BVI Noise Reduction Research with Canard Blade Tip

Tomoki Ota, Yuko Hashiguchi, Takanori Tsukahara,
Masahiro Obukata and Masaaki Nakadate
Fuji Heavy Industries Ltd., Utsunomiya, JAPAN

Abstract

A new configuration of the rotor blade for BVI (blade vortex interaction) noise reduction has been developed and validated in wind tunnel at Fuji Heavy Industries Ltd. (FHI). The tip of this rotor blade has two small lifting surfaces, a canard-like front wing and a rear wing. Employing two lifting surfaces, the tip vortex is divided into two vortices, which interact mutually and merge into a vortex with lower swirl velocity. Furthermore, the canard incidence is controlled to avoid the degradation of aerodynamic performance. The canard tip showed a reduction of almost 50% in the swirl velocity of the tip vortex compared to the baseline rectangular tip in a non-rotating blade tip wind tunnel test. The results in a rotating rotor wind tunnel test revealed that a reduction of 2.5 dBA in the SPL (sound pressure level) could be achieved. The performance penalty of the canard tip at high-speed flight could be minimized with proper control of the canard incidence. The aerodynamics design and control law of the canard tip will be presented as well.

1. Introduction

The most disturbing noise generated by the helicopter is the BVI noise, which is prominent especially during low speed descent. In such a flight condition, the tip vortex shed from a blade interacts with the succeeding blades, creates impulsive pressure peaks on the blade surfaces, and then leads to vast amount of BVI noise radiation.

In general, three ways are conceivable to reduce the BVI noise as follows: 1) increase the miss distance between the tip vortex and the blade; 2) alleviate the loading on the blade when the vortex interacts with the blade; and 3) weaken the tip vortex.

Higher Harmonic Control (HHC) (Refs. 1, 2 and 3) and Individual Blade Control (IBC) (Refs. 4 and 5) reduce the BVI noise by method (1) or (2), which is dependent on the scheduling of the control. Although these methods achieve considerable BVI noise reduction, rotor vibration often increases at the same time.

The subwing tip (Ref. 6) and vane tip (Ref. 7) reduce the BVI noise by method (3). These tips split the blade tip vortex into two separate corotating cores of ideally equal strength. During the BVI, the load fluctuations caused by each weaker core would produce less noise.

Based on the "canard tip", which we developed in the past (Ref. 8), this BVI noise reduction research has been focused on blade tip shapes that diffuse the tip vortices. In this research, the canard tip was further refined to maximize the diffusion. In addition, the canard incidence was controlled to minimize the performance penalty.

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2. Concept of the Canard Tip

The canard tip was primarily intended for the BVI noise reduction by lowering the swirl velocity of the tip vortex. As depicted in Figure 1, the tip of this rotor blade has two small lifting surfaces, a canard-like smaller front wing near the leading edge and a rear wing near the trailing edge, which make the tip look like the canard and wing of the fighter aircraft. With two lifting surfaces, the tip vortex is divided into two vortices, one from the front wing and the other from the rear wing, which interact mutually and then merge into a vortex with lower swirl velocity as they flow downstream. The advantage of applying two surfaces is that it gives us higher degree of the design freedom to the location and strength of the vortex shed from the tip of each lifting surface.

However, the canard tip affects the aerodynamic performance of the rotor. In other words, when the canard incidence is optimal for BVI noise reduction, shock could develop on the canard of the advancing blade and stall could occur on the retreating blade leading to an increase in power required. When the canard incidence is optimal for the aerodynamic performance, the distance between two divided vortices could be too wide to interact effectively each other. To avoid these shortcomings, a control law of the canard incidence is implemented and shown in Figure 2.

3. Aerodynamic Design of the Canard Tip

The canard tip shape was designed to realize the concept of canard tip described above efficiently. To simplify the concept, a rectangular tip with two small wings was used. A computational fluid dynamics (CFD) code called the MGAERO, solving 3-D Euler equations, was employed to determine the vortex swirl velocity at a distance of one chord length downstream of the trailing edge of the basic tip and the lift/drag ratio (Fig. 3). This in turn allows us to find the most promising combinations of the chord length and the span of the front wing as well as the rear wing. The effects of the canard incidence were also evaluated. An optimization example of the canard chord is shown in Figure 4. No. 1 and No. 2 canard tip were selected as the optimized combinations. Note that the CFD methods underestimate the swirl velocity due to the numerical dissipation making the difference among configurations. Accordingly, the effect of the canard tip was verified by using the designed canard tips in the wind tunnel.

4. Control Law of the Canard Incidence

The scheduling of the canard incidence was determined based on the analyses of how the tip vortex from a blade strikes the succeeding blades using the free wake model of the CAMRAD II comprehensive analysis code. Figure 5 shows the flight conditions of the BVI noise in terms of tip path plane angle versus advance ratio. This condition was determined by analyzing the condition of the prominent BVI noise that the tip vortex strikes parallel to the succeeding blade. The canard incidence was switched between the angles for the maximum BVI noise reduction and the least aerodynamic performance degradation. When a helicopter is flying in the BVI noise condition (Fig. 5), the canard incidence is controlled according to the scheduling shown in Figure 6. Otherwise, the canard incidence is fixed at the angle for the least aerodynamic performance degradation.

5. Blade Tip Wind Tunnel Test

It was verified that the canard tip generated a defused vortex in non-rotational condition. The wind tunnel test is shown in Figure 7. The test was conducted in the FHI 2-m by 2-m low-speed wind tunnel.

