Wind tunnel test for BVI noise and vibration reduction using Blade Active Control

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Abstract

Mitsubishi Heavy Industries, LTD. and JAXA (Japan Aerospace Exploration Agency) have been conducting a research on reduction of Blade-Vortex Interaction (BVI) noise and vibration of helicopter rotors using blade active control with trailing edge flaps(Ref 1, 2).

Last Year, we showed the result of BVI noise wind tunnel test with conventional rotor and our firstly applied active rotor with trailing edge flaps (Ref 3).

This paper presents the result of following wind tunnel test and the examined mechanism of BVI noise reduction from the data acquired.

Nomenclature

C_T	=Rotor thrust force coefficient
α_s	=Rotor shaft angle(positive nose up)
μ	=Advance ratio
ψ	=Blade azimuthal angle
δ_{AFC}	=Active flap deflection angle (positive trailing edge down)
δ_{0AFC}	=Active flap control amplitude
P_{AFC}	=Modulus of Active flap control
ψ_{AFC}	=Active flap control phase angle
dC_H	=Fluctuation of drag force coefficient
dC_T	=Fluctuation of thrust force coefficient
dC_M	=Fluctuation of pitching moment coefficient
SPL	=Sound Pressure Level

Introduction

Helicopter is one of the most convenient transportation. It can take us almost everywhere if enough space exist for landing or sling off us. The noise problem, however, has barred wide spread use of helicopters. Most of the commercial use helicopters fly near the town. The aeronautics research on reducing noise have been conducted to make helicopters more acceptable to the public. Active blade control methods have been applied to reduce blade noise since 1970's. The effectiveness has been confirmed but the practical applications of such methods are not realized yet. The difficulty exists on the blade control method. Several methods have been developed for this thirty years. HHC(Higher Harmonic Control) and IBC (Individual Blade Control) are the famous blade control systems. HHC is the method to control a swash plate at high frequency to reduce vibration or rotor noise. IBC is the method to control each blade pitch angle individually. Active flap method can be called one sort of IBC method, however, conventional IBC methods use actuators between blade root and swash plate. High response and power are required for the IBC actuators. The merit of the active flap is that little force is required to control blade in comparison with conventional IBC methods. The problem of the active flap method is developing the actuator, which is small enough to be embedded in a narrow space of rotor blade, and has enough power to deflect flap to required angle at required frequency. Piezoelectric actuator and SMA(Shape Memory Alloy) have been applied for the active flap actuator. The former one can actuate with high frequency but has small displacement. The latter can actuate with large power and displacement but with low frequency. In this study, piezoelectric actuator was selected as an active flap actuator and flap angle amplification mechanism was newly developed.

This paper presents the study of BVI noise and vibration reduction using active flap control. The study consists of three steps.

The BVI noise for the conventional blade was measured in a wind tunnel as the first step. In this step, the BVI noise for the conventional blade was measured (Fig 1(a)). Sound pressure and blade surface pressure histories were obtained and the locations of the interaction were acquired (Fig 1(b)).

As the second step, active flap model rotor was developed and its wind tunnel test was conducted to obtain data in order to estimate the noise reduction effect of the active flap method. In this step, the ability to reduce the BVI noise of the active flap model rotor was estimated, but the effect of the active flap was rather small (Fig 2). The accomplishments of these two steps were shown in the 30th European Rotorcraft Forum.

As for the third step, active flap model rotor was improved and its wind tunnel test was conducted to estimate improved BVI noise reduction effect. In addition, rotor vibration wind tunnel test was conducted to estimate the ability to reduce rotor

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vibration. This paper shows the result of this third step.
This study has been conducted under the joint research work between JAXA and Mitsubishi Heavy Industries, Ltd.

Active flap blade model description

A trailing edge active flap was installed on the each blade (Fig 3). The trailing edge flap system data is shown in Table 1. As shown in the table, flap chord and flap deflection amplitude was improved from old model. The flap chord of the old model was 25% blade chord in airfoil and the flap deflection amplitude was ±2degrees. The improved model was designed to have more influence on the BVI noise reduction than the old model.

Table 1 Active flap blade model description

Blade number	2
Rotor radius	1.0 m
Blade chord	0.065 m
Blade section airfoil	NACA0015
Blade twist	-8 deg. (linearly from hub to tip)
Flap chord*	40% blade chord (25% in airfoil, 15 % out of airfoil)
Flap span	5% blade radius
Flap location	75% blade radius
Flap deflection amplitude*	±3deg.
Flap control Frequency	40Hz(max)
Flap actuator	Piezoelectric Actuator

*) improved from old model

Wind tunnel test description

This test was conducted in 6.5m x 5.5m Low speed wind tunnel at JAXA from November 1st to December 7th 2004. Two-bladed rotor helicopter model was located in the center of the wind tunnel facility (Fig 4). Two-bladed rotor of the helicopter model was driven and controlled by rotor rotation system shown in Fig 5. This system has “control and drive system”, “collective & cyclic control system”, and “active flap control system”. Control and drive system, which has electric power unit, control unit and lubrication/cooling unit, drives motor with specified rpm. Blade pitch angle is controlled with collective & cyclic control system. Active flap control system receives a blade azimuthal angle signal in every one cycle, and sends active flap deflection angle signal of one cycle.

Steps of wind tunnel test

BVI wind tunnel test BVI wind tunnel test was conducted as follows.

1. Specification of advance ratio condition, in which BVI noise is significant.
2. Measurement of BVI noise in the wind tunnel without active flap control in various advance ratio and rotor shaft angle conditions.
3. BVI wind tunnel test with active flap control in significant BVI noise condition, which was determined from the result of the previous step.

Rotor vibration wind tunnel test Rotor vibration wind tunnel test was conducted as follows.

1. Measurement of rotor vibration in the wind tunnel without active flap control in various advance ratio and rotor shaft angle conditions.
2. Rotor vibration wind tunnel test with active flap control in significant rotor vibration condition, which was determined from the result of the previous step.

Measurements

Measurement system description is shown in Fig 6. Steady data of the wind tunnel test data is written down, and unsteady data is recorded in real time to the data logger as digital data, which converted from analog data.
Data shown in table 2 was measured. Unsteady data of this table, NO.3 to No.15 and No.18 and No.19 were recorded to the data logger.
Three microphones (MIC1,2,3) were located in order to measure the sound pressure level (Data No.9 to 11). MIC1 was located about 1.5m ahead of the center of the rotor, MIC2 was located about 1.5m behind, and MIC3 was located 0.8m beside. MIC1 and MIC3 were located in order to measure advancing side BVI noise, and MIC2 located for retreating side BVI noise.

Table 2 Measurements

No.	Measured data	
1	Wind tunnel free stream data	temperature
2		static pressure
3	Rotor 6 component forces	drag force
4		side force
5		thrust force
6		rolling moment
7		pitching moment
8		yawing moment
9	Microphone output	MIC1 output
10		MIC2 output
11		MIC3 output
12	Blade surface pressure (No.1 blade)	lower surface pressure at 75% radius, 4% chord
13		lower surface pressure at 90% radius, 4% chord
14	Blade angles	flapping angle
15		lead-lag angle
16		collective pitch angle
17		cyclic pitch angle (longitudinal, lateral)

18	Active flap drive signal	input signal to piezoelectric actuator (No.1/No.2 blade)
19	Active flap deflection angle	Active flap potentiometer output (No.1/No.2 blade)

Test conditions

Test conditions are shown in Table 3.

