rotor (0.7 to 1.0) is consistently higher than those of PVC and Nylon rotors. For larger and coarser rotors, relatively higher correlation coefficients are observed due to more electrostatic charge produced on the rotor surface.



(a) D=60 mm and Ra=3.2



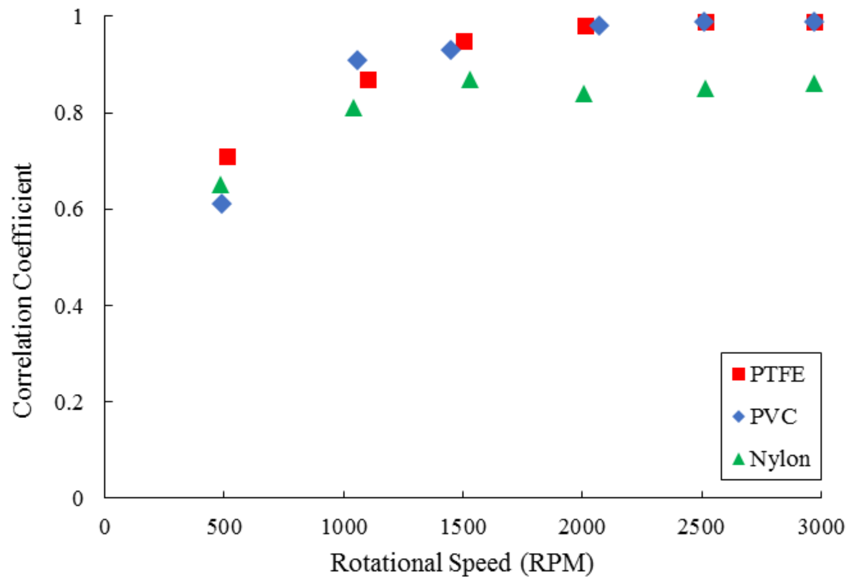
(b) D=60 mm and Ra=6.3



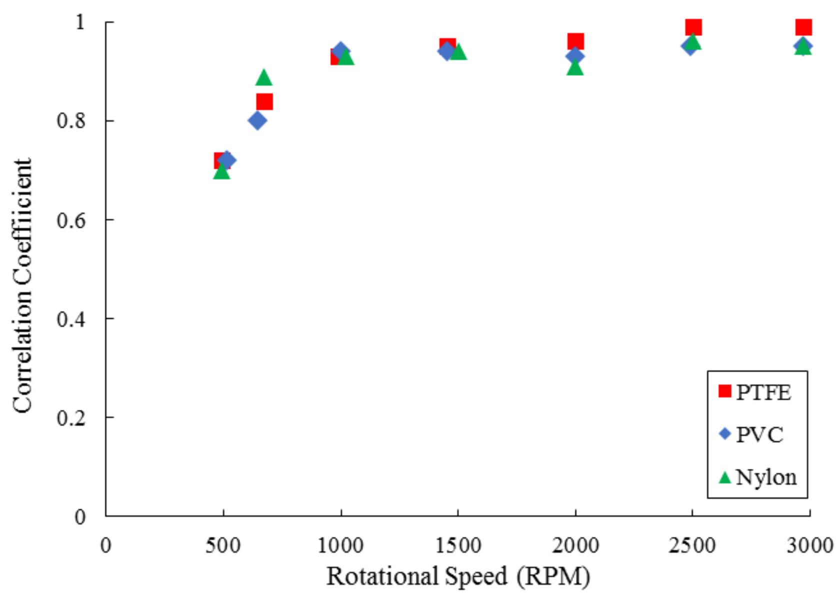
(c) D=120 mm and Ra=6.3

Fig. 11. Correlation coefficient from the single-sensor system.

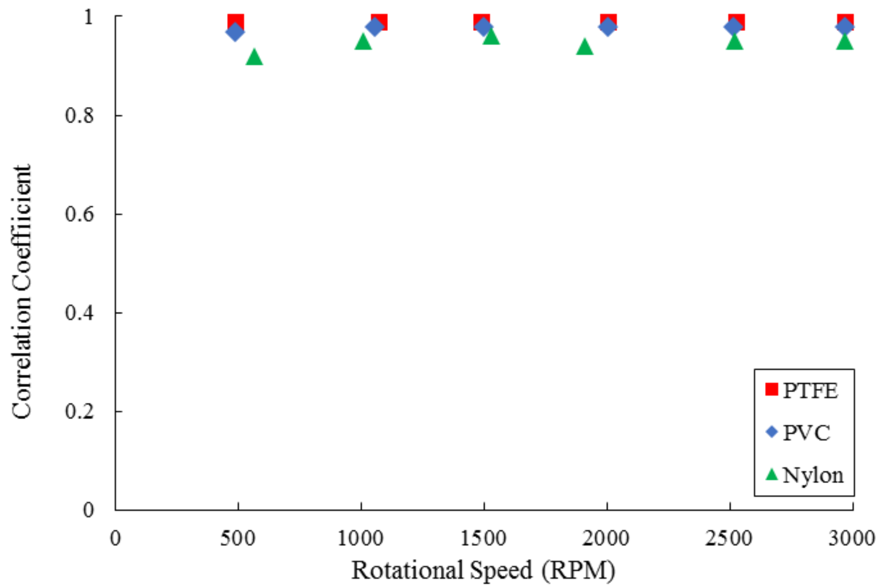
The correlation coefficient from the double-sensor system under different test conditions is shown in Fig. 12. As the rotational speed increases, the correlation coefficient improves in general. A comparison between Fig. 11 and Fig. 12 indicates that the difference in the correlation coefficients between the three materials for the double-sensor system is much smaller than that for the single-sensor system. This outcome illustrates that the double-sensor system is less sensitive to the effect of rotor materials.



(a) D=60 mm and Ra=3.2



(b) D=60 mm and Ra=6.3



(c) D=120 mm and Ra=6.3

Fig. 12. Correlation coefficient from the double-sensor system.

4. Conclusions

A performance comparison between the single-sensor and double-sensor systems has been conducted through experimental investigations. Experimental results have demonstrated that the single-sensor system yields a maximum error of ±1% while the double-sensor system produces an error within ±1.5% over the speed range of 500 - 3000 rpm for all tested rotors. Both measurement systems yield more reliable results for the PTFE rotor with a larger size at a higher rotational speed. Moreover, the double-sensor system is less sensitive to the effect of rotor material. Further research will be conducted to improve the signal-to-noise ratio and enhance the performance of the double-sensor system at lower rotational speed and extend the measurement range. Meanwhile, investigations into the environmental factors (i.e. ambient temperature and relative humidity) and industrial trials will be conducted in the near future.

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