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Fluid flow measurement in rotor ventilation ducts

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Christopher Micallef[1] ✉, Joseph Degabriele[1], Darren Camilleri[2]
[1]Department of Mechanical Engineering, Faculty of Engineering, University of Malta, Malta
[2]Cummins Generator Technologies Ltd, Peterborough, PE2 6FZ, UK
✉ *E-mail: christopher.micallef@um.edu.mt*

Abstract: Engineers are constantly developing different ways to cool electrical machines more efficiently. Ventilation ducts/channels are common in the stators of large electrical machines. Lately ventilation ducts on rotors of electrical machines are also being introduced. While measurement of fluid velocities inside stationary ventilation ducts, such as those present in and around the stator core of electrical machines, are relatively easy, measurement of fluid velocities inside rotating ventilation ducts, such as those present on the rotors of electrical machines, is quite challenging. This study describes a method which enables the measurement of fluid velocities inside rotating ducts on the rotor of electrical machines.

1 Introduction

In today's ‘more electric’ world, electrical machines are indispensable. Manufacturers give significant importance in designing low cost, yet efficient and long lasting electrical machines. Unfortunately, the conversion between electrical and mechanical power present in electrical machines is always accompanied by heat generation. In the lack of adequate thermal management, machines may heat up excessively which may lead to premature breakdown of the insulation system followed by machine failure. Therefore it is of utmost importance to incorporate an efficient cooling system within the machine design so as to limit the maximum temperature present in the machine.

Generally electrical machines make use of forced cooling techniques. A fan mounted on the driving end of the rotor shaft is used to force air through ventilation channels along the machine which convects heat away from the machine. Ventilation channels/ducts direct this cooling air to critical areas within the machine. Therefore, a thorough understanding of the air flow behaviour through these ventilation channels/ducts is critical in perfecting the flow path design.

Nowadays computational fluid dynamics (CFD) techniques are commonly used in industry, in the design process of ventilation channels. Confidence in the predictions of these CFD models is increased if the flow predictions are validated against experimental data. While measurement of fluid velocities in ventilation channels is relatively easy if the channels are stationary, the same cannot be said if they are rotating. This paper describes a method which enables the measurement of fluid velocities inside rotating ducts on the rotor.

2 Literature review

Axial ventilation ducts/channels which rotate around a parallel axis are the most commonly used cooling air flow paths in rotors of electrical machines. Due to the rotational motion of these cooling channels, secondary fluid flow structures are present. This makes the fluid flow pattern inside these channels complex.

In stationary ventilation channels present on and around the stator, such secondary flow patterns are not present. Thus correlations used on stationary ventilation channels cannot be used to predict fluid flow and heat transfer in rotating channels. Consequently, different experimental correlations must be used to predict the fluid flow and heat transfer in channels present on the rotor. Studies regarding fluid flow and heat transfer effects in ducts rotating about a parallel axis have been conducted over the years due to their importance in cooling systems of rotating machinery [1–3].

Secondary flow arises in rotating channels due to Coriolis and centrifugal forces. Studies carried out by Morris [4] show that for a heated duct, were secondary flow is present, the heat transfer is significantly improved. Further studies to determine the origin of the secondary flow structures in rotating ducts where carried out by Humphreys *et al.* [5]. The authors have shown that the swirl component at the duct inlet as well as centrifugal and Coriolis effects increase the heat transfer rate during rotation. These three factors are all directly related to the rotational speed of the duct and the Reynolds number of the fluid flowing through the duct. At high rotational speeds, the swirl along the entry region of the duct is increased resulting in high heat transfer rates. Heat transfer rates are also more pronounced along the duct at low Reynolds number. At high Reynolds number, the influence of rotation will diminish due to the high axial fluid flow inside the duct.

Coriolis forces are mostly prominent in the entry region of the cooling channel since the flow is yet to fully develop and velocity components perpendicular to the wall are considerably high. The Coriolis force is represented as a vector of air flow velocity and rotational velocity of the duct which is undergoing rotation. Both Coriolis forces as well as buoyancy effects enhance the heat transfer by the fluid passing through the duct. However in investigations carried out by Morris and Woods [6], it was concluded that for relatively short ducts with turbulent flow the Coriolis force is much more defined than the buoyancy effects.

