A STUDY OF CLOSED LOOP CONTROL FOR BVI NOISE REDUCTION BY MULTIPLE PRESSURE SENSORS

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Abstract: A feedback controller utilizing global model with on-line identification for the BVI noise reduction is developed and evaluated in the wind tunnel test, where the active flap is used as a test bed of the active technique. This paper presents the research activities of this control law study applicable to active technique for rotor noise reduction.

Taking into consideration for application to real helicopter, the pressure fluctuation on the blade is used for control object, because this enables the control system to be made only by on-board sensors with BVI detection method. A control object reduced from multiple pressure sensors, which can more sufficiently represent the BVI phenomenon on the blade than by a single sensor, is proposed and its capability is studied experimentally using a 1-bladed rotor system. Strong correlation between the sound pressure level measured near the blade and the surface pressure fluctuation by multiple pressure sensors is observed. Also, from closed loop test results, good convergence for active flap phase of minimum pressure fluctuation and minimum SPL is obtained. It is concluded that the validation of the proposed control law is demonstrated and the control object utilizing multiple pressure sensors is promising.

1 INTRODUCTION

Helicopters are more and more requested to cope with the needs imposed by the society utilizing their unique and distinguished flight performance such as vertical take off/landing capability on various terrain conditions.

But due to the serious noise problems, especially BVI (Blade/Vortex Interaction) noise generated during approach/landing, helicopters can be operated comparatively on constrained conditions. BVI noise is very difficult to be reduced by passive techniques such as airfoil/tip shape design efforts, because the promising countermeasure is to expand the miss distance between rotor blades and tip vortex trajectory based on many research activities. [1-4]

The technological solutions, which can effectively alleviate BVI noise, have long been researched and developed so far. [5-8] In order to develop an active noise reduction technique, it is essential to invent a promising active devise. But it is also imperative to develop a control law applicable to active technique corresponding to time varying flight conditions and able to generate proper set of operating quantities such as frequency, amplitude and phase promptly. [9]

For the purpose of constructing a closed loop control law, we developed an elemental closed loop control law as the first step and evaluated by a wind tunnel tests in 2003 and 2004. [10] This control law utilizes the sound pressure measured by microphones as an input. Using the sound pressure as an input to the control law for noise reduction, it is necessary to install microphones on the aircraft or on the ground. The former may pick up the noise irrelevant to the BVI, and the latter needs the up-link infrastructure which transmits the measured sound pressure to the aircraft in the air. Therefore, the both seem to be inefficient and challenging because of requirement for other technical resolutions in the phase of practically applying to the helicopters.

We noticed and try to utilize the blade surface pressure as an input to the control law on this background to construct an efficient control system, because the BVI phenomenon is clearly characterized by abrupt temporal changes of the blade surface pressure which can be measured by pressure transducers installed on the blade as shown in the previous studies [11,12]. The performance of this proposed closed loop controller was evaluated in a wind tunnel test using 1-blade rotor system. It is demonstrated by this wind tunnel test that the control law utilizing the blade surface pressure successfully functioned to reduce BVI noise with sufficient convergence. [13]

For enhancing the closed loop control law, a control object reduced from multiple pressure sensors which can more sufficiently represent the BVI phenomenon on the blade than by a single sensor is proposed and its capability is studied experimentally using a 1-bladed rotor system. This paper describes this stage of the research activities for the control law study and its evaluation by a wind tunnel test performed in 2006.

2 OBJECTIVES

The objectives of this research are as follows:

1. Develop a control law for the active technique utilizing multiple pressure sensors to better represent the BVI phenomenon on the blade and to enhance the convergence of the control law.
2. Evaluate and demonstrate the capability of the proposed control law by a wind tunnel test.

