STUDY OF DELTA WING CHARACTERISTICS AS A FAN BLADE MODEL*

(First Report; Visualization of Three-dimensional Flow by Smoke Wire Method)

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Flow around a flat delta wing is investigated in order to establish a technique of visualization of three-dimensional flow by smoke wire method, considering application to the study of steady and non-steady responses of single and cascades of delta wings. It is found that the structure of the leading-edge vortices, in particular reference to the breakdown of the vortex core over the wing surface as well as the structure of the free vortex zone can be investigated in detail by choosing proper combinations of relative attitudes and locations between the wing and the smoke wire, and taking photographs from three perpendicular directions.

Key Words: Flow Measurement, Flow Visualization, Smoke Wire Method, Three-Dimensional Flow, Delta Wing, Leading-Edge Vortices, Vortex Breakdown

1. Introduction

Low pressure propeller fans are widely used for ventilating fans, air-conditioners and other appliances, and high efficiency and low noise are very important factors for these fans. Unlike large axial flow fans which are housed in duct casings, aspect ratio of the fan blade is small and the flow field passing through the fan is strongly three-dimensional. It is known that the planform of the fan blade is an important factor for the fan characteristics, and delta wing shaped blades with pointed nose result in low noise fan.⁽¹⁾ However, the flow field around these fan blades is not understood well both theoretically and experimentally, and a detailed flow analysis is deemed necessary for improvement of efficiency and noise characteristics as well as for prevention of flow induced vibration.

On the other hand, delta wings are widely used for high speed jet airplanes and basic characteristics of the wing is well understood. It is known that a pair of vortices are generated along swept back leading-edges, and these leading-edge vortices have strong effect on the characteristics of the delta wing. Central part of the vortex is a vortex core with high vorticity and tends to attach to the leading-edge, resulting in a higher lift. Those vortex cores become unstable downstream and eventually burst into a turbulent flow, a phenomenon commonly referred to as 'vortex breakdown'. This occurs downstream of the trailing

edge when angle of attack of the wing is small, and starts to move upstream and the breakdown point appears over the wing surface,^{(2),(3)} resulting in a large fluctuation of pressure on the wing surface and flow separation. When a delta wing is considered as a fan blade model, the vortex breakdown over the wing surface has strong effect on the fan characteristics, i.e., surface pressure fluctuation causes aerodynamic noise and flow separation results in low efficiency.

Analysis of lifting surface theory in uniform shear flow for a delta wing as a fan blade model was made by Morita.⁽⁴⁾ However, the study was limited to within the framework of momentum theory and a detailed flow structure such as leading-edge vortices was not studied yet. Although structure and process of the breakdown of the leading-edge vortices in steady uniform flow have been studied by means of flow visualization,⁽²⁾ it is necessary to extend the study into the cases of unsteady flow response and wing cascade characteristics in case of fan blade model.

Main purpose of the present study is to understand the steady and unsteady responses of single and cascades of delta wings as fan blade model,⁽⁵⁾ mainly utilizing flow visualization technique. This paper describes the establishment of visualization technique of a three-dimensional flow field by smoke wire method.

2. Experimental Method

A suction type wind tunnel was used in this experiment. The inlet flow is controlled by honeycombs and screens as in usual wind tunnel, and it goes through the contraction of area ratio 9:1. The cross section of the test section is 0.5 m high and 0.4 m wide, with the free stream flow nonuniformity of less than 2 %

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and turbulence level of less than 1 %. Walls are made of plexi-glasses and the back ground for the flow visualization is painted black.

Stainless steel wire of 0.1 mm diameter and 60 cm long was used as a smoke wire, which was stretched vertically at the center of the cross section. The smoke was generated from mineral oil, and the oil was applied to the wire by releasing droplets of oil from the top of the wire by a motor-driven oil pump. This is an improved version of the method described by Corke, et al.⁽⁶⁾

Eight electronic flashes having Guide Number 12 and flash duration of 1/5000 sec were used simultaneously in the form of slit light source for photographing. However, the light was made rather wide in order to photograph a three-dimensional flow, and the width was adjustable between 50 and 200 mm. Power supply needed for smoke generation was DC 40 - 50V, 2A. Delay time from the smoke generation to the camera and flash operation was adjustable by a control circuit. Schematic diagram of the test section and the visualization equipment are shown in Fig. 1. A 35mm camera with motor drive was used with lenses of 75-150 mm/f3.5 or 135 mm/f2.

