LDV Measurements of Wake-Induced Unsteady Flow within a Turbine Rotor Cascade

by

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ABSTRACT

The unsteady flow field within an annular turbine rotor was investigated experimentally using an LDV system with emphasis on the influence of turbine stator wake on the rotor flow field. Detailed measurements of time-averaged and time-dependent distributions of the velocity, the flow angle, and the turbulence intensity were carried out at design operating conditions. The obtained data was analyzed from the viewpoints of both absolute flame of reference (stationary coordinate system) and relative flame of reference (rotating coordinate system) by vectorial addition of the circumferential velocity component of the rotor speed.

Figure 1 shows the time-dependent distributions of the absolute velocity, absolute flow angle, relative velocity, relative flow angle, and turbulence intensity. The low velocity area caused by the wake behind the stator periodically affects the flow field around the rotor. These shapes of time-dependent distributions were re-analyzed as animations for flow visualization to gain a better understanding of the unsteady flow phenomenon in a turbine rotor.

Fig. 1 Time-dependent flow distributions around turbine rotor cascade
1. INTRODUCTION

The flow field around the blades of a turbine is highly unsteady and complex. One of the major causes of unsteadiness is the aerodynamic interaction between the turbine stator and the turbine rotor, namely “rotor-stator interaction”. Boundary layer behavior, loss generation, and heat transfer in turbines are strongly affected by the rotor-stator interaction. Even though unsteady flow plays an important role in axial flow turbines, turbines are designed using steady flow calculation methods. Because actual models of the loss generating mechanisms in unsteady flow do not exist, empirical correlations are used to account for the effect of unsteadiness. Thus more knowledge of unsteady rotor-stator interaction is essential to increase the performance of turbines (Dring et al, 1982, Sharma et al, 1985, Binder, 1985, Binder et al, 1985, 1987, Rao et al, 1992, Bisby et al, 1998, Venable et al, 1998, Kost et al, 2000). Although the experimental verification of the flow field within rotating blades is rather complicated, Laser Doppler Velocimetry (LDV) can enable non-intrusive measurement of the flow in a turbine rotor (Zaccaria and Lakshminarayana, 1995).

In this study, the unsteady flow field within an annular turbine rotor was investigated experimentally using an LDV system. Detailed measurements of the time-averaged and time-dependent distributions of the velocity, the flow angle, and the turbulence intensity were carried out at design operating conditions. The obtained data was analyzed from the viewpoints of both absolute (stationary) flame of reference and relative (rotating) flame of reference. The effect of the turbine stator wake on the flow field inside the rotor passage was clearly captured.

2. EXPERIMENTAL METHOD

2.1 Experimental Facility

Figure 2 shows a cross-section and photograph of the annular turbine wind tunnel we used. This wind tunnel is an air suction type with low turbulence intensity. The total length of the wind tunnel is approximately 3.5 meters. The outer and inner annular wall diameters of the test section are 500 mm and 350 mm, respectively. A single-stage turbine designed using a free vortex method was installed at the test section. The geometries of the stator and rotor cascades are shown in Fig. 3 and 4. The geometric design of the profiles was carried out in the traditional manner by superimposing a thickness distribution on a camber line. The specifications of the stator and rotor cascades are given in Table 1. For the LDV measurements, the stator and rotor cascades were painted with a flat black paint to reduce surface reflections.
2.2 Experimental Condition

The Reynolds number based on the rotor chord length and rotor exit velocity is \( Re_{out} = 3.8 \times 10^4 \). The wind tunnel originally had a low residual turbulence intensity with a value of 0.5\% at the midspan of the stator inlet. The axial velocity at the test section was 4.4 m/s and rotor speed was 400 rpm to attain design operating conditions (design rotor inlet flow angle). The flow in this experiment was considered to be incompressible because the Mach numbers based on the exit conditions was very low \( M_{out} = 0.029 \).

2.3 Experimental Techniques

Figure 5 shows schematically the various experimental techniques used throughout this research. Measurements using a 5-hole pressure probe and hot-wire anemometry have been reported in previous papers (Matsumura et al., 1998, 1999). The LDV system used was a standard two-color, four beam, two-dimensional measuring system with a fiber-optic probe (TSI Incorporated). It consisted of a 4-W argon-ion laser tuned to the 488 nm (blue) and 514.5 nm (green) lines. The fiber optic probe was mounted on a three-dimensional traverse gear which could be automatically controlled from a personal computer. The half-angle between the beams was 4.29 deg. and the calculated dimensions of the measurement volume at \( c^2 \) intensity locations were 0.85 mm in length and 0.073 mm in diameter. DANTEC Safex fog fluid “Standard” with a mean diameter of 1.068 \( \mu \)m was used to seed...
the flow. The liquid was atomized using a DANTEC Safex fog generator Model 2001. The tracer particles were introduced into the test section from the wind tunnel inlet.