3 CONTROL LAW

In order to evaluate BVI relief effect with respect to active flap phase, the pressure fluctuation index ΔCpmax which physically means the maximum value of the difference in the pressure coefficient between the successive ψ's is introduced and defined as shown in Ref.4, which is repeated below for convenience.

$$\begin{aligned}&\mathrm{Pr}\,essure\,Fluctuation\,Index: \Delta C_{p\max} = \max(\Delta C_p(\psi_i))\\&\Delta C_p(\psi_i) = C_p(\psi_i) - C_p(\psi_{i-1})\\&\psi_i - \psi_{i-1} = 0.9\,\mathrm{deg}.\\&C_p = \frac{P - P_s}{q}\end{aligned} \tag{1}$$

where

P : measured blade surface pressure
Ps : static pressure
q :dynamic pressure at 85%R as V_W=0m/sec, rotor speed=600rpm

The effect of active flap phase on ΔCpmax measured at the blade leading edge is shown in Fig.1 comparing with the sound pressure level. The correlation between the sound pressure level and ΔCpmax with respect to active flap phase can be seen. Active flap phase range around 160deg. simultaneously has the largest rotor noise reduction indicated by the sound pressure level and the maximum BVI relief effect represented by Δ Cpmax. This characteristic of ΔCpmax with respect to active flap phase is useful as an input to the control law, because the BVI can be detected and evaluated by only on-board sensors.

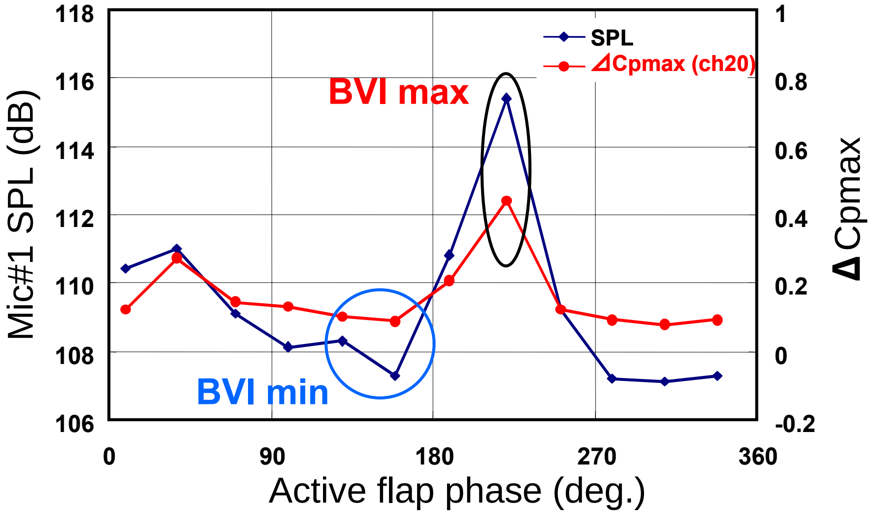

Figure 1: Correlation between ⊿Cpmax and SPL w.r.t. Active Flap phase

In this study, a global model is used to represent the relationship between the plant and the control input, although a local model also can be defined for this study. Because it is shown by the wind tunnel test that the correlation between ΔCpmax and active flap phase as shown in Fig.1 is stable so that the transfer function can be assumed invariant over the control cycles. This yields the following T-matrix global model:

$$Z_n = Z_0 + T\theta_n \tag{2}$$

θ_n represents active flap input vector consisting of frequency, amplitude and phase. Therefore, the number of the components in this vector is generally double the number of the frequencies superposed to the blade pitch control to express amplitude and phase of each frequency of active flap. In this study, however the 1-bladed rotor system, which is used for the control law evaluation, can only automatically change active flap phase because of the mechanical limitation.

Although this enables θ_n to be a scalar not a vector, we proposed the following transformation for θ_n to make use of the empirically obtained sinusoidal property of Δ Cpmax with respect to active flap phase shown in Fig.1, which is to avoid redundancy for solving θ_n.

$$\theta \equiv \begin{bmatrix} \cos\phi_{AF} \\ \sin\phi_{AF} \end{bmatrix} \tag{3}$$

where

ϕ_{AF} : active flap phase

Making use of the correlation between sound pressure and blade surface pressure as shown in Fig.1, the quadratic performance function for the control law is proposed to utilize blade surface pressure instead of sound pressure as follows:

$$J = Z_n^T W_z Z_n + \theta_n^T W_\theta \theta_n + \Delta\theta_n^T W_{\Delta\theta} \Delta\theta_n \tag{4}$$

where

$Z_n = \Delta Cp_{\max}$
W_Z : weighting matrix for Z
θ_n : control input representing active flap frequency, amplitude and phase
W_θ : weighting matrix for θ
$\Delta\theta_n$: the difference of θ between successive control cycles
$W_{\Delta\theta}$: weighting matrix for $\Delta\theta_n$

Furthermore, in order to quantify the plant property, two kinds of identification are used. The first one is off-line identification by the least square method to identify only initial values of transfer matrix T and Z_0. The other one is on-line identification by Kalman filter to identify the transfer matrix on each control cycle.