5.1 Test Equipment

(1) Blade model

The test models have three kinds of tip shapes which are baseline rectangular tip, subwing tip and canard tips. The base blade in Figure 8, which is a part-span model of a rotor, is used as a baseline rectangular tip. The rectangular tip provides basic data for a comparison with other tip models. The base blade becomes the subwing tip or canard tip by connecting tip attachments (Fig. 8). The canard tip shapes tested were designed in chapter 3. The subwing tip shape was based on Reference 6.

The base blade is 900 mm in span and 300 mm in chord with a constant airfoil section of 12% thickness (NACA0012). The base blade and the tip attachments have no twist. The subwing tip and the canard tip have 0 deg. incidence to the centerline of the base blade.

The model is mounted vertically on the wind tunnel floor and has a splitter plate at the root.

5.2 Data Acquisition

(1) Downstream velocity measurement

A five-hole Pitot (yaw meter) is used for the flowfield measurement. The Pitot is mounted on an industrial robot and a flowfield up to 6-chord length downstream of the trailing edge of the tip models can be measured. The measurement was conducted at grid points perpendicular to the wind tunnel free stream direction with the spacing of 5% chord length (15 mm) in both vertical and horizontal direction.

(2) Aerodynamic force

A three-component balance is used to measure lift, drag and pitching moment. The balance is placed on the root of the blade model.

5.3 Test Result

Figure 9 shows a comparison of vortex contours among baseline rectangular, subwing and canard tips. As can be seen from the figure, the baseline rectangular tip generated one big vortex with the highest vorticity vortex, while the subwing tip generated two closely located small vortices with lower total vorticity than that produced by the baseline model. Finally, the canard tip produced one diffused vortex with a 50% vorticity compared to the rectangular tip.

Figure 10 shows a summary of the maximum swirl velocity comparison. The canard No. 2 showed a reduction of almost 50% in the swirl velocity compared to the baseline rectangular tip.

Figure 11 shows how the swirl velocity diffuses as the tip vortex flows downstream. The swirl velocities of the rectangular tip and the canard tip were measured at 1, 3 and 6 chord length downstream of the blade. The swirl velocity of the canard tip is lower than that of the rectangular tip in all conditions.

6. Rotor Wind Tunnel Test

The other wind tunnel test was conducted using a model rotor in the same wind tunnel as the blade tip wind tunnel test to validate the BVI noise reduction of the canard tip with the canard incidence fixed as well as controlled in rotating conditions (Fig. 12).

6.1 Test Equipment

(1) Model rotor system

The rotor system is mounted on the wind tunnel floor (Fig. 13). The rotor system has a teetering rotor of

1500mm in diameter. The direction of the downwash is upward so that the positive thrust is directed downward. The system has a pivot for the mast tilting to tilt the tip path plane of a rotor so that the various descending conditions can be simulated.

(2) Model rotor

The specification of the model rotor is listed in Table 1. The blade has a mechanism of a control of canard incidence. (Fig. 15). The shaft of the canard tip control is penetrated through the blade at 11.25% chord position from the leading edge.

The blade has two kinds of tip shapes which are a rectangular tip and a canard tip. The tip shapes are changed by the tip attachments (Fig. 14). The No.2 canard tip is used as a canard tip in this test since it reduced the swirl velocity better in the blade tip wind tunnel test.

Table 1 Rotor Model Specification Summary

Hub	Teetering
Number of Blades	2
Rotor Diameter	1500 mm
Blade Chord Length	90 mm
Airfoil	NACA0015
Blade Twist	0 deg.
Rotor Speed	1000 rpm
Tip Speed	78.5 m/s

(3) Control system

The mechanism of the control system is shown in Figure 16. The control system has two swashplates. One is similar to that used in the conventional helicopter for the blade cyclic and collective pitch controls. The other is for the canard control mounted on the non-rotating portion of the swashplate for the blade pitch control. The canard control rod transmits the control from the canard control swashplate to the canard control shaft in the blade model. By tilting the canard control swashplate relative to the blade pitch control swashplate, the canard incidence changes in a 1/rev manner as the blade rotates. The amplitude and phase of the canard control can be changed by the amount and direction of tilting

6.2 Data Acquisition

The data acquisition system is shown in Figure 17. This system consists of the following two parts.

(1) Sound pressure measurement

Figure 17 shows the general arrangement of noise measurement. Note that no anechoic treatment is made to the wind tunnel since it was verified that the sound pressure of the BVI noise was much higher than the wind tunnel background noise.

Specific locations of the microphones are shown in Figure 18. Note that positive notation for the azimuth angle is clockwise because the model rotor is mounted upside down. One microphone (microphone No. 1) is located at the azimuth angle of ψ = 180 deg., 1.5 radii from the center of the model rotor and 30 deg. above the rotor plane, the others (microphone No. 2 and 3) are located at ψ = 270 and 90 deg., one radius from the center of the rotor and 30 deg. above the rotor plane. Microphone No. 3 was chosen to evaluate BVI noise since the peak of the sound pressure of the BVI noise was the highest among all microphones.

The data acquired are converted into the A-weighted sound pressure level (dBA) to evaluate the noise. The 1/3-octave band analyses are performed using the sound pressure data of 5-second duration.

(2) Aerodynamic load measurement

A three-component balance, placed just above the motor for blade rotation, is used to measure the lift, drag and torque.

6.3 Test Result

(1) Fixed canard test results

(a) Noise evaluation

Noise reduction effect was evaluated by the flight condition of the advance ratio μ=0.15～0.17 and the angle of tip path plane α_{TPP}=10～12 deg. where the BVI noise of the baseline rectangular tip was prominent.

