11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

THE EFFECT OF A SINGLE PROTRUSION ON THE BOUNDARY LAYER AROUND A CYLINDER ROTATING IN AN AXIAL FLOW - CONDITIONAL MEASUREMENT IN THE INTERMITTENT REGION OF A TURBULENCE WEDGE

Shintaro YAMASHITA[1], Masashi ICHIMIYA[2] and Ikuo NAKAMURA[3]

[1]Dept Mechanical Engineering, Gifu University, 1-1 Yanagido, Gifu 501-11, JAPAN

[2]Tokushima University, 2-1 Minami-josanjima, Tokushima 770, JAPAN

[3]Nagoya University, Furocho, Chikusaku, Nagoya 464-01, JAPAN

ABSTRACT

A turbulence wedge which develops downstream of a single protrusion installed on a rotating cylinder in an axial flow is experimentally investigated. Turbulent/non-turbulent discrimination is made for this non-stationary turbulent flow. Conditioned by this discrimination, mean and fluctuating velocities are obtained using ensemble average over realizations, each of which is the data for every single revolution of the cylinder. The radial profiles of the conditional averaged mean velocities in the axial direction at the center of the wedge differs from those at the interfaces of the wedge. The velocity profiles in the peripheral direction show that turbulent fluids in the turbulence wedge are carried by the streamwise vortices. The mean velocity distribution expressed in the polar diagram and streamline coordinates show that the streamwise vortices consist almost entirely of turbulent fluid. The peripheral profiles of the fluctuating velocities show that turbulent average contributes to the peaks of the profiles.

NOMENCLATURE

a : radius of the cylinder
U, V : mean velocity components in the x- and y- directions, respectively
u : fluctuating velocity component in the x- direction
u' : rms value of u
U_1, U_2 : mean velocity components in the streamline coordinates
U_e : mean velocity at the edge of the boundary layer
U_m : reference main flow velocity at $x = 0$
U_R : relative main flow velocity
V_0 : peripheral velocity of the cylinder
x, y, z : coordinate system
α_p : azimuthal angle measured from the protrusion
α_{pr} : azimuthal angle measured from a relative main streamline which passes through the protrusion
Ω_m : reference speed ratio = V_0 / U_m
γ : intermittency factor

Subscript

T : turbulent average
N : non-turbulent average

INTRODUCTION

The purpose of this study is to clarify the structure of the turbulence wedge produced by a single roughness element or protrusion installed on a cylinder spinning in an axial uniform stream. When a three-dimensional roughness element exists in a laminar boundary layer on a flat plate, if the Reynolds number based on the dimension of the roughness exceeds a certain critical value, a wedge-shaped turbulent region whose vertex is at the position of the roughness element extends downstream (Tani, 1981). Some workers who have studied this flow confirmed that horseshoe vortices were generated around a roughness element as well as streamwise vortices which followed the horseshoe vortices (Gregory and Walker, 1951; Mochizuki, 1961a, 1961b; Tani et al., 1962; Gupta, 1980; Gibbings et al., 1986). How these streamwise vortices and turbulence wedge are affected in a rotating field is an interesting problem, since this would relate to the mechanism of the origin of turbulence in swirling boundary layers.

The authors already studied characteristics of the mean and fluctuating velocities in the turbulence-wedge region on a rotating cylinder in an axial uniform flow (Yamashita et al., 1988, 1990). This report mainly deals with the intermittent structure of this turbulence-wedge flow, and conditional measurement according to turbulent/non-turbulent discrimination has been made in the intermittent region where the streamwise vortices exists. The conditional measurement is one method to determine the interaction between the turbulent and non-turbulent fluids in and out of the wedge. Since the turbulence-wedge flow on the rotating cylinder is non-stationary but statistically periodic, the data from the hot-wire anemometer have been distinguished into turbulent or non-turbulent, and then processed by using an ensemble average method in which each realization occurs for every single revolution of the cylinder.

EXPERIMENTAL APPARATUS AND PROCEDURES

The wind tunnel employed for this experiment is a suction type. The cylinder, with a radius of 40 mm and length of 1200 mm, is made of aluminum alloy, and is supported from both sides. In order to assure uniform incoming flow to the cylinder, the leading edge of the cylinder is knife-edged, and suction is done. Figure 1 shows the coordinate system and shape of the single protrusion on the cylinder. The protrusion is a column 2 mm in diameter and 2 mm in length with a hemispherical head. It has been placed 100 mm downstream from the leading edge of the rotating cylinder. The condition that the turbulence wedge develops from the protrusion is satisfied (Tani et al., 1962). The experiment has been performed under conditions where the Reynolds number, based on the radius of the cylinder and reference speed, is kept to 3×10^4 (Reference speed is about 11 m/s) and the pressure gradient in the axial direction is nearly equal to zero. The speed ratio has been varied, but limited to relatively low values ($\Omega_m \leq 0.2$) in order to identify the turbulence wedge. Measurements have been made using V-shaped hot-wire probe.