Solving the performance function to get $\partial J / \partial \theta_n = 0$ applying the global model with on-line identification:

$$\theta_n = (\hat{T}_{n-1}^T W_z \hat{T}_{n-1} + W_\theta + W_{\Delta\theta})^{-1} \left\{ (\hat{T}_{n-1}^T W_z \hat{T}_{n-1} + W_{\Delta\theta}) \theta_{n-1} - \hat{T}_{n-1}^T W_z Z_{n-1} \right\} \tag{5}$$

$$\hat{T}_n = \hat{T}_{n-1} + (Z_n - \hat{Z}_{0n-1} - \hat{T}_{n-1}\theta_n) K_n^T$$

$$\hat{Z}_{0n} = \hat{Z}_{0n-1} + (Z_n - \hat{Z}_{0n-1} - \hat{T}_{n-1}\theta_n) K_{zn}$$

$$K_n = P_n \theta_n / r$$

$$P_n = M_n - M_n \theta_n \theta_n^T M_n / (r + \theta_n^T M_n \theta_n)$$

$$M_n = P_{n-1} + Q$$

where

K_n : Kalman gain
P_n : covariance of error after measurement
M_n : covariance of error before measurement
Q : covariance of process noise

r : covariance of measurement noise

$\wedge$: estimated value

The cycle to generate θ_n is repeated until the performance function sufficiently converges.

In order to obtain converged θ_n in the form of Eqn.(3), the following consideration is proposed. Taking into account measurement noise, the relationship between the plant and the control input is slightly modified,

$$Z_n = Z_0 + T\theta_n + v_n \tag{6}$$

where

v_n : measurement noise

Substituting Eqn.(6) into Eqn.(5), we have

Transfer state:

$$\theta_n = (\hat{T}_{n-1}^T W_z \hat{T}_{n-1} + W_\theta + W_{\Delta\theta})^{-1} \left\{ \hat{T}_{n-1}^T W_z \left(\hat{T}_{n-1} - T \right) \theta_{n-1} + W_{\Delta\theta} \theta_{n-1} - \hat{T}_{n-1}^T W_z \left(Z_0 + v_{n-1} \right) \right\} \tag{7}$$

Making $\hat{T}_{n-1} = T$,

Steady state:

$$\theta = \left(T^T W_z T + W_\theta + W_{\Delta\theta} \right)^{-1} \left\{ W_{\Delta\theta} \theta - T^T W_z \left(Z_0 + v \right) \right\} \propto \left(T^T W_Z T + W_\theta + W_{\Delta\theta} \right)^{-1} T^T W_Z v \tag{8}$$

Studying the coefficient matrices of v in Eqns.(7) and (8), it is inferred that the conditions described in Eqn.(9) assures the existence of θ_n without divergence by making the coefficient matrices of v diminish as the control cycle proceeds.

$$\begin{aligned} \left\| G_t \right\| &\equiv \left\| \left(\hat{T}_n^T W_z \hat{T}_n + W_\theta + W_{\Delta\theta} \right)^{-1} \hat{T}_{n-1}^T W_z \right\| < 1 \\ \left\| G_s \right\| &\equiv \left\| \left(T^T W_z T + W_\theta + W_{\Delta\theta} \right)^{-1} T^T W_z \right\| < 1 \end{aligned} \tag{9}$$

where

G_t : coefficient matrix for v_{n-1} for transfer state (Eqn.(7))

G_s : coefficient matrix for v for steady state (Eqn.(8))

Satisfying Eqn.(9), it is necessary to select the combination of large W_θ and small $W_{\Delta\theta}$, which is searched practically by trial and error in the wind tunnel test to evaluate the proposed control law.

4 WIND TUNNEL TEST SET UP

This wind tunnel test is performed to study the performance of the control law applied to the 1-bladed rotor system which has active flap as an noise reduction active technique.

4.1 Model description

The rotor system is set up in the 2.5x2.5m low speed wind tunnel of Kawada Industries, Inc. using a one-bladed rotor system as shown in Fig.2. The main features of this rotor system are shown in Table 1.