Noise contours of the rectangular tip and +5 deg., 0 deg., +5 deg. canard tip are shown in Figures 19(a) through (d) respectively. Table 2 summarizes the peak noise values in these contours. It is shown that the noise reduction from the baseline rectangular tip comparing to the canard tip is 2.5 dBA when the angle of canard incidence is -5 deg. (nose down). And the change of the canard incidence affects BVI noise reduction effect because the relative position of two vortices has been changed.

Table 2 Comparison of Peak Noise Value (Fixed canard tip)

	BVI Peak [dBA]	Difference from Rectangular Tip	Referenced Figure
Rectangular Tip	97.8	-	Fig.19(a)
Canard Tip (+5 deg.)	96.4	-1.4	Fig.19(b)
Canard Tip (0 deg.)	96.6	-1.2	Fig.19(c)
Canard Tip (-5 deg.)	95.3	-2.5	Fig.19(d)

(b) Aerodynamic performance evaluation

Hovering performance curves of the rectangular tip and the canard tip are shown in Figure 20. The result indicates that hovering power with the canard tip increases slightly compared to the rectangular tip because the tip vortex from the front wing has struck the rear wing so that the rear wing seems to have produced more drag. It is also shown that the change of canard incidence affects hovering performance. Especially, -5 deg. of the canard incidence has the smallest power increase because the vortex from the front wing has less interacted with the rear.

Forward flight performance was evaluated at cruise flight speed. Forward flight performance curve is shown in Figure 21. The figure indicates that the forward flight power with the canard tip increases slightly compared to the rectangular. It is also shown that the change of canard incidence affects forward flight performance. Especially, 0 deg. of canard incidence has the smallest power increase.

(2) Controlled canard test results

(a) Canard control definition

The scheduling of the angle of the canard incidence was determined by the result of the fixed canard evaluation. The summary of the canard tip effect in the fixed canard test is in Table 3. The noise reduction position and the low aerodynamic degradation position were chosen at 0 deg. and –5 deg. respectively. Because of the canard control mechanism, the scheduling of the angle needed to be approximated by a sine curve. As a result, the scheduling of the angle of canard incident is shown in Figure 22.

(b) Noise evaluation

The noise contours of the controlled canard tip are shown in Figure 19(e) and 19(f). The peak values are listed in Table 4. The result shows that the controlled canard reduces the BVI noise by 1.3 dBA. However, the maximum noise reduction with the controlled canard tip is less than that with the fixed canard.

(c) Aerodynamic performance evaluation

Forward flight performance evaluation is shown in Figure 23. It is shown that the forward flight performance with the controlled canard tip slightly improves compared to that with the fixed canard tip.

Table 3 Summary of Canard Incidence Effect

Canard Incidence	Noise Reduction (BVI Peak [dBA])	Aerodynamic Performance ($C_{DE} \times 10^4$)*
0 deg.	96.6 (fair)	37.3 (good)
-5 deg.	95.3 (good)	37.9 (fair)

*)@C_L=0.068, cruise speed flight

Table 4 Comparison of Peak Noise Value (Controlled canard tip)

	BVI Peak [dBA]	Difference from Rectangular Tip	Referenced Figure
Canard Tip (Pattern ①)	96.5	-1.3	Fig.19(e)
Canard Tip (Pattern ②)	96.6	-1.2	Fig.19(f)
Canard Tip (0 deg.)	96.6	-1.2	Fig.19(c)
Canard Tip (-5 deg.)	95.3	-2.5	Fig.19(d)

6.4 Full Scale Estimation

The noise reduction effect and the aerodynamic performance effect for a full-scale helicopter are estimated in Table 5.

(1) Fixed canard tip

When the fixed canard tip is equipped, the BVI noise can be reduced by 2.5 dBA compared to a rectangular tip. As far as aerodynamic performance is concerned, hovering power is the same as the rectangular tip and forward flight power increases slightly.

(2) Controlled canard tip

When the canard tip is controlled ideally by selecting the best canard incidence for hovering, forward flight and BVI condition, BVI noise can be reduced by 2.5 dBA with –5 deg. fixed canard incidence. Hovering power is the same as the rectangular tip with -5 deg. fixed canard incidence.

Table 5 Estimation of Canard Tip Effect on a Helicopter

		Noise Reduction*1	Hovering Power*1,2	Cruise Flight Power
Fixed Canard Tip (-5 deg.)		-2.5 dBA	0% torque	+1.2% torque
Controlled Canard Tip	Constant Schedule	-1.3 dBA	-	+1.0% torque
	Ideal Schedule*3	-2.5 dBA	0% torque	+1.0% torque

*1)Peak value compared to a rectangular tip effect

*2)To consider that the area of blade with a canard tip is the same as one with a rectangular tip, the values are compensated.

*3)canard control pattern is changed properly according to flight condition

And forward flight power increases by +1.0% with the controlled canard tip.

As a future work, the noise reduction concept needs to be validated with a full-scale helicopter because the tip speed of the helicopter is much faster than that of the rotor model in this research.

7. Conclusions

Through the blade tip wind tunnel test and the rotor wind tunnel test, it was confirmed that the canard tip was a valid means to reduce the BVI noise as follows:

(1) The blade tip wind tunnel test showed that the canard tip reduced the swirl velocity of the tip vortex by about 50% compared to the rectangular tip.

(2) The rotor wind tunnel test with the fixed canard incidence showed that the noise reduction from the baseline rectangular tip by the canard tip was 2.5 dBA. The hovering power with the fixed canard tip was the same as that with the rectangular tip. And forward flight power increased slightly.