Table 3 Test Conditions

Rotor revolution speed	800rpm
Thrust coefficient (C_T)	0.004
Rotor shaft angle(α_s)	1.0, 4.0 degrees (BVI test) -2.0, -5.0 degrees (vibration test)
Advance ratio (μ)	0.0 to 0.25 (BVI & vibration test without flap control) 0.12, 0.16 (BVI test with flap control) 0.07, 0.15 (vibration test with flap control)

Active flap actuation

As for the input waves for the active flap control actuation, both sine wave and rectangular wave were applied. Active flap deflection angle is defined as following equation and Fig 7 (positive trailing edge down).

(sine input wave)

$\delta_{AFC}=\delta_{0AFC}\sin(P_{AFC} \times \psi + \psi_{AFC})$

(rectangular input wave)

$\delta_{AFC}=\delta_{0AFC}\sin(P_{AFC} \times \psi + \psi_{AFC}) / |\sin(P_{AFC} \times \psi + \psi_{AFC})|$

Flap actuation parameters in above equations were as follows.

δ_{0AFC} (Active flap control amplitude):about 3 degrees

P_{AFC} (modulus of active flap control): 2/rev, 3/rev

ψ_{AFC} (Active flap control phase angle):

every 45 degrees from 0 to 315 degrees

(every 15 degrees from 210 to 330 degrees for some cases of BVI wind tunnel test)

Results and Discussions

BVI wind tunnel test

BVI wind tunnel test result First, we specified advance ratio condition in which BVI noise was significant by simple analysis. An example of this analysis is shown in Fig 8. Free stream flows left to right and the rotor is rotating anticlockwise in these figures, which are top view of rotor rotating. The tip vortex, shed from blade tip, flows left to right simply with the free stream velocity. BVI noise is considered to become significant, when the vortex interacts parallel with the blade at 90% radius as shown in Fig 8. By sweeping free stream velocity condition (advance ratio condition), advance ratio conditions in which BVI noise was significant were specified.

BVI wind tunnel test was conducted without active flap control in condition of various rotor shaft angle and advance ratio. Significant spiky peaks of BVI noise were measured in specified advance ratio condition (Fig 9).

As a result of 1/3 octave band analysis for sound pressure data of the wind tunnel test, 600Hz to 2000Hz band sound pressure level was enlarged in significant BVI noise conditions (Fig 10). So, we named this band sound pressure level “BVI sound pressure level”. We used it as the index for quantitative BVI noise estimation.

In the condition of rotor shaft angle 1.0 degree and advance ratio 0.12, BVI wind tunnel test was conducted with active flap control. Active flap actuation was applied according to the equation described previously. The results of “BVI sound pressure level” reduction are shown in Fig 11. Vertical axis shows the difference of BVI sound pressure level between flap control on and off. Advancing side BVI was reduced Max 3dB with active flap control (modulus of control: 2/rev, control phase angle: 285deg.). Retreating side BVI was reduced Max 2dB with active flap control (modulus of control: 2/rev, control phase angle: 0deg.). Fig 12 shows the BVI sound pressure level data of max BVI noise reduction case in comparison with same condition without active flap control. Spiky peaks of BVI noise at blade azimuthal angle about 66 degrees and about 246 degrees were weakened.

BVI noise reduction mechanism It is known that BVI noise level has much correlation with miss-distance between the blade and the tip vortex at interaction. It is considered that flap actuation has influence on vertical position of the tip vortex and that the BVI noise is much reduced when miss-distance between the blade and the tip vortex is enlarged with flap actuation. So we specified vertical position of the tip vortex with two different approaches as follows.

A. The study with CAMRAD II The conditions of the CAMRAD II study were a little different from that of the wind tunnel test. The advance ratio condition was as same as the wind tunnel test, but the rotor shaft angle was set to more nose up condition than the wind tunnel test. It is because the CAMRAD II is considered to predict the tip vortex position lower. As the result of estimation by CAMRADII in the rotor shaft angle condition where significant BVI noise was measured in the wind tunnel test, specified vertical position of the tip vortex was too low and had too much distance from blade to induce significant BVI noise. The wake model of this study was single trailer model.

B. The "simple study" to predict vertical position of the tip vortex The other approach to predict vertical position of the tip vortex was the "simple study" as following. The blades and these trailing edge flaps are assumed to have effect on the tip vortex position at following 4 events before the blade and the tip vortex interaction in case of advancing side BVI in the conducted wind tunnel condition (Fig 13).

1. When the tip vortex generates.
2. When following blade crosses the tip vortex at first time
3. When following blade crosses the tip vortex at second time
4. When following blade crosses the tip vortex at third time

Active flap deflection angle at each event has influence on the tip vortex position. The active-flap-up makes the tip vortex upper than that of no active flap actuation and the active-flap-down makes lower than that of no active flap actuation at each event. Total effect of active flap at each event decides vertical position of the tip vortex at BVI.

Fig 14 shows trajectory of the tip vortex, which interacts parallel with the blade at 90% radius at azimuthal angle about 50degrees, estimated by CAMRAD II. The tip vortex, shed from a blade tip, is pushed down by the downwash when a blade crosses it. The tip vortex position changes upper or lower than that of no active flap actuation according to active flap position (up or down). The vertical position of the tip vortex changes by the active flap actuation at same situations where the active flaps are assumed to have effect on the tip vortex position in the "simple study". Fig 15 shows the specified vertical position of the tip vortex with two approaches as a function of control phase angle. The trends of two approaches correspond to each other. Fig 15 also shows the comparison between the specified vertical position of the tip vortex and BVI noise reduction result of the wind tunnel test. These trends vs. control phase angle correspond to each other. We predict that the tip vortex position was at the lowest and the miss-distance between the tip vortex and the blade at interaction was enlarged with the active-flap-down position in every event at the tip vortex generation and at three crossing point of the blade and the tip vortex. In addition rectangular wave control input makes active flap always down with maximum deflection angle at every flap effective event, so the BVI noise with active flap control by rectangular wave input was more reduced than that by sine wave input.

Rotor vibration wind tunnel test

In addition to the BVI wind tunnel test, the rotor vibration wind tunnel test was conducted.
First, the wind tunnel test was conducted without active flap control in various conditions of advance ratio and rotor shaft angle. Fig 16 shows the result of this test. Fluctuation of thrust force coefficient (dC_T) was estimated as following equation (other fluctuations of coefficient were estimated by the same way).

$$dC_T = \sqrt{ave[\{C_T(\psi) - ave(C_T(\psi))\}^2]}$$

, where ave(x) is the function of average

Advance ratio 0.07, 0.15 and rotor shaft angle -2.0 degrees were selected for the conditions of the rotor vibration wind tunnel test with active flap control, because the rotor vibration were locally maximum in these conditions.
Rotor vibration wind tunnel test with active rotor control was conducted. Active flap actuation was applied according to the equation described previously. Fig 17 shows the result of the test, significant rotor vibration reduction was achieved with 2/rev control and reduction of dC_T(Fluctuation of thrust force coefficient) was about 14%.
Fig 18 shows dC_T reduction in relation to control phase angle(ψ_{AFC}). Rotor vibration of dC_T were reduced when control phase angles were 270 degrees to 315 degrees. Control phase angle was estimated as an important parameter for rotor vibration reduction. This effective control phase angles for rotor vibration reduction corresponded to that for BVI noise reduction. It is different from the result of past studies (e.g. HART (Ref 4)). The reason is not clear in the present circumstance, but further investigation will be done in future.