The active flap installed on the blade and its schematic drawing for the drive mechanism is shown in Fig.3. The main features of the active flap are also shown in Table 1. The rotor is driven by the electric motor, Rotor drive motor, and the active flap mechanism is driven by the separate electric motor, HHC motor. These two motors are synchronized electrically by the encoder installed in each motor in order to make the proper active flap phase angle shifting with respect to the rotor azimuth angle.

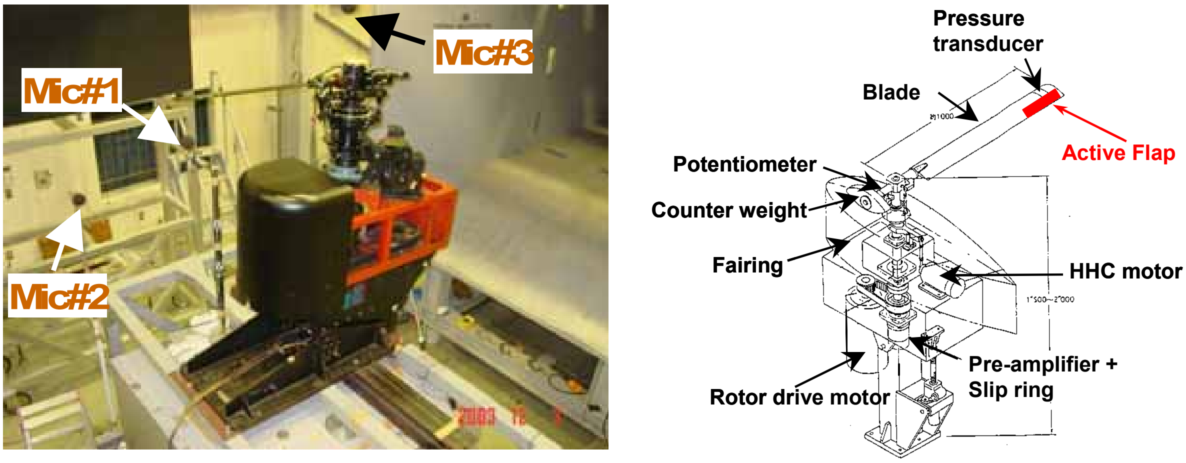

Figure 2: One-bladed rotor system

Table 1 Features of rotor system and Active Flap

Hub type	rigid in flap and lead-lag
Rotor radius	1m
Blade chord	0.12m
Airfoil	NACA0012
Blade plan form	Rectangular
Rotor rpm	1200rpm (max)
Collective pitch	-5 to +15deg.
Cyclic pitch	0deg. (fixed)
Active Flap	Amp. : 30deg.(max)
	Freq. : 20Hz
	Phase : variable
	Chord : 25%c
	Span : 80 ~ 98%R

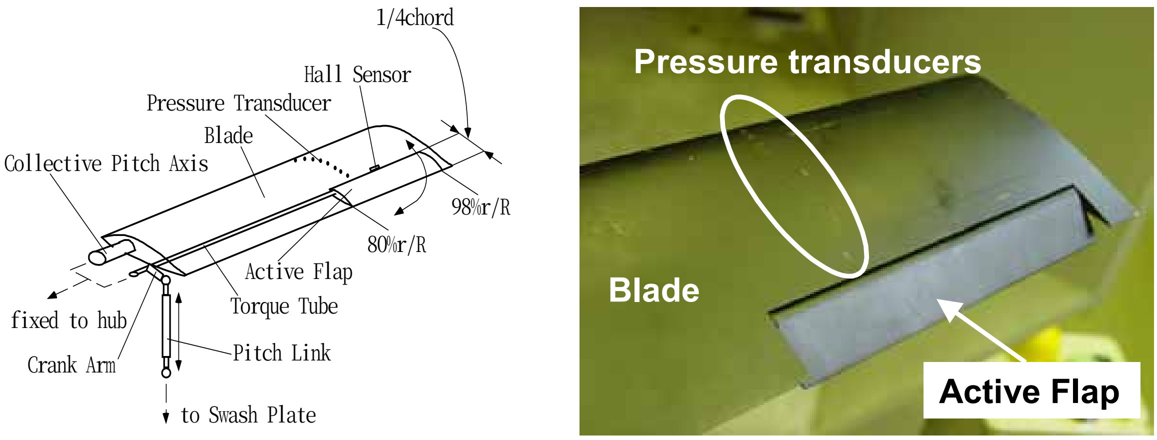

Figure3: Active Flap installation

The vertically reciprocating movement of the swash plate for the active flap actuation is generated by the lever and crank mechanism which is driven by the eccentric disk installed on the output shaft of the active flap motor. This movement is transmitted to the pitch link which makes the rotary reciprocation of the torque tube via. the crank arm and the active flap installed on the other end of the torque tube is oscillated.