(3) The effect of the controlled canard tip was verified and the ideal scheduling of the canard incidence, which reduces the BVI noise by 2.5 dBA with the least aerodynamic performance degradation, was determined

8. Acknowledgement

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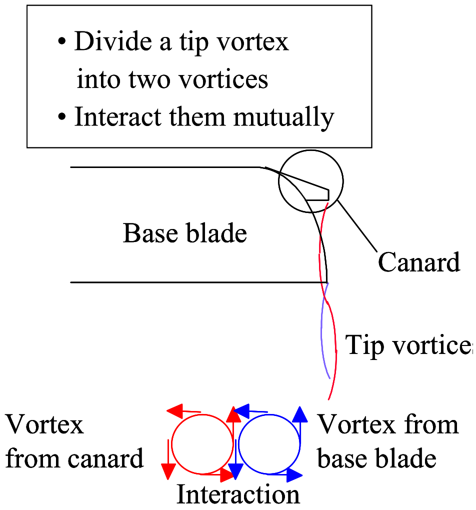


Fig. 1 Canard Tip Concept

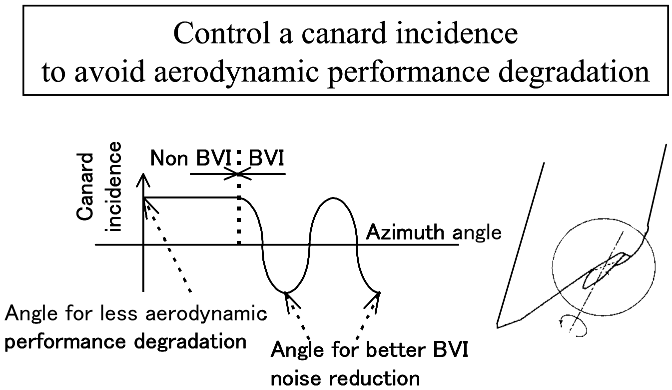


Fig. 2 Canard Incidence Control Concept

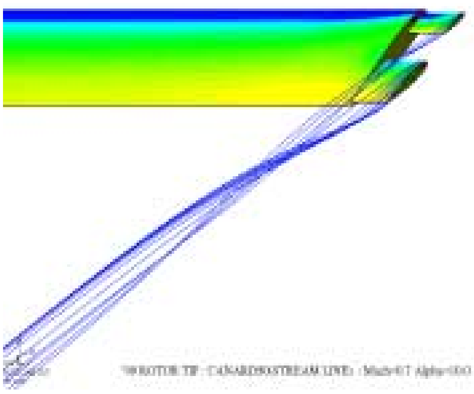


Fig. 3 CFD Analysis
(by MGAERO)