Considering that the flow is fully developed and buoyancy effects are negligibly small, the Coriolis force will be equal to zero since the axial velocity of the flow is parallel to the angular velocity of the duct during rotation. Coriolis forces are completely neglected when significant centrifugal buoyancy effects are present in the form of vortices across the cross-section of the duct [1–3].

3 Experimental setup

A synchronous generator, which was kindly donated by Cummins Generator Technologies Ltd., was used to investigate the air velocity present inside axial rotating rotor ventilation ducts. Hot wire anemometry (HWA) was the instrumentation chosen to measure the fluid flow in the rotor ventilation ducts. Consequently, in order to avoid electromagnet interference with the velocity measurement system, the generator was demagnetised and all windings were disconnected to make sure that no current was flowing in the windings when the generator rotor was rotating. Each of the four poles present on the rotor incorporated axial

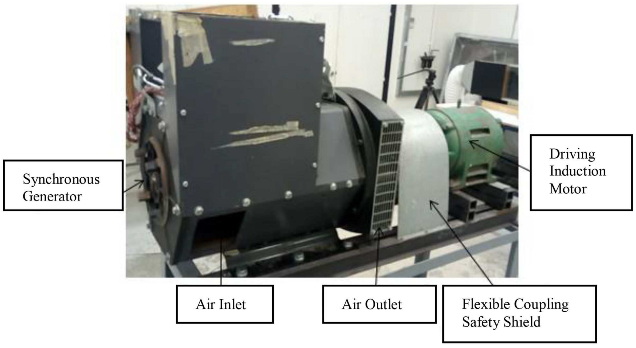

Fig. 1 *Experimental test rig*

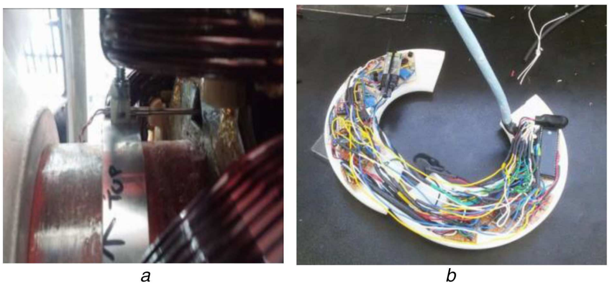

Fig. 2 *Illustration of hot-wire probe and measurement system*
(a) Hot wire probe mount, ***(b)*** Measurement system housing

ventilation channels running parallel to the axis of rotation. The unexcited generator was driven by an induction motor through a flexible coupling as shown in Fig. 1.

A hot-wire probe was mounted on the shaft, at the exit region of one of the axial ventilation channels situated on the rotor core, by means of an aluminium fixture located between the fan and the rotor stack as illustrated in Fig. 2*a*. In order to measure the air speed present during rotation, a hot wire amemometer, signal conditioning unit and data logging system, shown in Fig. 2*b*, were also mounted on the shaft, in a nylon housing close to the non-driving end. The HWA circuit employed a constant temperature anemometer adopted from the design proposed by Kirchhoff *et al.* [7], which is reproduced in Fig. 3. This consisted of a wheatstone bridge having the hot wire probe on one of its four arms while the opposite arm was connected to a variable resistor (R_3). When the wheatstone bridge is balanced, the resistance of the hot wire sensor equals the resistance of the variable resistor (R_3) which was used to control the overheat ratio. A servo amplifier consisting of a fast acting op-amp and a Darlington pair combination powered the wheatstone bridge through a regulated 5 V supply. The whole setup was powered by 9 V batteries.

The signal from the HWA was fed into a signal conditioning unit. In order to utilise the full range of the analogue-to-digital converter (ADC), the signal conditioning unit offset the signal and amplified it tenfold before it was fed to a 10 bit ADC. An 18F452 PIC microcontroller was used in order to convert the HWA analogue signal into digital data which was then transferred to a computer via a bluetooth serial link (HC-05 module). The probe used in this experiment consisted of a 5 μm tungsten wire spot welded onto steel prongs using a silver electrode.