The pressure transducers are flush mounted on the blade as shown in Fig. 3, except for the active flap portion because of difficulty for wiring between non-oscillating blade and oscillating active flap. The distribution of pressure transducer is shown in Fig.4.

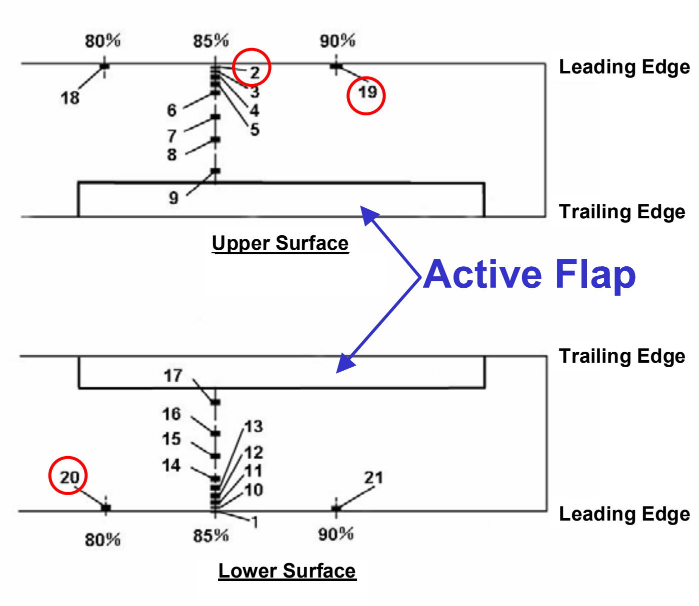

Figure4: Pressure transducer distribution

4.2 Test condition

The test condition is as follows;

- Wind tunnel
    - Wind speed : 18m/sec
    - Test section : open
- Rotor system
    - Rotor speed : 600rpm (10Hz)
    - Collective pitch angle : 8.3deg
    - Cyclic pitch angle : 0deg
    - Rotor shaft angle : 2deg. nose up
- Active Flap
    - Frequency : 20Hz (2/rev)
    - Amplitude : 18deg.
    - Phase : 0 ~ 360deg.

4.3 Measurement

The schematic view of the whole measurement system is shown in Fig.5. The blade surface pressure distribution is measured by pressure transducers mainly located on the 85%R position of the upper and lower sides of the blade. Two microphones are set in the wind tunnel as shown in Fig.2 to evaluate the active flap effect for rotor noise reduction. The active flap deflection is detected by a Hall sensor installed at the mid span of the active flap and a potentiometer installed at the center of the rotor hub measures blade pitch angle. A pulse encoder generating 1/rev signals is installed beneath the rotor plane at about ψ=0deg.