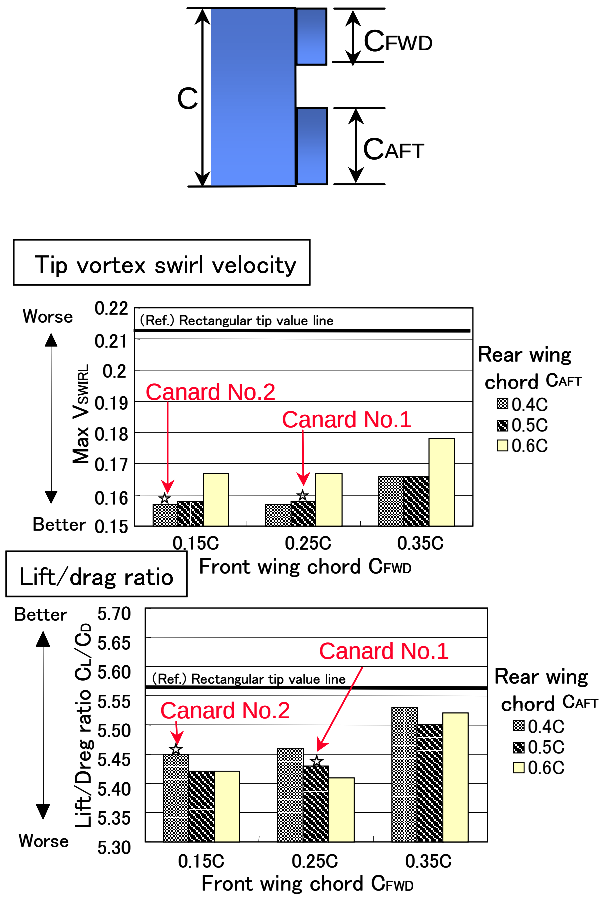


Fig. 4 Canard Chord Optimization

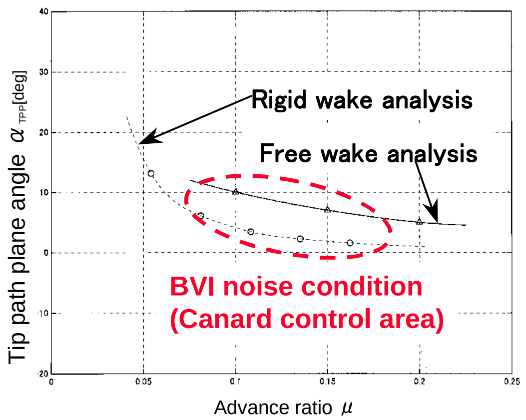


Fig. 5 Flight Condition for BVI Noise

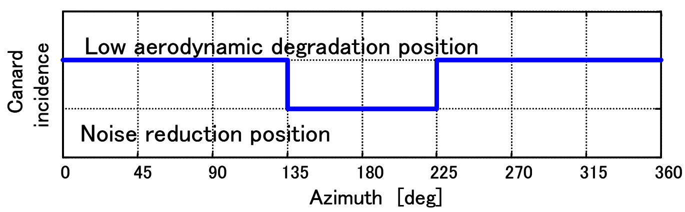


Fig. 6 Canard Incidence Schedule

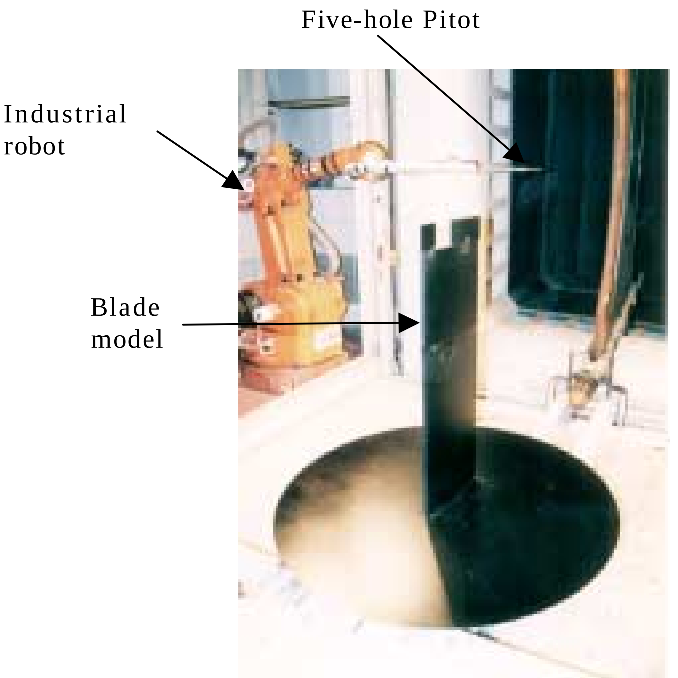


Fig. 7 Blade Tip Wind Tunnel Test

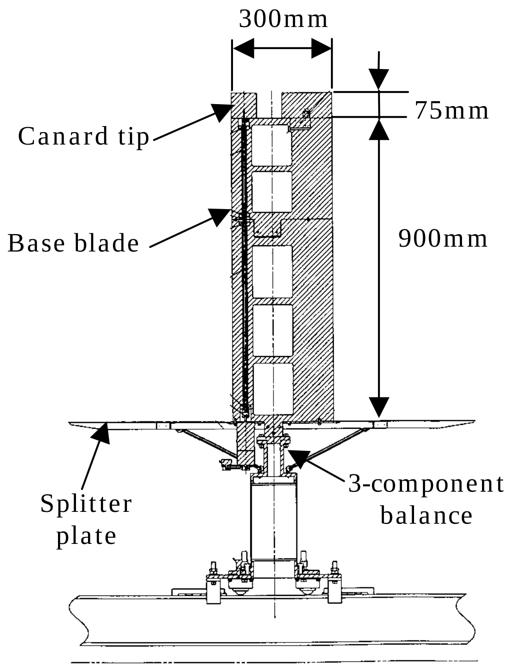
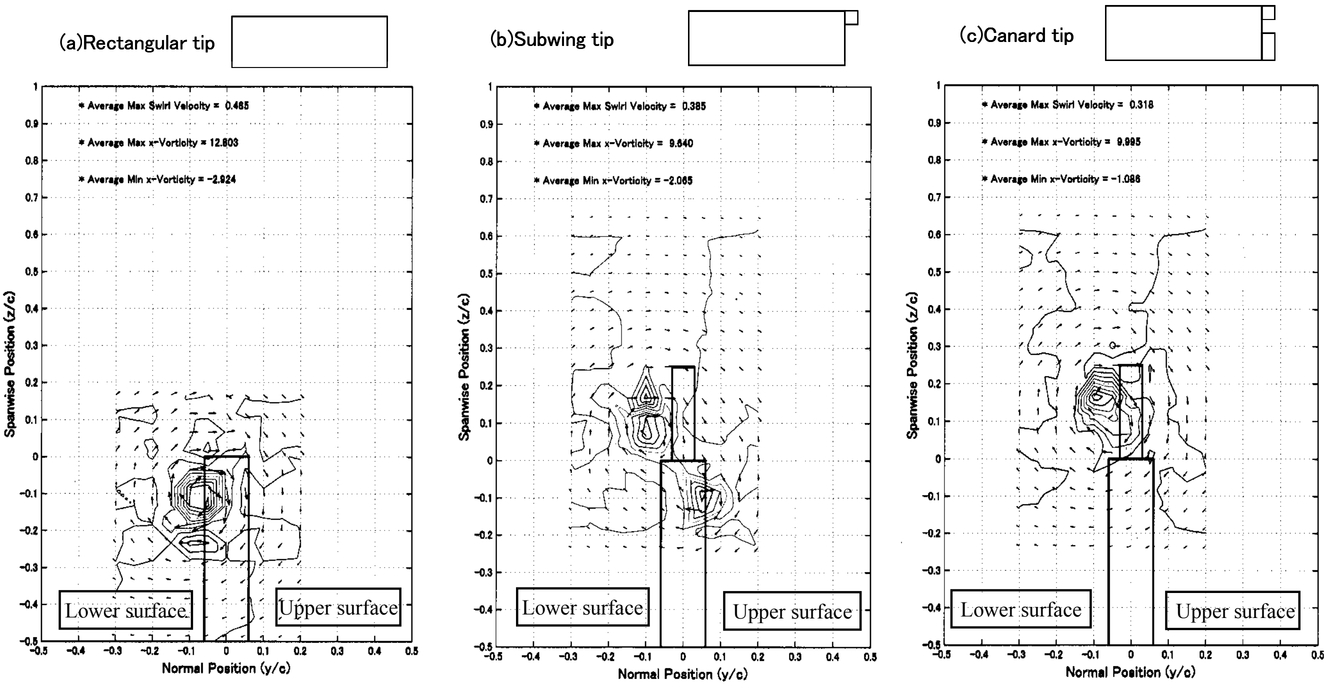