To perform the ensemble average, the output voltage from the hot-wire has been digitized at a 5 kHz sampling frequency; these data have been then discriminated into turbulent or non-turbulent, and then conditionally averaged mean and fluctuating velocities in the x- and y-direction, and the intermittency factor have been calculated.

RESULTS AND DISCUSSION

Properties of Intermittent Structure

Figure 2 shows the isovels of the intermittency factor γ at x = 350 mm. The intermittency factor is unity within the turbulence wedge, which is surrounded by the intermittent region. The intermittent left and right portions in these figures correspond to the front and rear sides of the wedge, respectively. Depressions of the contours can be seen in the central part of the wedge, which is mainly due to the streamwise vortices which exist on both sides of the wedge (Yamashita et al., 1988, 1990). When the speed ratio Ω_m is small, the distributions are almost symmetric with respect to the center of the wedge, but as the speed ratio increases they seem asymmetric. Perhaps this phenomenon relates to the fact that the streamwise vortices on both sides of the wedge become asymmetric due to the Coriolis force (Yamashita et al., 1990).

Mean Velocity

Figure 3 is the radial distribution of the conditionally averaged mean velocity component in the axial direction at three different stations of α_{pr}. The distribution of turbulent average U_T/U_e shows different profiles for the center (α_{pr}=0°) and both interfaces of the wedge. In the center of the wedge, the profiles of normal, turbulent and non-turbulent average are similar to those of flat-plate turbulent boundary layer measured by Kovasznay et al.(1970) drawn by dotted lines, as shown in the figure on the right.

The circumferential distribution of this velocity component is shown in Fig. 4. Each figure consists of three parts; the normal average, the turbulent/non-turbulent average, and the intermittency factor at the lower, middle and upper parts, respectively. The width of the turbulence-wedge region can be defined using γ, say, the region of $\gamma \geq 0.5$. At z = 0.3 mm non-turbulent average U_N/U_e takes a larger value in the interfaces of the wedge than in the outside of wedge. At the interfaces the turbulent average U_T/U_e is larger than the non-turbulent average. It is also smaller than the turbulent average inside of the wedge.

Figure 5 is the circumferential distribution of the mean velocity component in the peripheral direction. The flow outside of the wedge is non-turbulent and the value is constant at any peripheral position. At $z \leq 1.5$ mm the non-turbulent average V_N/V_0 increases at the front interface, while it takes a

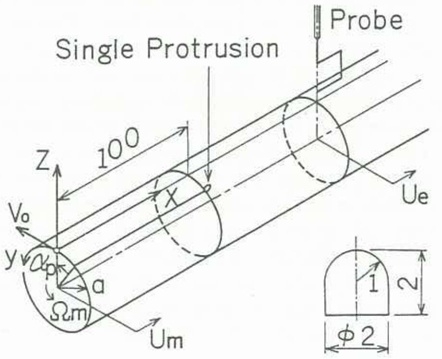

Fig. 1 Coordinate system and shape of the protrusion

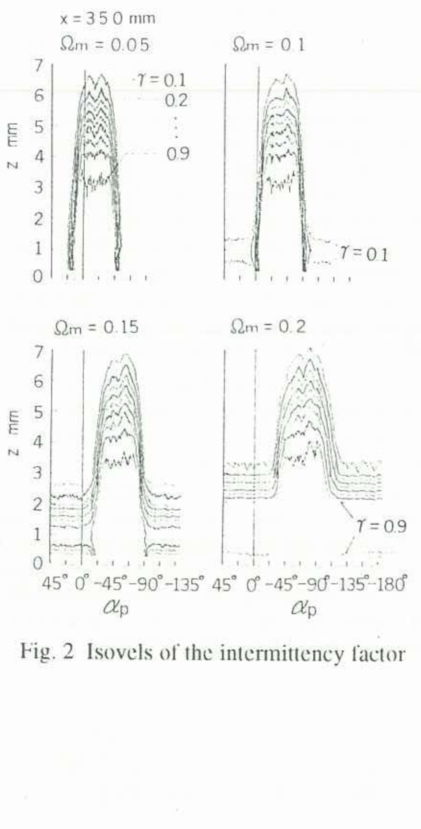

Fig. 2 Isovels of the intermittency factor

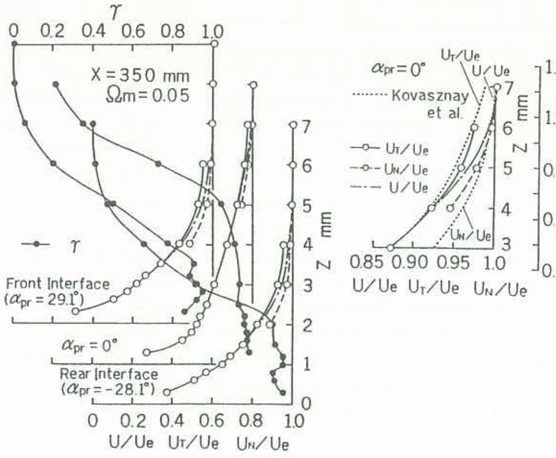

Fig. 3 Radial distribution of the conditionally averaged mean velocity component in the axial direction