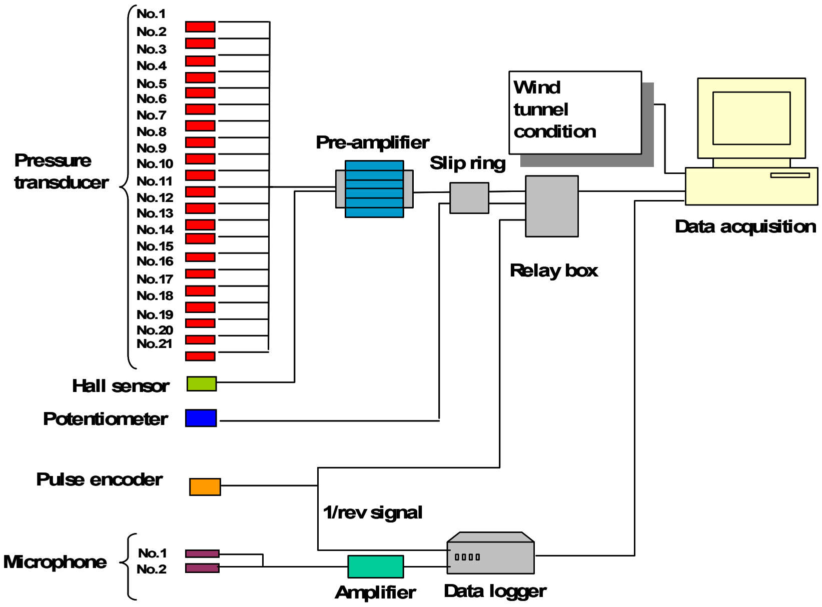

Figure 5: Measurement system

4.4 Data acquisition/procession

The above mentioned measured items are acquired simultaneously and processed with 1/rev output signals of the pulse encoder in order to be related with the rotor azimuth angle. The sample rate for microphones is set at 10kHz and that for the others such as the blade surface pressures and Hall sensor is set at 4kHz by the limitation of data storage.

All the data acquired in the time domain are ensemble averaged of 40 revolutions equal to 4sec. in order to eliminate the random noise from the measured data and to make the periodical aeroacoustic and aerodynamic characteristics caused by rotor revolution clear.
The other details of the data acquisition/procession are described in Ref.14.

4.5 Control system for closed loop operation

Fig.6 shows the control system in the wind tunnel testing for evaluating the closed loop control law, which was conducted using a 1-bladed rotor system. Because of the mechanical limitation that the rotor system can change only active flap phase automatically, the closed loop control law is applied to generate active flap phase only in this study.

The blade pressure signals coming from the three sensors are conditioned on the rotating frame before transmitted to the non-rotating frame by a slip ring where the signal can be easily contaminated electrically. On the non-rotating frame, the conditioned blade pressure signals are ensemble averaged to minimize the electrical random noise in order to be sufficiently used as an input to the control law. Compromising between the time consumed and the data quality, 10 rotor revolutions for blade pressure signal ensemble averaging is selected based on measured data of 1,3,5,10and 20 revolutions in this study.

Then, the BVI index, ΔCpmax, is generated by processing the ensemble averaged blade pressure signal in a time domain and used as an input to the control law which outputs active flap phase. This control cycle is repeated until the performance function sufficiently converges.

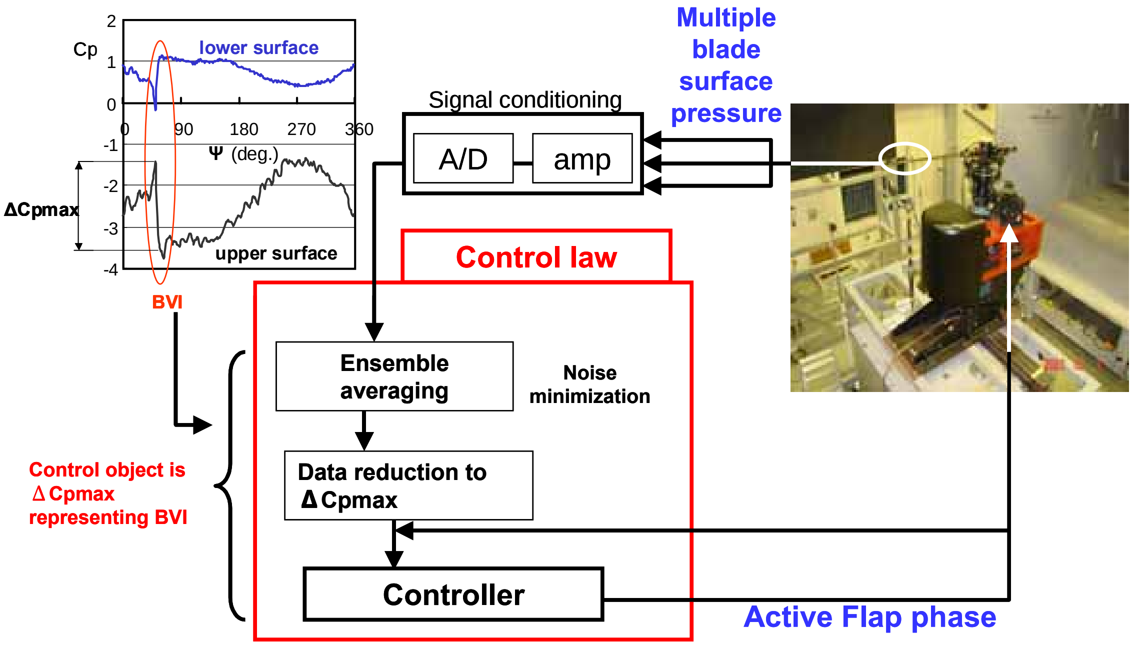

Figure 6: Control system in wind tunnel testing

5 RESULTS AND DISCUSSION

The wind tunnel test for the control law evaluation is carried out using two kinds of control input, such as 1)ΔCpmax by a single pressure sensor and 2)the compound ΔCpmax by multiple pressure sensors in order to compare the performance of the two kinds of the control input.