Concluding Remarks

Active control rotor was improved and estimated the ability to reduce the BVI noise and vibration by the low speed wind tunnel test.

BVI Noise Reduction with Active Control Flaps

- ✓ Advance ratio conditions with significant BVI noise level were estimated.
- ✓ The maximum BVI noise reduction of 3dB was achieved by Active Control Flaps.
- ✓ The mechanism of BVI noise reduction estimated with CAMRAD II and with other additional analysis has a correlation with the data of the wind tunnel test.

Vibration Reduction with Active Control Flaps

- ✓ Advance ratio conditions with vibration level at local maximum were estimated.
- ✓ The vibration level reduced about 14% (maximum) by Active Control Flaps.

- ✓ Effective control phase angles for vibration control corresponded to that for BVI noise reduction.

References

(1) Nakao, M., Uchiyama, N., Maeda, I., Hattori, K., Saito, S., Aoyama, T. and Kondo, N., “Research for the BVI noise reduction using the Blade Active Control,” Aircraft symposium 2003.

(2) Nakao, M., Uchiyama, N., Maeda, I., Saito, S., Aoyama, T. and Kondo, N., “On Helicopter BVI Noise Prediction,” NAL SP-57 2003.

(3) Hattori, K., Nakao M., Uchiyama, N., Yoshimoto, M., Saito, S. and Kondo, N., “Research for the BVI noise reduction using the Blade Active Control,” 30th European Rotorcraft Forum 2004.

(4) Splettstoesser, W. R., Kube, R., Wagner, W., Seelhorst, U., Boutier, A., Micheli, F., Mercker, E. and Pengel, K. “Key results from a higher harmonic control aeroacoustic rotor test (HART),” J. of the American Helicopter Society, 42 (1), 1997

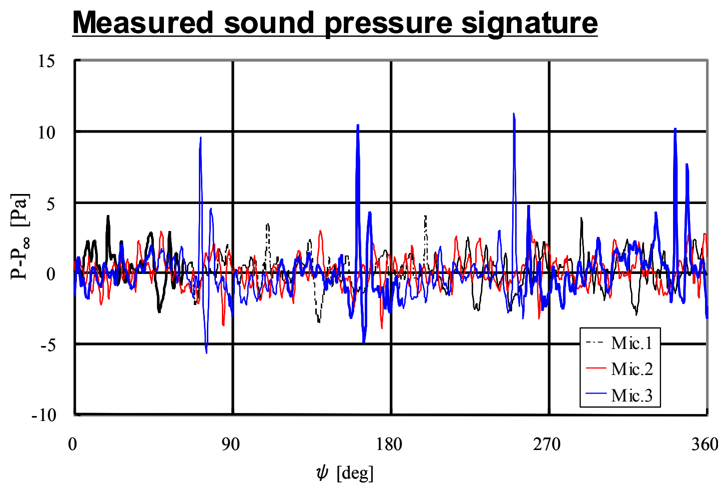


Fig 1(a) Measured BVI sound pressure signature with conventional blade rotor

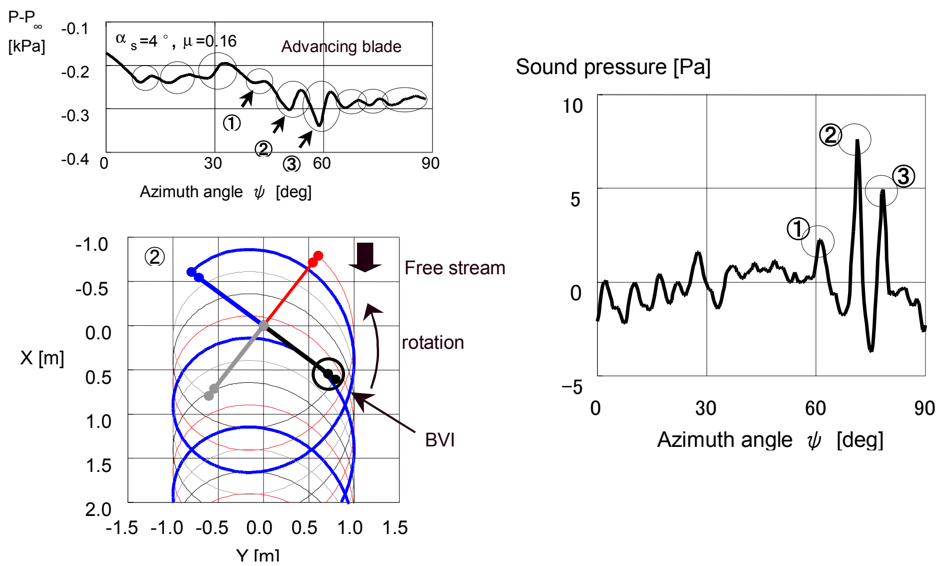
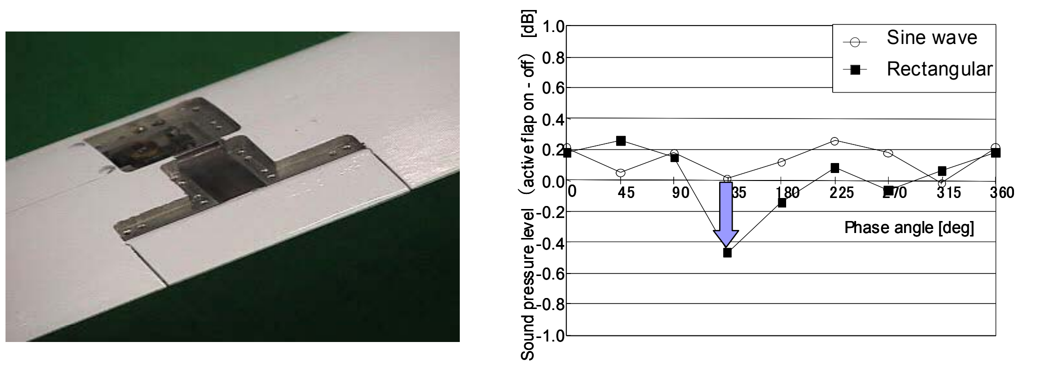


Fig 1(b) Sound pressure and blade surface pressure histories under interaction



(advancing side BVI noise reduction(2/rev control))

Fig 2 Firstly developed active flap model rotor and its effect for BVI noise reduction