4 Theory

This section introduces key definitions used throughout this paper.

A fluctuating velocity (u) may be decomposed into an average velocity ($\bar{U}$) and a fluctuating component (u') superimposed on it

$$u(t) = \bar{U} + u'(t) \tag{1}$$

Based on this decomposition, turbulence intensity (TI) is defined as

$$\mathrm{TI} = \frac{u'_{\mathrm{rms}}}{\bar{U}} \tag{2}$$

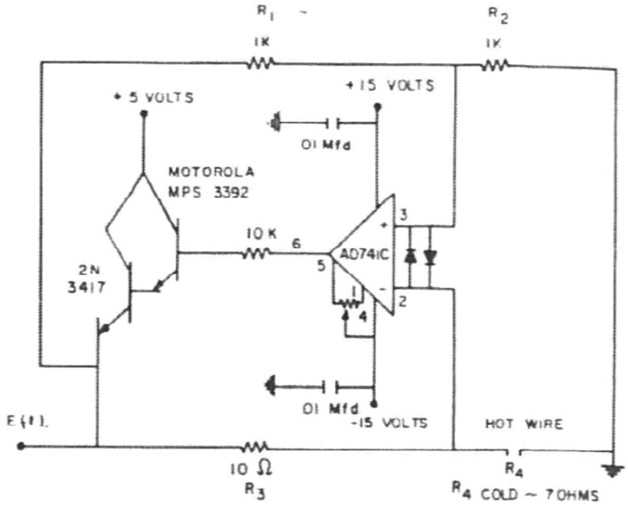

Fig. 3 *HWA circuit proposed by Kirchhoff [7]*

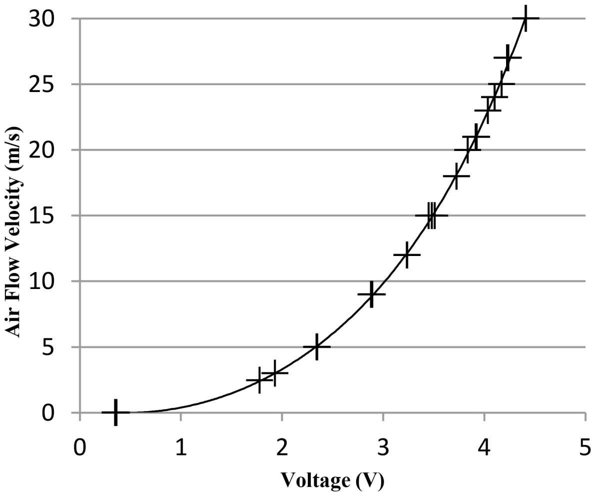

Fig. 4 *Hot wire probe calibration curve*

TI is a quantitative measurement of the amount of fluctuation present in the flow field. It is a very good indication of the turbulence level of the fluid flow and is directly related to the convective heat transfer from the walls (rotor core) to the cooling fluid.

In HWA the overheat ratio (OHR) is defined as

$$\mathrm{OHR} = \frac{R_T - R_{\mathrm{amb}}}{R_{\mathrm{amb}}} \tag{3}$$

where R_T is the sensor resistance at its operating temperature (T) and R_{amb} is the sensor resistance at ambient temperature.

5 Methodology

The velocity measurement system was calibrated in a wind tunnel for a velocity range of 0–30 m/s using a pitot static tube and an inclined tube manometer setup. HWA readings were taken at specific air velocities while the air velocity was ramped up from 0 m/s to 30 m/s and ramped back down to 0 m/s. A fifth-order polynomial was fitted to the experimental data points as shown in Fig. 4. Each data point represents the average of 50 sample readings taken at a sampling rate of 75 samples per second.

When the calibration curve was established, the velocity measurement system was mounted on the generator shaft. The instrumented rotor was then assembled in the generator. The generator was aligned with the driving motor drive shaft axis and connected through a flexible coupling.