5.1 Control input = ΔCpmax by a single pressure sensor

Fig.7 shows the test results of the control law utilizing ΔCpmax by a single pressure sensor. The selected pressure sensors are ch2, 19 and 20, because they are representative of BVI and active flap effect on BVI suppression to be located in the vicinity of the leading edge of the blade as shown in Fig.4.

The open loop test was conducted at first to investigate the target value of active flap phase which can minimize BVI noise as shown in the left side figures of Fig.7 comparing the properties of ΔCpmax and SPL. These figures indicate that the substantial correlation between ΔCpmax and SPL can be seen on each sensor, although some minor discrepancy in active flap phases on ch19 and 20 regarding where ΔCpmax and SPL have minimum values. It can be seen that the target value of active flap phase =158deg to get maximum noise reduction on this wind tunnel test condition where active flap phase generated by the closed loop control law is supposed to converge.

Then, the closed loop test utilizing ΔCpmax as an input generated by each pressure sensor is carried out to evaluate the performance of the closed loop control law as shown in the right side figures of Fig.7. These figures show the converging trend of ΔCpmax to the target value obtained by the open loop test along with SPL tendency which is not control by the control law but is only monitored for confirming that ΔCpmax converges to the value where SPL simultaneously converges to its minimum value. ΔCpmax and SPL of ch20 converge to each target value, however, those of ch2 and 19 do not converge completely.