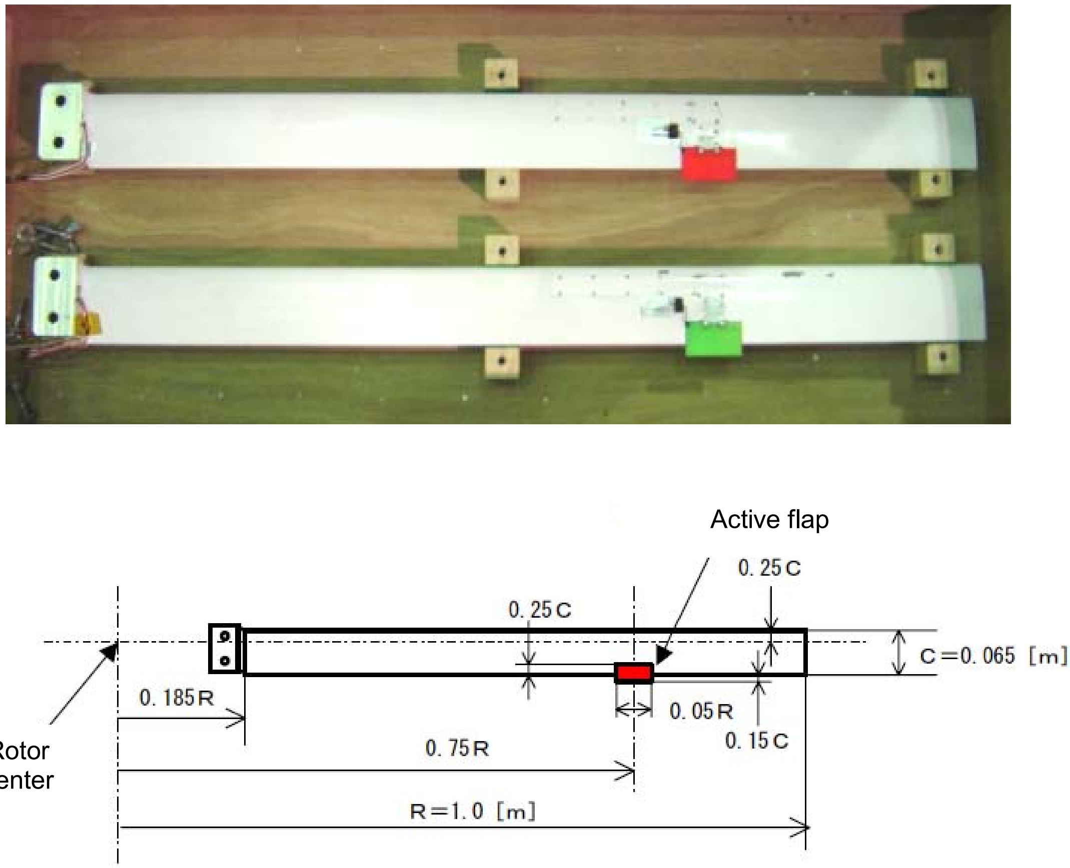


Fig 3　Active flap blade model

Fig 4　JAXA 6.5m x 5.5m Low speed wind tunnel

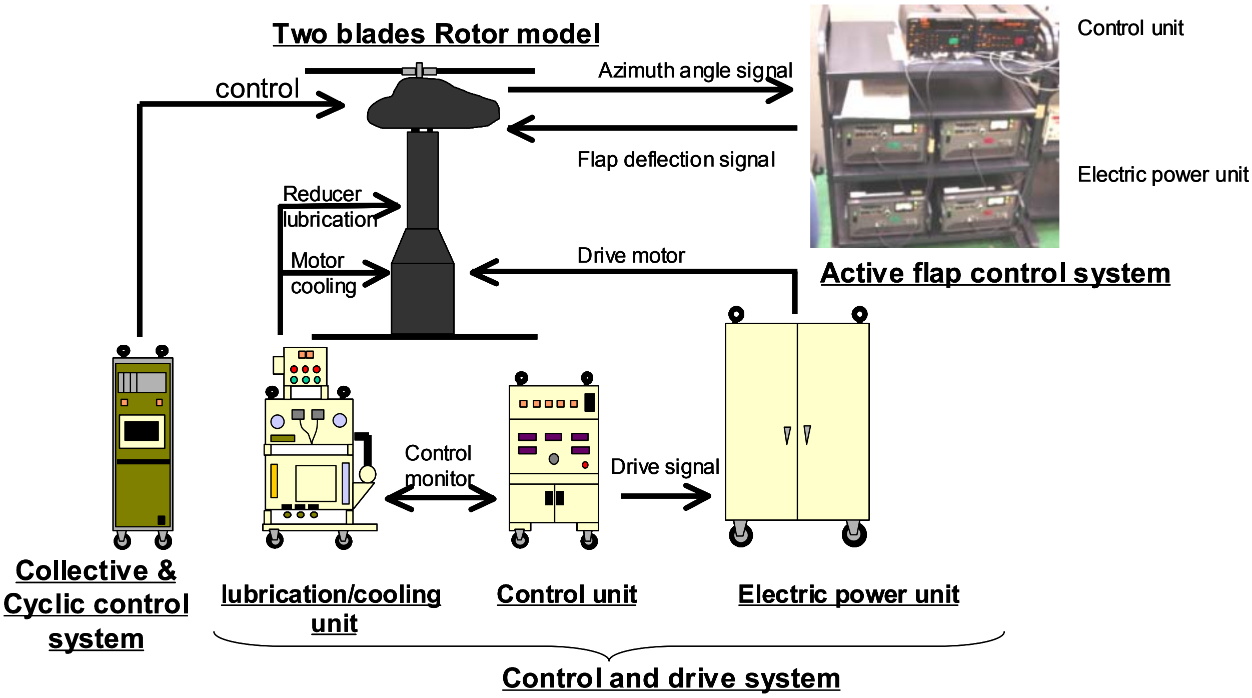


Fig 5　Rotor rotation system description

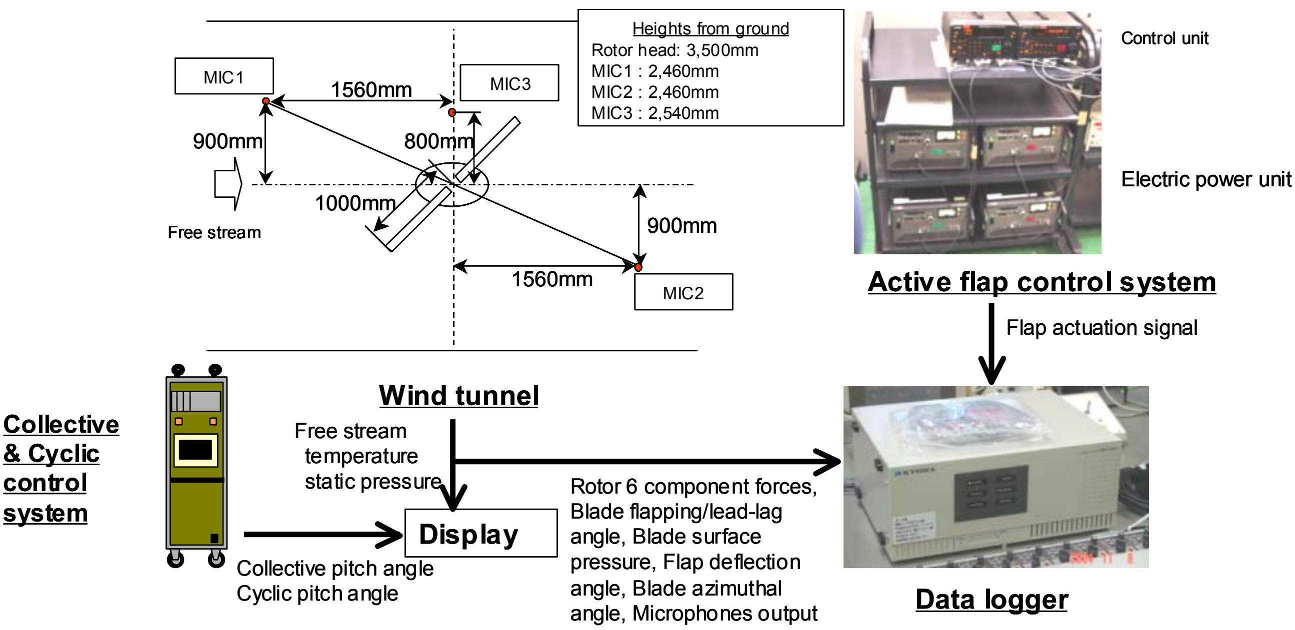
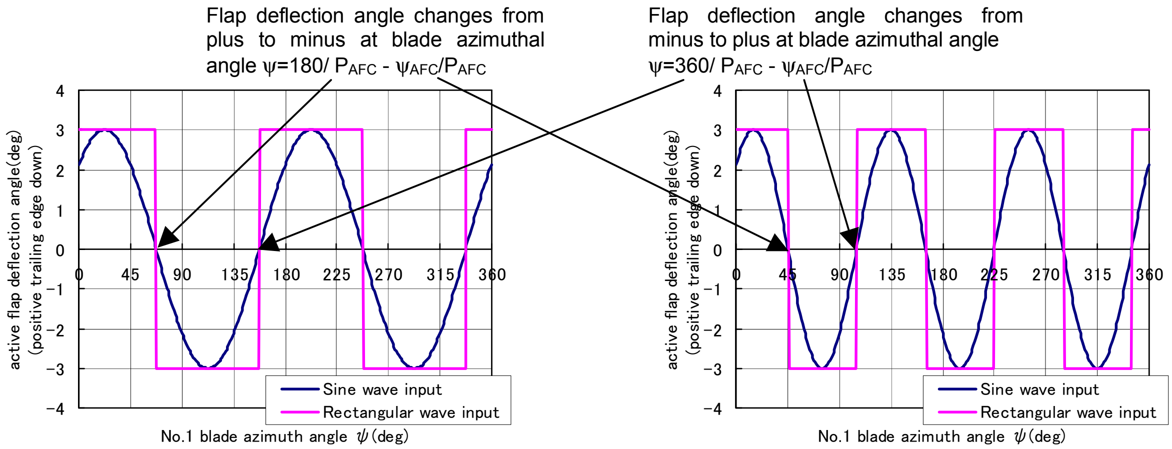
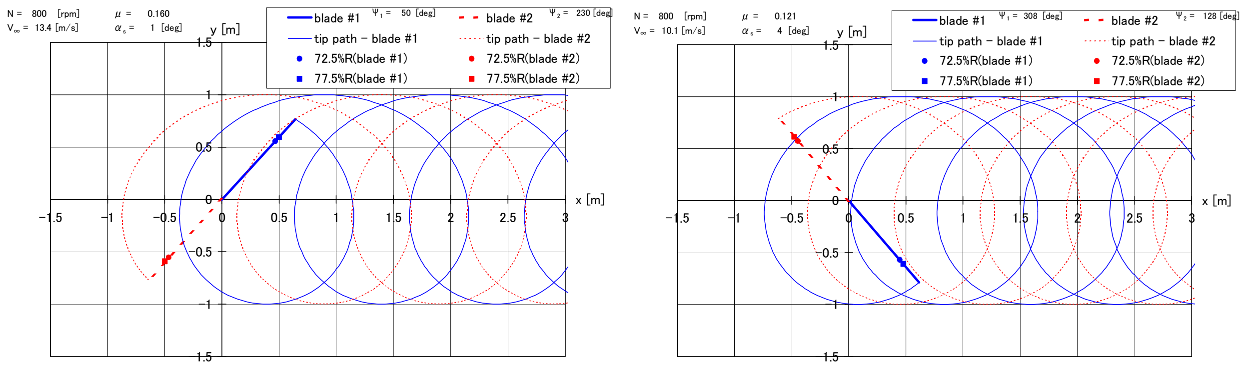