Figure 6 shows the LDV measurement locations at the blade midspan. Measurements were made at 43 axial locations from just downstream of the stator to downstream of the rotor, and 32 pitch-wise locations. At each point 10,000 velocity measurements were acquired. An incremental rotary encoder (1800 pulses/revolution) was attached to the rotor shaft to detect the rotor angle position. One rotor passage was divided into 58 locations (encoder pulse number 1800 / rotor number 31), which represent different relative positions between the stator and the rotor. Figure 7 shows a photograph of the wind tunnel with the LDV setup.
Fig. 9  Time-dependent absolute velocity distributions (absolute frame of reference)

Fig. 10  Time-dependent absolute angle distributions (absolute frame of reference)
3. RESULTS AND DISCUSSION

3.1 Absolute Frame of Reference

Figure 8 shows time-averaged absolute flow distributions. The rotor was mounted between the two dotted lines. As a consequence of the integration procedure from the viewpoints of the absolute coordinate system, the rotor blades are not visible in these distributions. In the absolute coordinate system, the swirl flow which came out of the stator cascade decelerates in the rotor cascade.

Figure 9 shows the time-dependent unsteady absolute velocity distributions at 8 different stator-rotor locations. Measurements were not obtained in the white region close to the rotor due to the shadow of the blade on the optical laser. The absolute velocity was normalized by the pitch-wise average of the time-averaged absolute velocity at the farthest point downstream of the rotor (Axial position $Z/C_{ax}=1.41$). The low-velocity area caused by the wake behind the stator cascade affected the flow field around the rotor. Figure 10 shows the time-dependent absolute flow angle distributions. The absolute flow angle around the rotor was also affected by the stator wake.

The pitch-wise distributions of the time-dependent absolute velocity and flow angle at three different axial positions are shown in Fig. 11 and 12. At the stator exit (Fig. 11a), the velocity deficit due to the stator wake is clearly identifiable, and there is seldom any effect from the rotor. At the rotor inlet (Fig. 11b), the velocity defect of the stator wake decreased from the mixing of the mainstream and the wake of the stator blade, and the effect of the rotor increased. Downstream of the rotor (Fig. 11c), the periodic fluctuation of the absolute velocity due to the stator wake was about 20% of mean velocity. The rotor induces 38 deg of the periodic fluctuation of the absolute...
flow angle. The stator also induces 8 deg of angle fluctuation (Fig. 12c). It was proven that the stator wake affects the flow downstream of rotor.

3.2 Relative Frame of Reference

Figure 13 explains the velocity triangles that indicate the correlation between the absolute flow and relative flow. The absolute and relative flows are illustrated by blue and red vectors, respectively. The flow inside the rotor passage in the relative frame of reference can be analyzed by adding rotor blade speed (circumferential velocity component) to the velocity vector measured in the absolute coordinate system.

Figure 14 shows the time-averaged flow around the turbine rotor cascade. The laminar separation breaks out on the rotor suction surface near the trailing edge of the cascade.
Fig. 15 Time-dependent distributions of relative velocity (relative frame of reference)

Fig. 16 Time-dependent distributions of relative flow angle (relative frame of reference)
Figures 15, 16, and 17 show time-dependent distributions of the relative velocity, the relative flow angle, and the turbulence intensity, at 8 different stator-rotor locations. The relative velocity and turbulence intensity were normalized by the pitch-wise average of the time-averaged relative velocity at the point farthest downstream of the rotor ($Z/C_{ax}r_t=1.41$). The stator blades move from top to bottom, observed from the relative coordinate system that rotates with the rotor blades.

The relative velocity and flow angle around the rotor were influenced by the rotor-stator interaction. The width of the rotor wake changes periodically due to the influence of the stator wake, as shown in Fig. 15. The high-turbulence intensity region which corresponds to the wake can be clearly observed in Fig. 17. The straight lines of high-turbulence intensity caused by the stator wake were distorted when they pass through the rotor passage. This occurs because the flow region near the rotor suction surface moves faster than the flow near the rotor pressure surface. At the rotor exit, complex unsteady distributions of high-turbulence intensity are formed by the coalescence of the stator and rotor wakes.

Figure 18 shows pitch-wise distributions of time-dependent relative velocity, relative flow angle, and turbulence intensity at rotor inlet. The profiles of the relative velocity and relative flow angle presented in Fig.18(a) and (b) show that the rotor leading edge had a significant effect on the flow field even at 14 percent of the rotor axial chord upstream, with the change in velocity and flow angle a 0.2 (40% of mean velocity) and 30 deg, respectively. The periodic changes due to the stator wake were approximately 0.1 (20%) of the relative velocity and 15 deg of the relative flow angle.

Pitch-wise distributions of the time-dependent flow at the rotor exit are shown in Fig. 19. The fluctuation of the velocity deficit along the suction surface was larger than that of the pressure surface side, because the flow separation on the suction surface near the trailing edge was strongly influenced by the stator wake.
4. CONCLUSIONS

Laser Doppler Velocimetry (LDV) was successfully applied to provide detailed data on steady (time-averaged) and unsteady (time-dependent) flow field near and within the rotor of an annular single-stage turbine. Data analysis was performed in both absolute and relative coordinate systems. The effect of the turbine stator wake on the flow of the turbine rotor, namely the rotor-stator interaction, was examined qualitatively and quantitatively.

ACKNOWLEDGMENTS

This work was supported by Grants for Core Research for Evolutional Science and Technology (CREST) from Japan Science and Technology Corporation.

REFERENCES