Fig. 8 Blade Tip Model



(U_∞=40m/s, Base blade angle of attack=10 deg., Re=9.4×10^5 @ 3 chord length downstream of the blade)

Fig. 9 Vectors of Downstream Velocity and Vorticity Contour

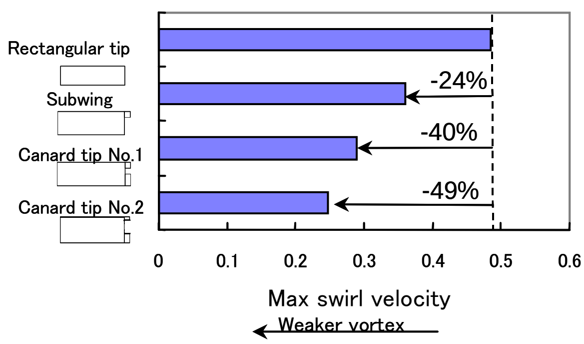
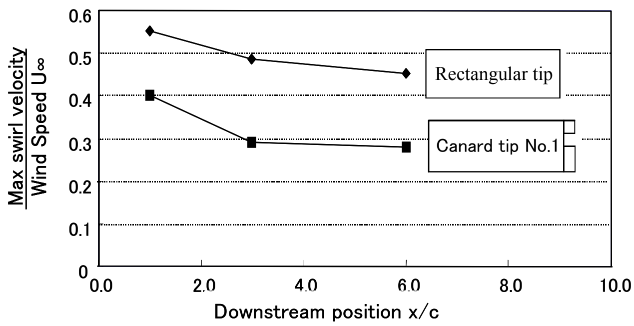


Fig. 10 Comparison of Swirl Velocity



(U_∞=40m/s, Base blade angle of attack=10 deg., Re=9.4×10^5)