Fig 6　Measurement system description



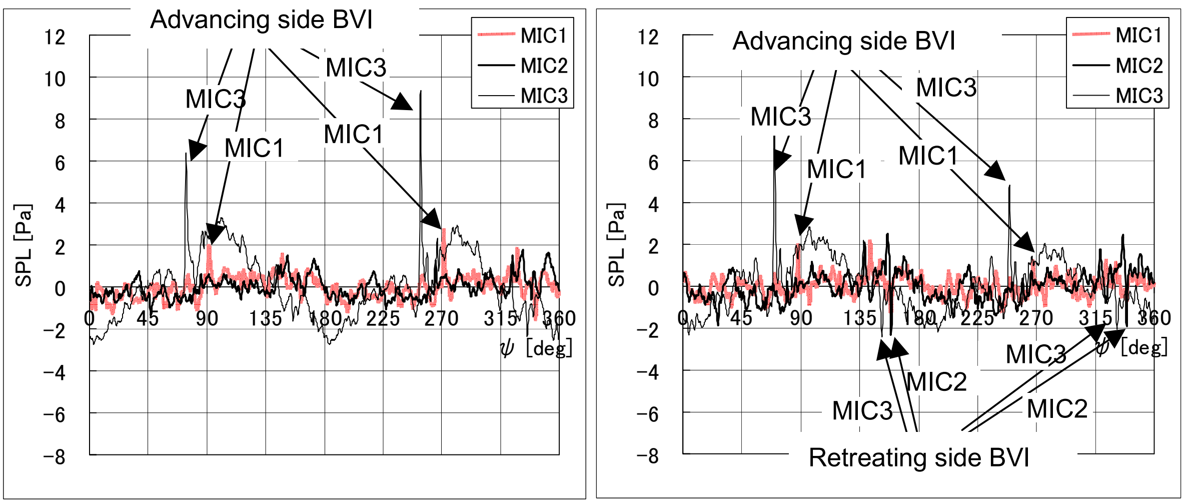
example: P_{AFC}=2/rev, ψ_{AFC}=45deg. example: P_{AFC}=3/rev, ψ_{AFC}=45deg.

Fig 7 Input wave for active flap control actuation



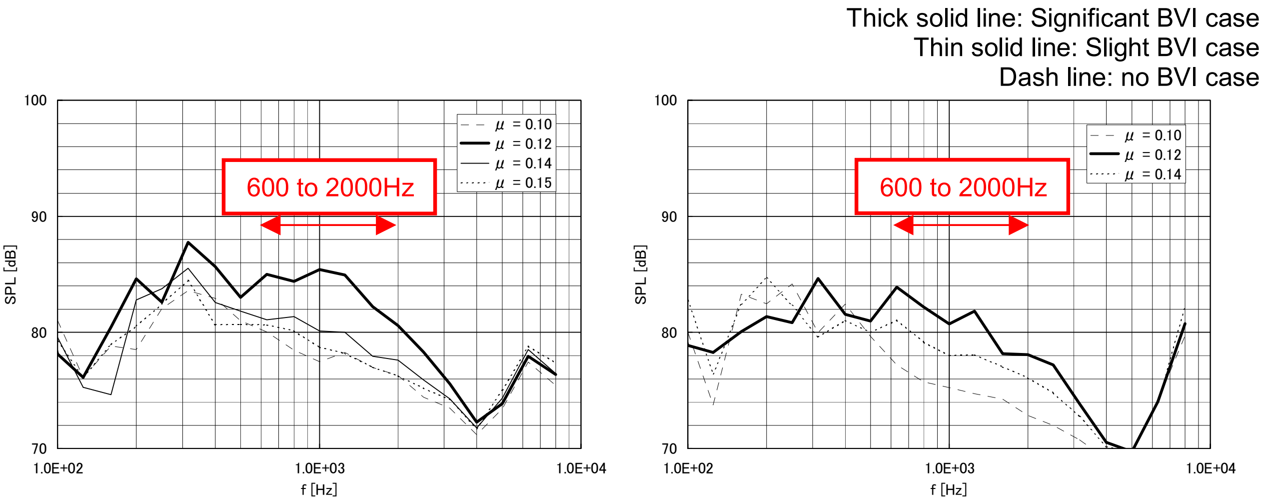
μ=0.16, Advancing side BVI μ=0.12, Retreating side BVI