Tested model has 0.15 m span and 0.2 m central chord length which give aspect ratio of 1.5. It is made of 2 mm thick flat aluminum plate, painted black. The model is supported by an 8 mm diameter circular rod at the center of the bottom (pressure side) surface in order to avoid unwanted interaction of the visualized part of the flow and the support.

Flow visualization by smoke wire is appropriate and it is widely used for two-dimensional flows since the smoke is generated in the form of a thin flat sheet. On the other hand, the flow field around a delta wing is strongly three-dimensional, and it requires combinations of various experiments in order to get full understanding of such a complicated flow by smoke wire flow visualization. Several combinations of different relative attitudes and positions between the smoke wire and the model were tried in this study for establishment of visualization technique of a three-dimensional flow.

Experiments reported here are divided into two as follows.

Experiment I Smoke wire was stretched in parallel with the spanwise direction of the model as shown in Fig. 2. Four different relative locations between the wire and the model designated as cases a - d were used.

a: near nose, b: center, c: near trailing-edge, d: above nose (smoke sheet passes over the suction side of the wing).

Pictures were taken from three perpendicular directions, x, y, and z but not simultaneously since it was not possible to obtain proper lighting for simultaneous photographing. Three pictures, therefore, do not show exactly the same flow. Special care was taken in order to obtain the representative pic-

Fig. 1 Flow visualization facility and test section.

Fig. 2 Relative locations between wing and smoke wire for Experiment I.

Fig. 3 Relative locations between wing and smoke wire for Experiment II.

tures of the flow by taking approximately thirty pictures for each side view after careful examinations of the flow by eyes from various directions.

Experiment II Smoke wire was set perpendicular to the spanwise direction as shown in Fig. 3. Relative locations between the wire and the model are designated as a - c.

a: near nose (10 mm outside from the center line), b: midway between the center line and wing tip, c: near wing tip.

These three cases a, b, and c correspond to the cases a, b, and c in Experiment I respectively concerning the point of the smoke flow-in position for the wing. Therefore, it is possible to obtain meaningful pictures for three-dimensional flow visualization by combining all of these pictures.

3. Experimental Results

All the experiments reported here were performed at mean free stream velocity of 3 m/s, which was most suitable for photographing, although the vertical smoke wire of this type could be used at free stream velocity of up to 10 m/s. Reynolds number based on the maximum chord length was approximately 4×10^4 .

Angle of attack of the wing is an important parameter for the flow field characteristics. At an angle of 20° , formation and breakdown of the leading-edge vortices were well observed but a

violent flow separation over the wing did not occur. Most pictures were, therefore, taken at the angle of 20° , and cases of 10° and 30° are also shown in order to see the effect of angle of attack. In the following descriptions and figures, the angle of attack is 20° unless otherwise noted.

Figure 4 shows pictures taken by cameras A, B, and C for Experiment I, wire position b. The smoke streak passing near the wing turns around the leading-edge sharply and goes upward a little, then swirls into the inside of the leading-edge vortex. Flow in this region is turbulent, and Fig. 4(c) shows that the flow pattern is similar to the flow around a typhoon with an 'eye', and the flow around the eye is turbulent. It is not clear from Fig. 4 only whether this turbulent flow results from a vortex breakdown or not. Figure 4(a) also shows that the flow passing at certain distance from the leading-edge also swirls into the vortex systematically.

Figure 5 shows pictures taken by cameras A and B for Experiment II, wire position b. Fig. 5(b) shows the flow pattern in a vertical plane which could not be seen in Fig. 4. It must be mentioned here that the depth of the flow field can not be shown in one picture and often a thick trace of the smoke seems as if it were in foreground. It is, therefore, very important to compare pictures taken from various directions in order to understand the flow field correctly.

(a) Camera A

(c) Camera C

(b) Camera B

(d) Illustration of the vortices

Fig. 4 Experiment I, wire position b.

Figure 6 shows pictures taken by cameras A and C for Experiment I, wire position a, and Fig. 7 shows pictures taken by cameras A and B for Experiment II, wire position a. Those figures indicate that a flow passing near the wing nose constitutes the vortex core, and the closer the flow is to the nose, the deeper into the core it goes. The flow passing the region of approximately $1/3$ of the front part of the leading edge goes into the core where vorticity is high. The core is formed along the leading edge, and it breaks down at the mid-chord location. It is clear here that the turbulent inner part of the vortex shown in Fig. 4(c) is a broken down vortex core, and that the flow passing central $1/3$ portion of the leading edge shown in Fig. 4 swirls into the outside of the vortex core which is already broken down and becomes turbulent.