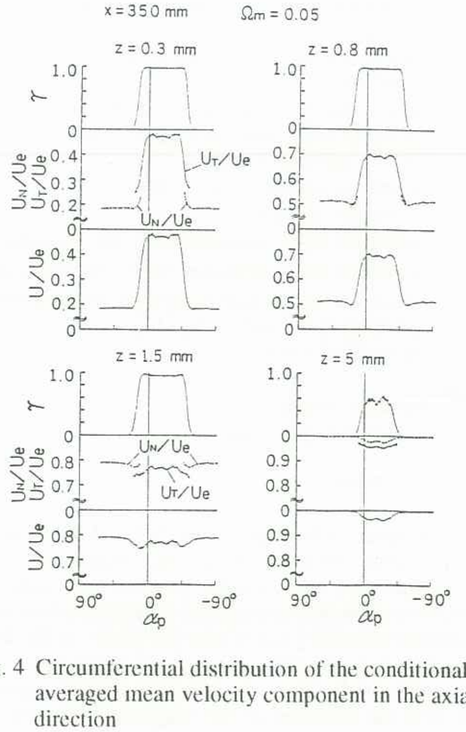

Fig. 4 Circumferential distribution of the conditionally averaged mean velocity component in the axial direction

constant value on the outside of the wedge. At the rear interface it takes a smaller value than in the outside. The turbulent averages V_T/V_0 at z = 0.3 and 0.8 mm are larger in the front interface and smaller in the rear interface than the non-turbulent averages in the respective positions. These distributions show that the turbulent fluids within the wedge near the wall are carried out of the wedge due to the streamwise vortices.

Figure 6 shows a polar diagram of the velocity distribution for the purpose of examining the relationships between velocity components; the distributions of the turbulent and non-turbulent averages are drawn. The arrows indicate the direction of the change in velocity distribution as the cylinder rotates. The laminar region outside of the wedge shows values indicated as filled circles. At Ω_m= 0.05 the variation in the shape of the turbulent average distribution relative to the non-turbulent average is fairly large. This is mainly because the turbulent average of normalized peripheral mean velocity changes considerably in the wedge. This figure confirms the existence of the streamwise vortices.

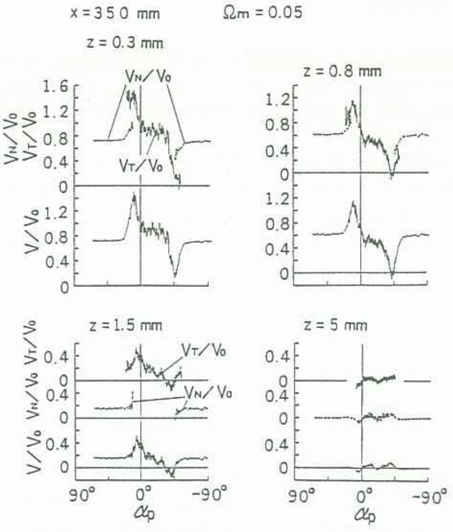

Fig. 5 Circumferential distribution of the conditionally averaged mean velocity component in the peripheral direction

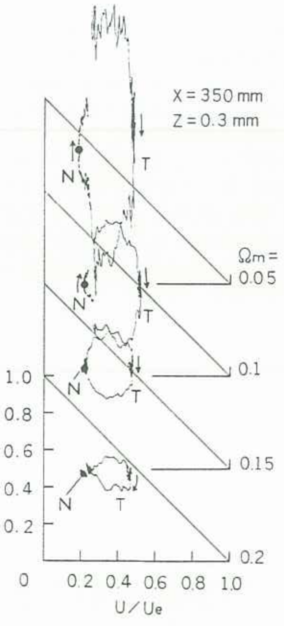

Fig. 6 Polar diagram
N : Non-Turbulent
T : Turbulent

Figure 7 shows mean velocities U_1 and U_2 in the streamine coordinates which rotate with the cylinder, where U_1 and U_2 are the components in and normal to the main flow direction, respectively, in the x-y plane. The value of U_2 shows a deviation of the velocity vector from the relative main flow direction. The turbulent average U_{2T}/U_R shows the existence of a pair of streamwise vortices which rotate opposite to each other at the interfaces. On the other hand, the non-turbulent average U_{2N}/U_R is very small and contributes little to the streamwise vortices. Therefore it can be said that most of the streamwise vortices consist of turbulent fluid.