Fig 8 Specification of advance ratio condition where BVI noise is significant



α_s=1deg., μ=0.16, C_T=4.0 x 10^{-3} α_s =4deg., μ=0.12, C_T=4.0 x 10^{-3}

Fig 9 Measured BVI sound pressure



Advancing side BVI (MIC3) Retreating side BVI (MIC2)

Fig 10 1/3 octave band analysis of BVI [α_s =4deg., μ=0.12, C_T=4.0 x 10^{-3}]

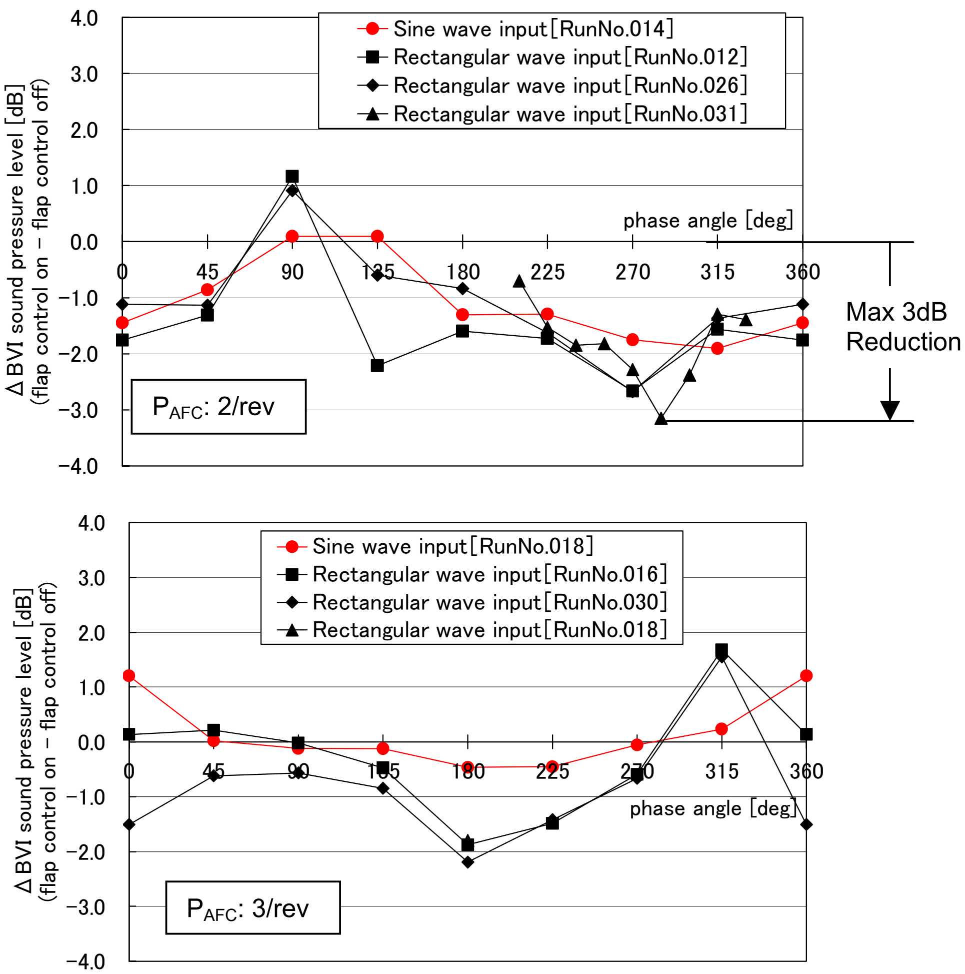


Fig 11(1) Reduction of BVI noise with active flap control(advancing side BVI)
[α_s =4deg., μ=0.12, C_T=4.0 x 10^{-3}]

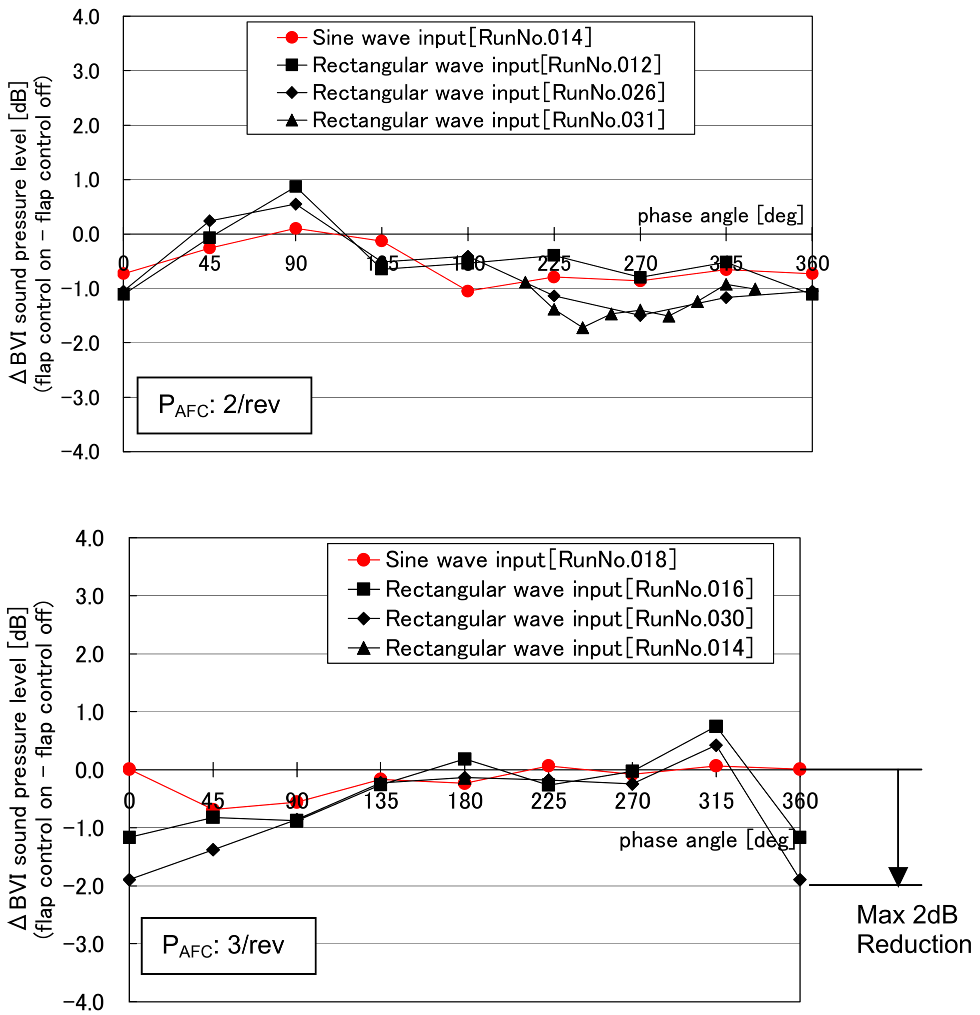
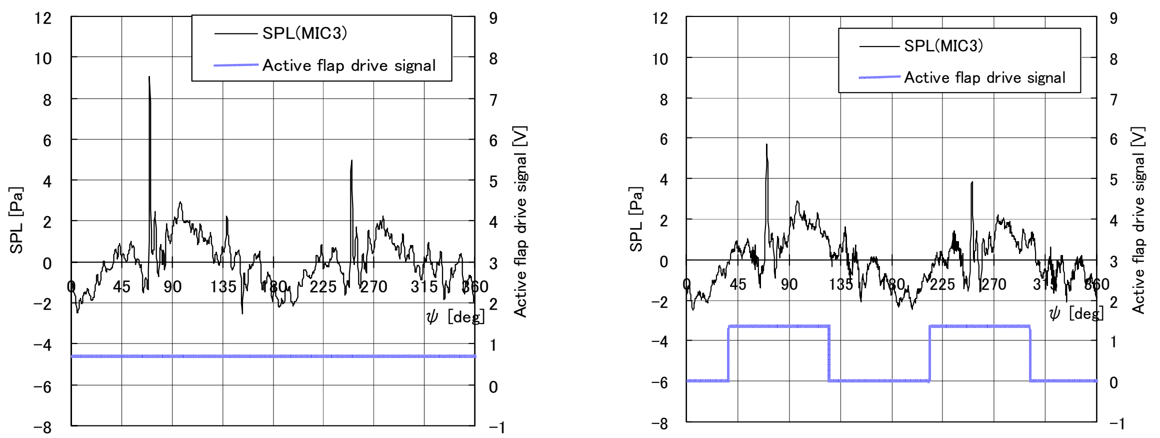