Four distinct air flow velocity measurements were taken at speeds of 1500 and 1800 rpm corresponding to 50 and 60 Hz

Table 1 Results at rotational speed of 1500 rpm (open rotor channel)

Run	Average speed, m/s	Turbulence intensity %
1	23.0	7.6
2	22.9	8.3
3	23.7	6.3
4	23.3	7.7

Table 2 Results at rotational speed of 1800 rpm (open rotor channel)

Run	Average speed, m/s	Turbulence intensity %
1	28.0	7.2
2	27.6	8.9
3	28.3	7.4
4	28.2	8.7

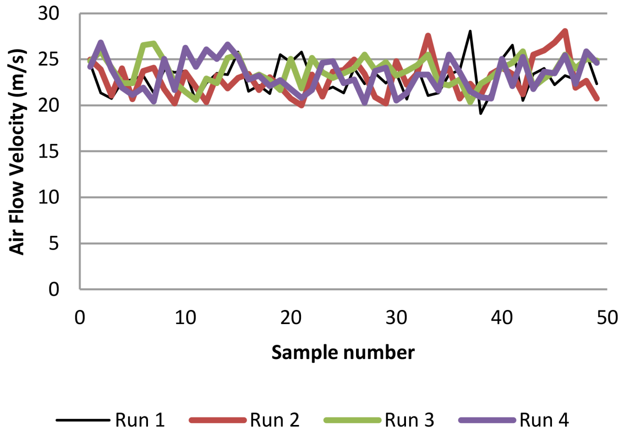

Fig. 5 *Open rotor channel rotating at 1500 rpm*

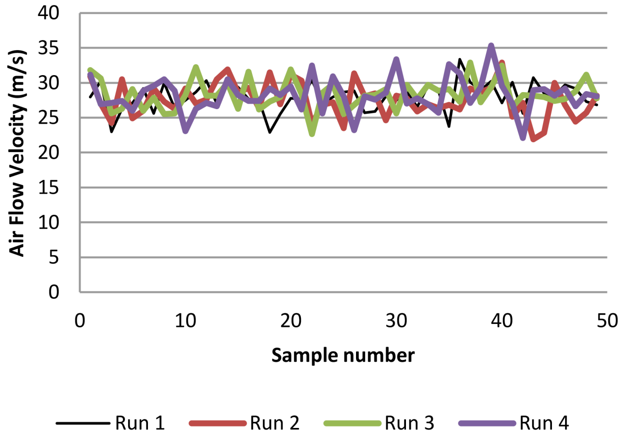

Fig. 6 *Open rotor channel rotating at 1800 rpm*

operation, respectively. These tests were also repeated with the inlet of the cooling channel blocked off with duct tape. This was done in order to assess the influence of the centrifugal forces on the hot wire sensor. Each measurement was calculated based on a sample of 50 readings taken at a sample rate of 75 samples per second.

After all measurements were completed, the generator was disassembled and the velocity measurement system was unmounted and set up again in the wind tunnel. A verification exercise was performed in order to make sure that the calibration curve was still valid. This validation exercise confirmed the accuracy and reliability of the velocity measurement system.

6 Results

Table 3 Results at rotational speed of 1500 rpm (blocked rotor channel)

Run	Average speed, m/s	Turbulence intensity %
1	0.6	32
2	0.6	33
3	0.5	60
4	0.5	56

Table 4 Results at rotational speed of 1800 rpm (blocked rotor channel)

Run	Average speed, m/s	Turbulence intensity %
1	0.7	36
2	0.8	25
3	0.7	58
4	0.6	55