Fig. 11 Swirl Velocity vs. Distance behind the Blade

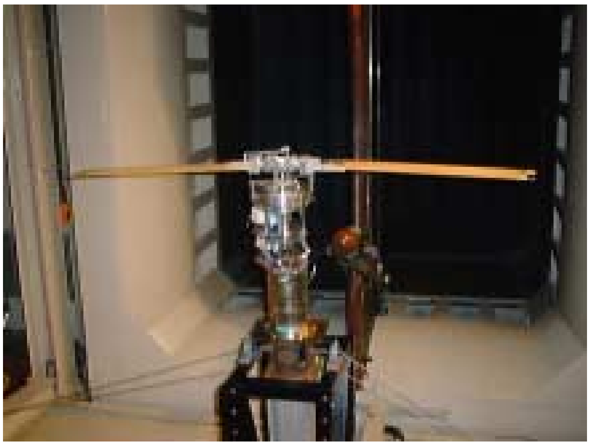


Fig. 12 Rotor Wind Tunnel Test

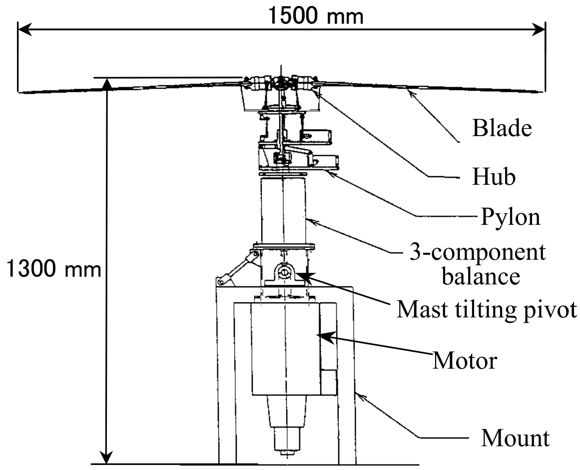


Fig. 13 Model Rotor System

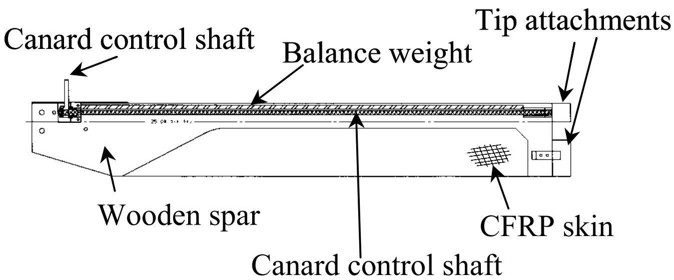


Fig. 14 Blade Model

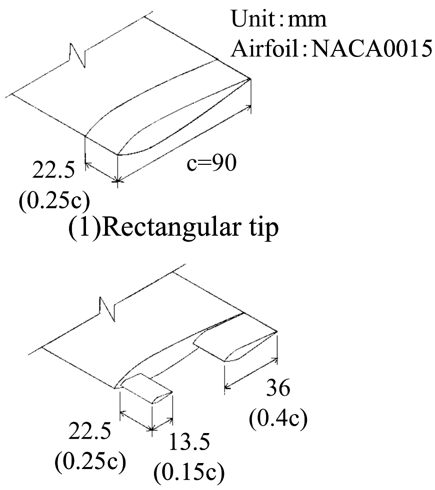


Fig. 15 Tip Attachment

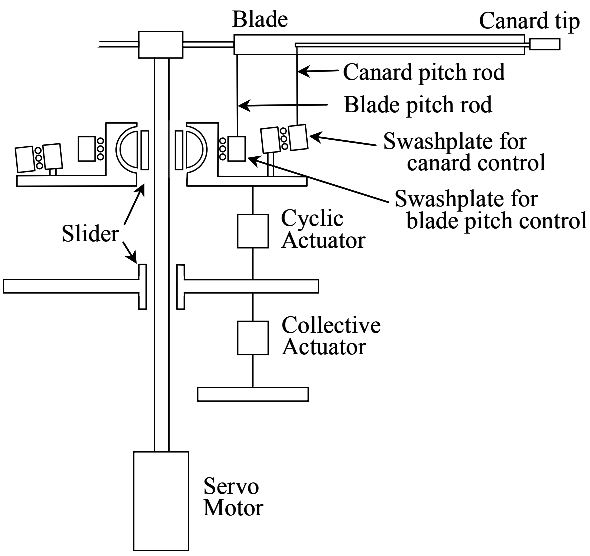


Fig. 16 Control System Mechanism

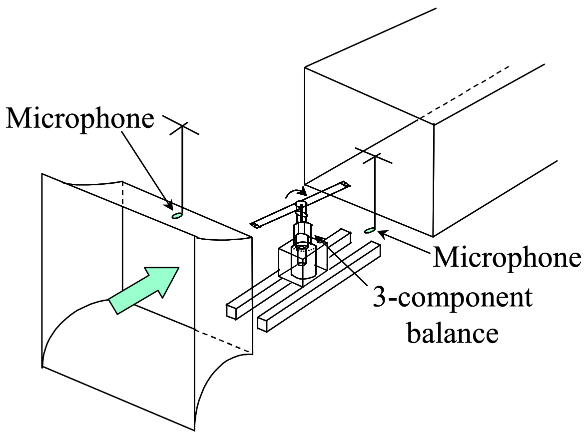


Fig. 17 Data Acquisition System