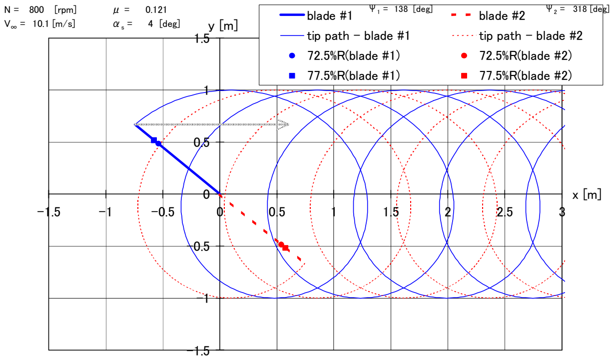
Fig 11(2) Reduction of BVI noise with active flap control (Retreating side BVI)
[α_s =4deg., μ=0.12, C_T=4.0 x 10^{-3}]



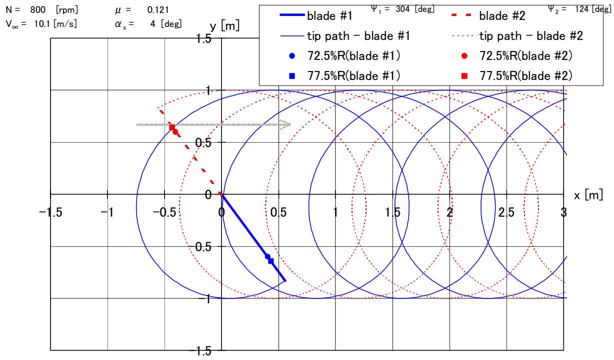
without active flap control

max BVI noise reduction case
with active flap control(P_{AFC}: 2/rev, ψ_{AFC}: 285 deg.)

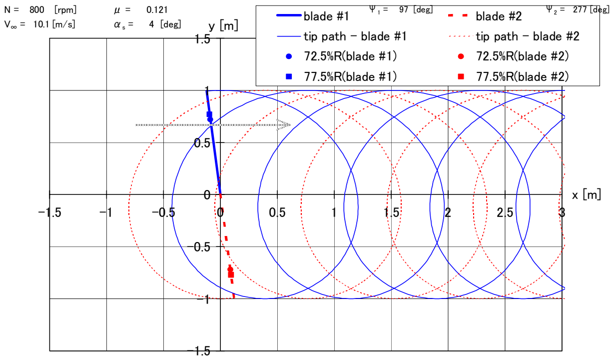
Fig 12 BVI sound pressure comparison
[α_s =4deg., μ=0.12, C_T=4.0 x 10^{-3}]



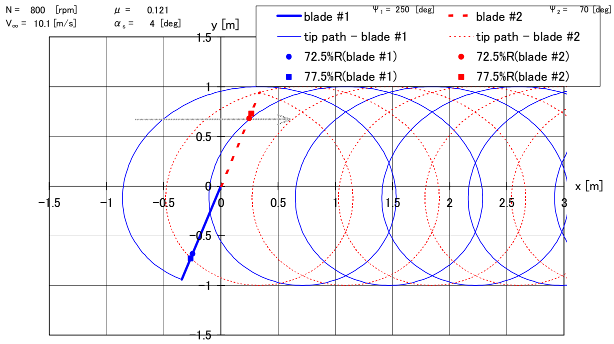
1. The tip vortex generates



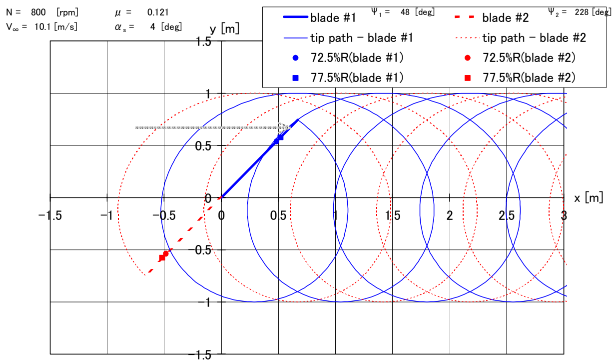
2. First encounter of the following blade and the tip vortex



3. Second encounter of the following blade and the tip vortex



4. Third encounter of the following blade and the tip vortex



5. blade and tip vortex interaction

Fig 13 The events where active flaps have effect the position of the tip vortex, which interacts with the blade of 90% radius (advancing side BVI).