The flow over the wing does not separate even after the core is broken down at this angle of attack in Fig. 7(b).

In Fig. 6(b), a bright vertical line indicates the trailing edge of the wing. Front part of the wing is not seen here because the slit light is narrower here than in Fig. 4. Therefore, Fig. 6(b) shows a slice of the flow shown in Fig. 6(a) at the trailing edge. Outer part of the smoke shown in Fig. 6(b) is a large scale free vortex region of the flow, swirled systematically as shown in Fig. 6(a). A pair of small spots on the trailing edge

(a) Camera A

(b) Camera B

Fig. 5 Experiment II, wire position b.

(a) Camera A

(b) Camera C

Fig. 6 Experiment I, wire position a.

(a) Camera A

(b) Camera B

Fig. 7 Experiment II, wire position a.

near wing tip look like the vortex cores. However, Fig. 7 shows that the core is already broken down at the trailing edge. Observation by eyes reveals that these spots are flow elements passing slightly outside of the leading edge, which are then swirled into the vortex over the wing. As these elements approach the wing surface, they are stretched and the vorticity is concentrated. A few of this kind of vortex elements are observed in Fig. 6(a), and these vortices also break down, as seen in Fig. 6(a).

Figure 8 shows a picture taken by camera A for Experiment I, wire position c and Fig. 9 shows a picture taken by camera B for Experiment II, wire position c. These pictures do not give information about the flow over the wing because the smoke flows into the wing near the trailing-edge. However, characteristics of the flow downstream of the wing can be obtained.

Figure 10 shows pictures taken from cameras A, B, and C for Experiment I, wire position d. Elements of the flow approaching the wing above the nose do not acquire a vorticity because they do not go around a sharp leading-edge. They are systematically swirled into the free vortex region, outer part of the vortices.

Results mentioned above indicate that for the case of the angle of attack $\alpha = 20^\circ$, the case of wire position a shows details of the flow field over the wing and the flow around the delta wing can be analyzed

Fig. 8 Experiment I, wire position c, camera A.

Fig. 9 Experiment II, wire position c, camera B.

(a) Camera A

(c) Camera C.

(b) Camera B

Fig. 10 Experiment I, wire position d.

by flow visualization by comparing the experiments with wire positions a and b.

Finally, cases of $\alpha=10^\circ$ and 30° are examined for Experiment II, wire position a in order to study the effect of angle of attack on the flow field. Figure 11 shows the case of $\alpha=10^\circ$. The vortex core does not break down over the wing and the number of smoke elements swirled into the leading-edge vortices is smaller than that for the case of $\alpha=20^\circ$.

On the other hand, a violent vortex breakdown is observed in the case of $\alpha=30^\circ$ as shown in Fig. 12. Diameter of the core is larger, and the breakdown occurs further upstream than for the case of $\alpha=20^\circ$. Moreover, the flow over the wing seems to be separated because the streamlines become wider apart after the location of the vortex breakdown, indicating a slow down of the flow velocity.

4. Conclusions

Following conclusions were obtained from the smoke wire visualization of a three dimensional flow around a delta wing as a model of a fan blade.

(1) The cases of smoke wire position a, Experiments I and II show the process of formation and breakdown of the leading-edge vortices most clearly, and with the aid of the case of smoke wire position b, Experiment I, the global structure of the flow field can be examined.

(2) Examination of the smoke traces by eyes from various angles is quite important to interpret a complicated three-dimensional flow field correctly.

(3) Flow elements passing near the leading-edge are swirled into the leading-edge vortices, and the elements closer to the edge go deeper into the vortex and form a vortex core. Outer flow elements are swirled into the free vortex region, however, elements fairly close to the leading-edge acquire the vorticity and form small vortices, which are swirled between the core and suction side of the wing.

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(a) Camera A

(b) camera B

Fig.11 $\alpha=10^\circ$, Experiment II, wire position a.

(a) Camera A

(b) Camera B

Fig.12 $\alpha=30^\circ$, Experiment II, wire position a.