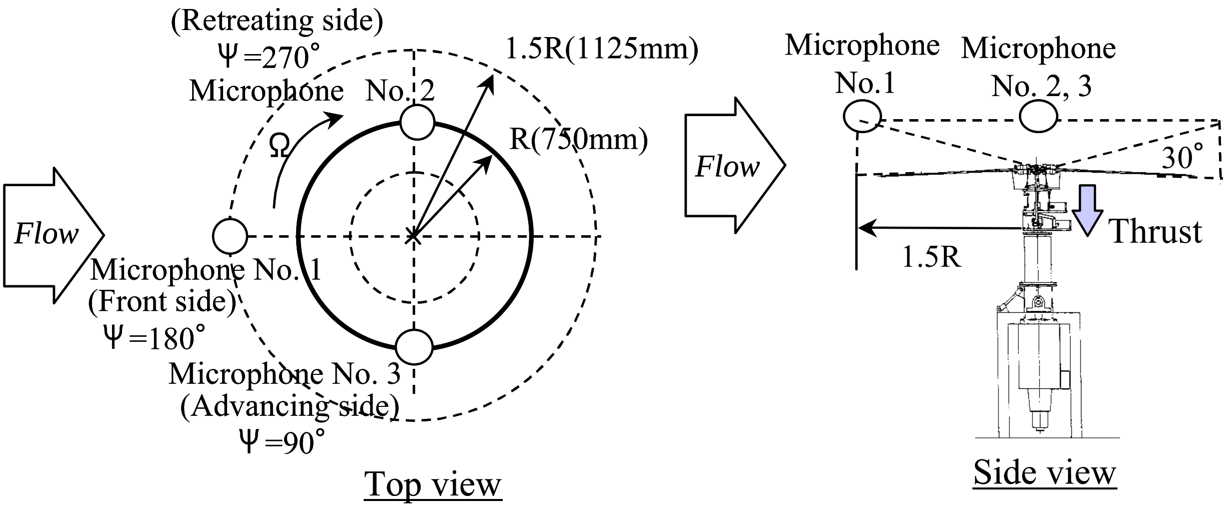


Fig.18 Microphone Location

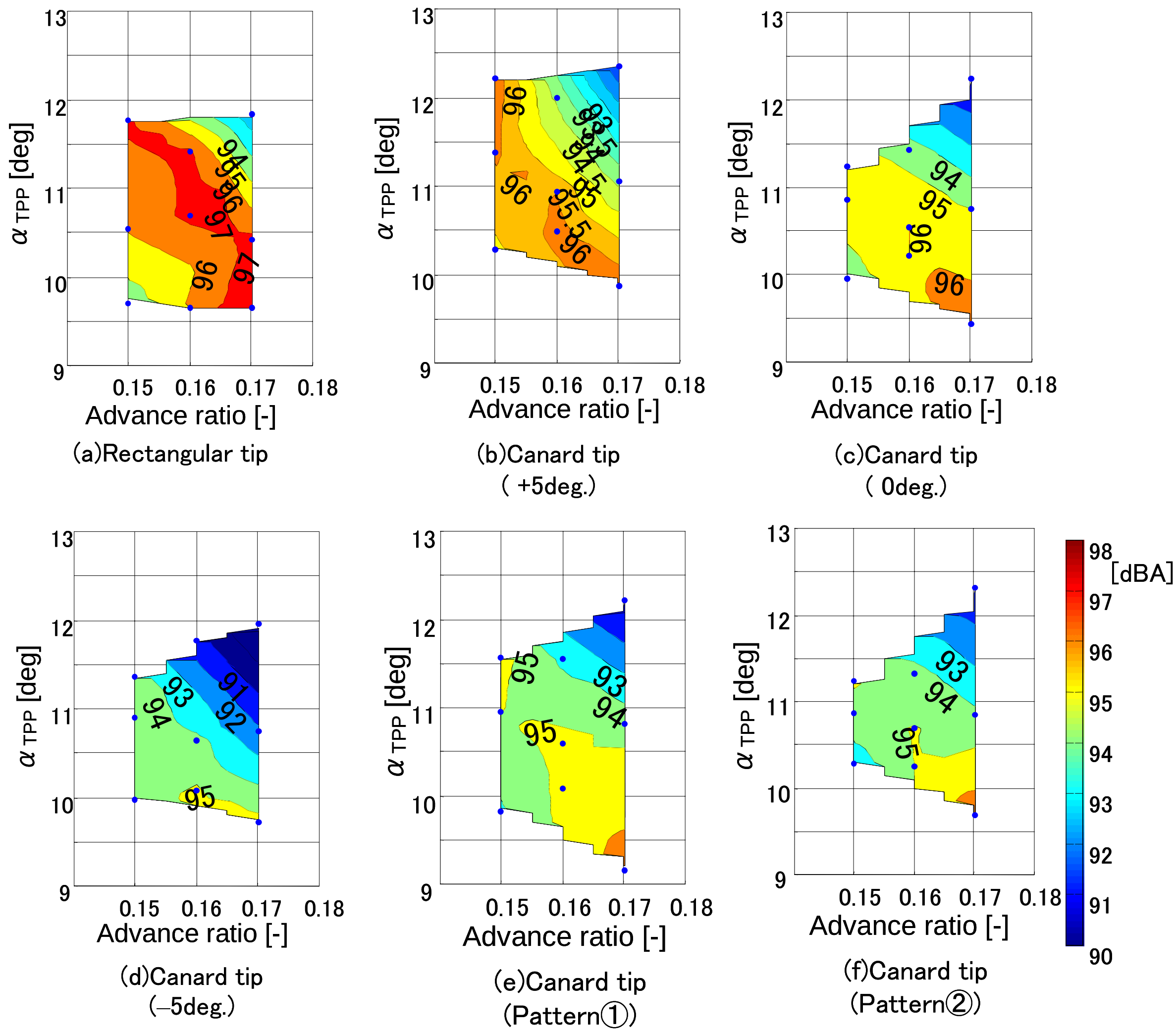


Fig.19 Noise Contour

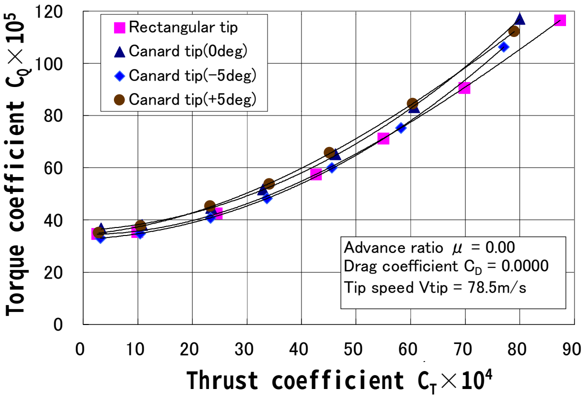


Fig.20 C_Q～C_T Curve
(Hovering, fixed canard tip)

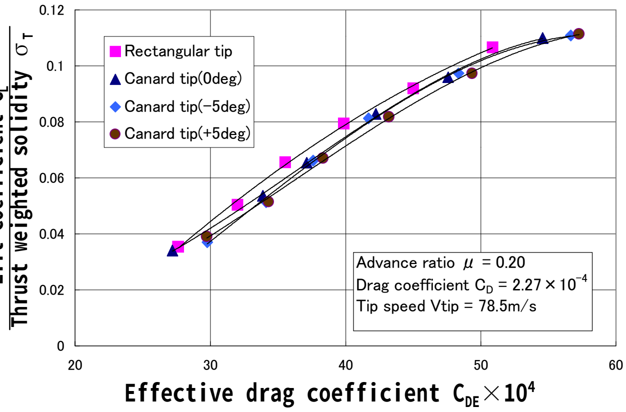


Fig.21 C_L/σ_T～C_{DE} Curve
(Cruise flight, fixed canard tip)

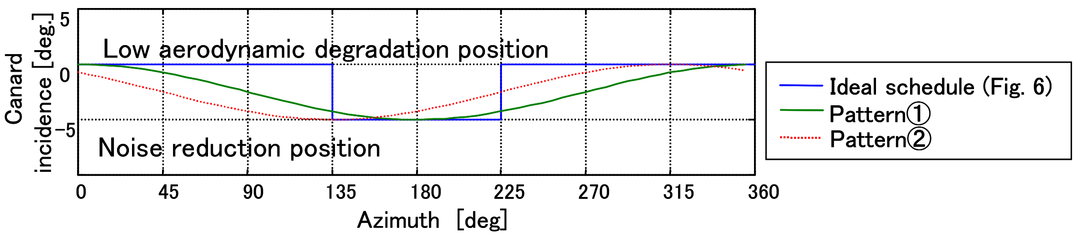


Fig.22 Canard Incidence Schedule

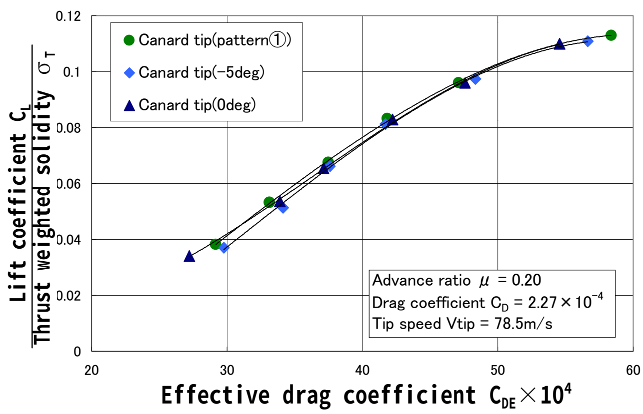


Fig.23 C_L/σ_T～C_{DE} Curve
(Forward flight, controlled canard tip)