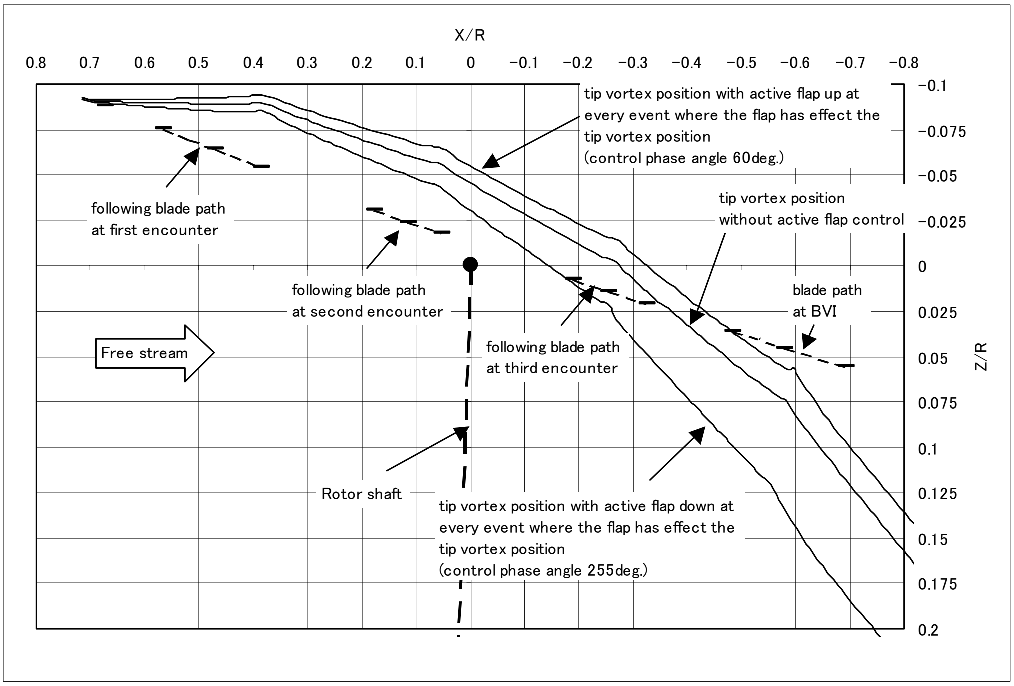


Fig 14 Trajectory of the tip vortex (side view)
(estimated with CAMRADII, advancing side, 2/rev control)

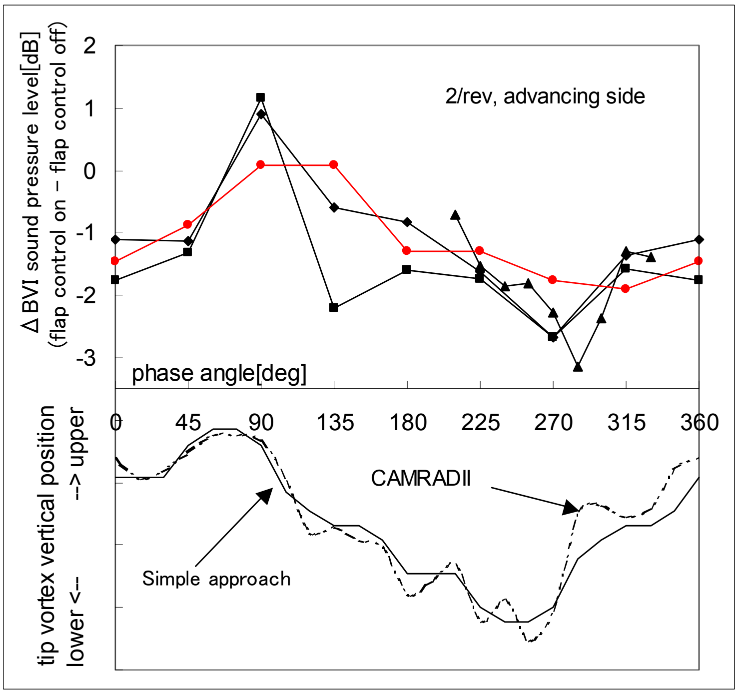


Fig 15 Specified tip vortex vertical position as function of phase angle,
in comparison with BVI noise reduction result of the wind tunnel test
(advancing side, 2/rev control)

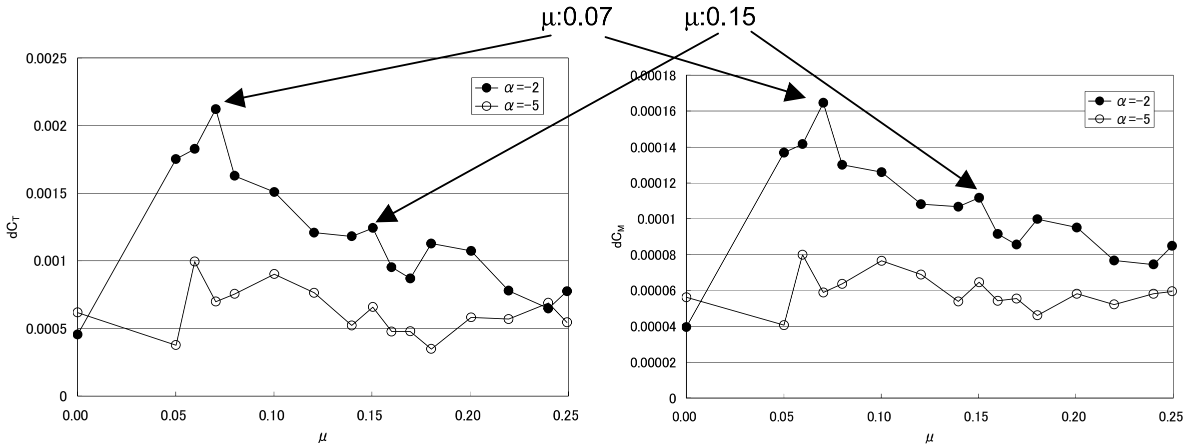


Fig 16 Result of Rotor vibration wind tunnel test without active flap control
(left: dC_T(Fluctuation of thrust force coefficient), right: dC_M(Fluctuation of pitching moment coefficient))

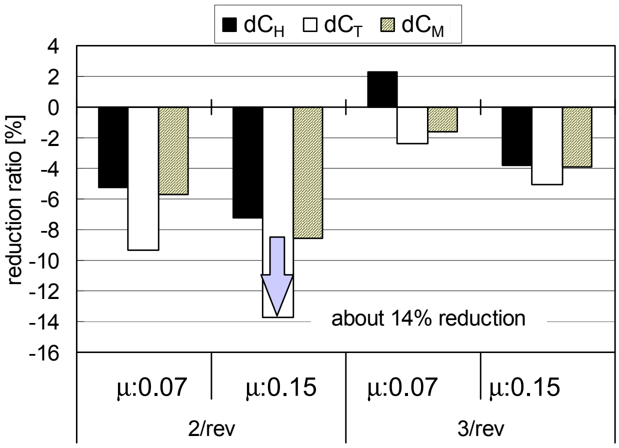


Fig 17 Reduction of vibration level with flap actuation

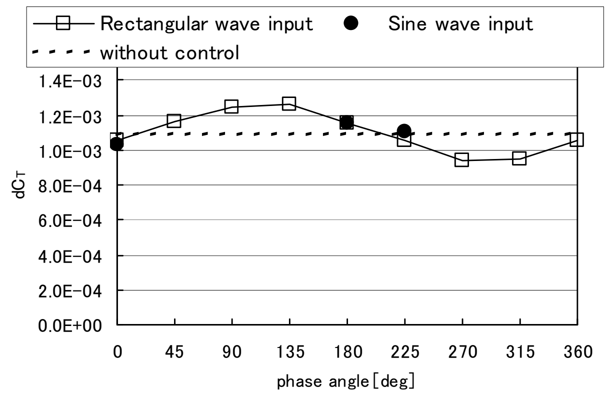


Fig 18 Relation between dC_T and control phase angle