Fluctuating Velocity

Although the axial and peripheral components of the fluctuating velocities and the Reynolds stress have been obtained, here only the fluctuating velocity component in the axial direction are represented in Figs. 8 and 9.

Figure 8 is the radial distribution. The profiles in the center of the wedge are similar to those of flat plate boundary layer drawn by dotted lines. The intermittent nature of the central part of the wedge is similar to that in the turbulent boundary layer.

The circumferential distributions of this component are shown in Fig. 9. At z = 0.3, 0.8 and 1.5 mm the peaks can be

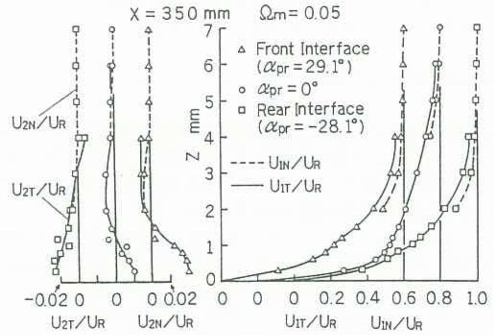

Fig. 7 The conditionally averaged mean velocity distribution expressed in the streamline coordinate

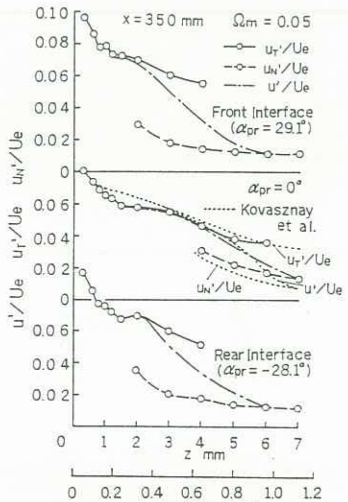

Fig. 8 Radial distribution of the conditionally averaged fluctuating velocity component in the axial direction

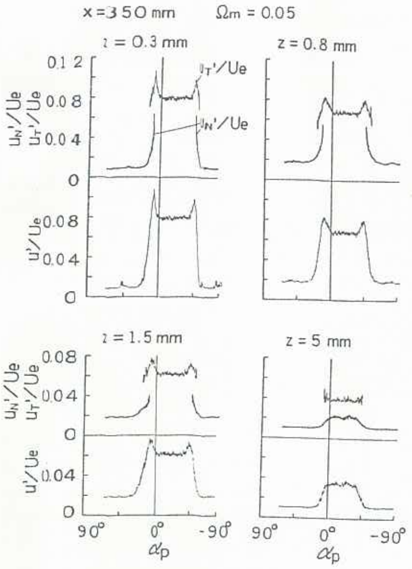

Fig. 9 Circumferential distribution of the conditionally averaged fluctuating velocity component in the axial direction

seen at the front and rear interfaces of the normal average. The turbulent average u_T'/U_e also has peaks. The non-turbulent average u_N'/U_e suddenly increases and takes fairly large values at the interfaces, but it is the turbulent average that contributes to the peaks in the normal average profiles.

CONCLUDING REMARKS

The present study of the conditional measurement for the turbulence-wedge region which develops downstream of a single protrusion on the cylinder rotating in an axial uniform flow leads to the following conclusions.

(1) The isovels of the intermittency factor have depressions in the central part of the wedge due to the streamwise vortices. When the speed ratio is small, the profiles are almost symmetric with respect to the center of the wedge.

(2) For the radial distribution of the mean velocity component in the axial direction, the distribution of the turbulent average shows a different profile in the center and both interfaces of the wedge. The circumferential distribution of this velocity component exhibits a difference between the profiles of the turbulent and non-turbulent averages.

(3) The circumferential distribution of the mean velocity component in the peripheral direction shows that the turbulent average is larger at the front interface of the wedge and smaller at the rear interface than the non-turbulent average. This feature indicates that the turbulent fluids in the wedge near the wall are carried out of the wedge by the streamwise vortices.

(4) Velocity distributions expressed in the streamline coordinates and the polar diagram reveal the existence of the streamwise vortices. From the conditionally averaged profiles it can be said that the streamwise vortices consist almost entirely of turbulent fluid.

(5) The radial distribution of the fluctuating velocity component shows that both the turbulent and non-turbulent average have profiles similar to the flat-plate boundary layer. The circumferential distribution of this velocity component shows that the turbulent average contributes to the peaks at the interfaces of the wedge and the non-turbulent average at the interfaces has a larger value than outside of the wedge.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to Mr. T. Kushida of Nagoya University for his assistance, and to Mr. K. Ogiwara of Hitachi Co., Ltd. for his generous cooperation.

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