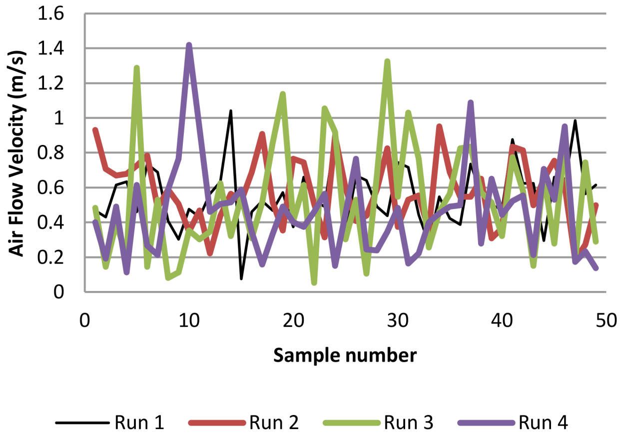

Fig. 7 *Blocked rotor channel rotating at 1500 rpm*

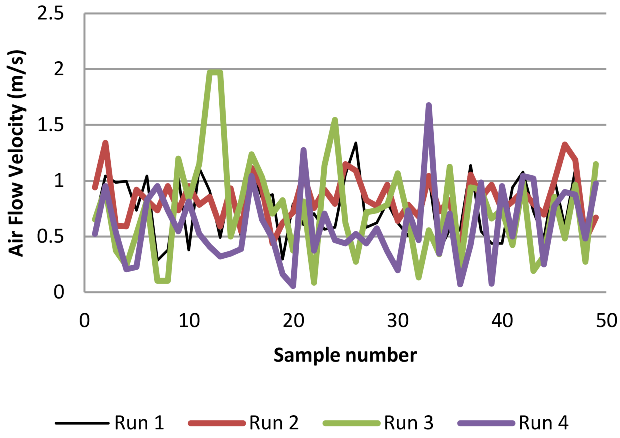

Fig. 8 *Blocked rotor channel rotating at 1800 rpm*

Tables 1–4 summarise the results obtained in each of the tests described above. Tables 1 and Table 2 are the results when the rotor ventilation channel was open and therefore cooling air was flowing through the channel while Tables 3 and 4 are the results when the inlet of the rotor ventilation channel was blanked off using duct tape and therefore no air flow was present in the channel.

Figs. 5–8 show the plots of all 50 air flow velocity samples taken during these tests. The sample rate used for all data capture was 75 samples per second.

7 Discussion

Generally, HWA is not recommended for measuring low velocities since the assumption that the forced convection heat transfer is much larger than the other modes of heat transfer (i.e. natural convection, radiation and conduction) does no longer hold. Therefore, the velocity readings when the rotor ventilation channel was blocked should be considered as highly unreliable. However, this data confirms that there was no flow of the cooling air through the blocked rotor ventilation channel.

Additionally according to Hah and Lakshminarayana [8], rotation does not alter significantly the heat transfer or aerodynamic characteristics of the wire. Therefore, hot wire anemometry can be used in applications involving rotation. This highlights the validity of the results presented in this paper when an air stream was present through the rotor ventilation channel.

Experimental results of tests conducted on the generator, operated at 50 Hz, reveal a 4°C reduction in the average temperature of the rotor windings when the rotor ventilation ducts were present compared to a similar machine without rotor ventilation ducts. Although this result is outside the scope of the work presented in this paper, it shows that the benefits of rotor ventilation ducts are tangible and therefore highlights the importance and validity of the present research work.

An average velocity of 23.2 m/s was recorded in the rotor ventilation channel when the rotor was rotated at 1500 rpm corresponding to 50 Hz operation. This was increased to 28.0 m/s when the rotor was rotated at 1800rpm corresponding to 60 Hz operation. This corresponds to a 20% increase in air velocity in the rotor ventilation channels for a corresponding 20% increase in rotational speed of the rotor.

The levels of turbulence intensity recorded during these tests were in the range of 6–9%. This corresponds to turbulent flow in pipes. The high turbulence intensities registered when the ventilation channels were blanked off are excessively high due to the very low average velocity readings and the unreliability of the air velocity measurement system at low velocities.

8 Conclusions

This work presents a means of measuring the fluid flow inside rotor ventilation channels located parallel to the axis of rotation. Initial generator test results are encouraging and further research is planned to investigate fluid flow measurements in radial rotor ventilation channels/ducts located orthogonally to the axis of rotation.

9 Acknowledgments

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