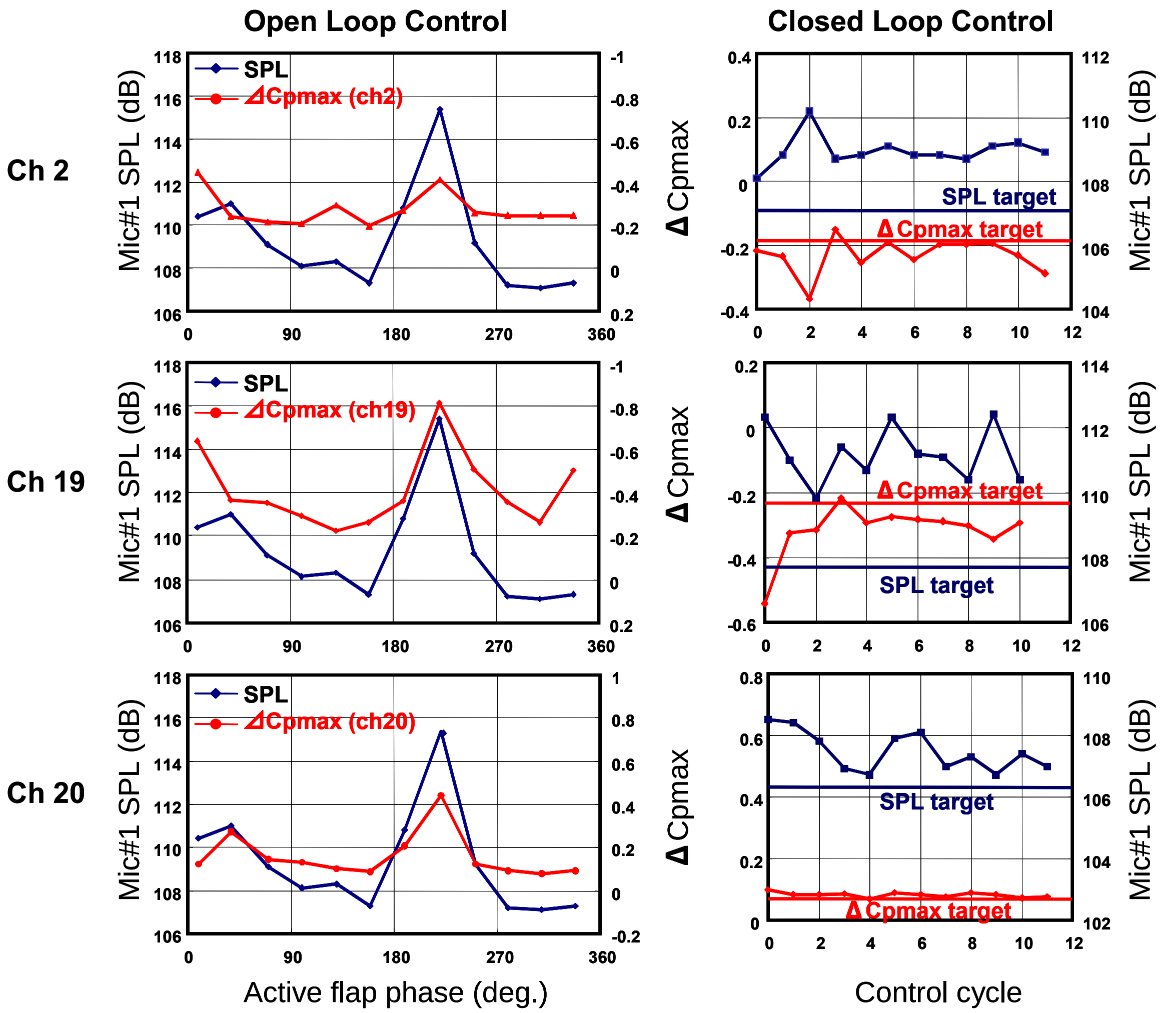

Figure 7: Wind tunnel test result of closed loop control with ⊿Cpmax by a single pressure sensor

5.2 Control input = Compound ΔCpmax by multiple pressure sensors

The testing procedure is the same as that utilizing ΔCpmax by a single pressure sensor mentioned above. Fig.8 shows the wind tunnel test result of the closed loop control which utilizes the compound ΔCpmax as an input of the control law. In this study, the compound ΔCpmax is obtained by arithmetic average as shown in Eqn.(10) as an example procedure.

$$Compound\ \Delta Cp_{\max} = \frac{\Delta Cp_{\max}(ch2) + \Delta Cp_{\max}(ch19) + \Delta Cp_{\max}(ch20)}{3} \qquad (10)$$

Fig.9 shows that the correlation between the compound ΔCpmax and SPL can be seen better than that of the single pressure sensor ΔCpmax as shown in Fig.8 and that SPL and ΔCpmax converges to the target values obtained by the open loop test. The converging history also has a good property to make fully use of the noise reduction capability of the active flap.

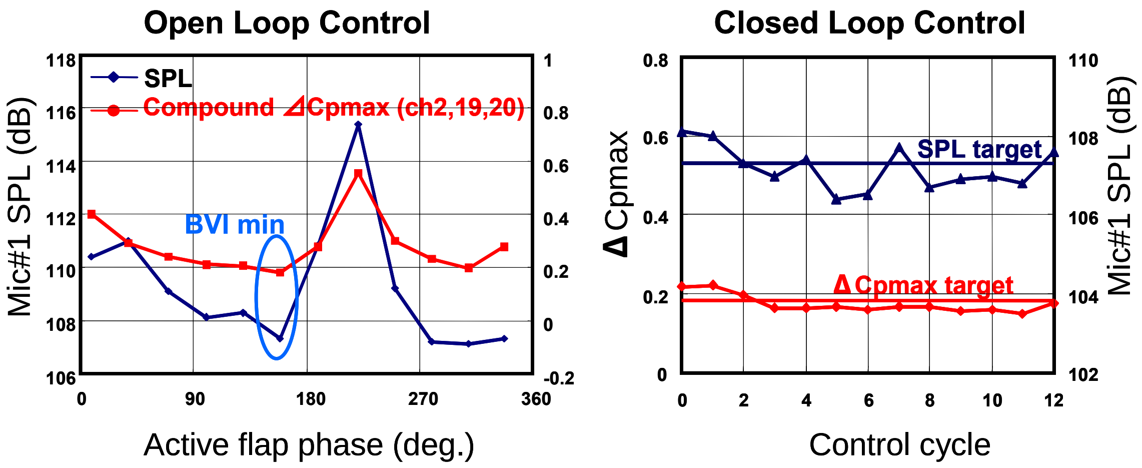

Figure 8: Wind tunnel test result of closed loop control with compound ⊿Cpmax

6 CONCLUSIONS

In this study, the blade surface pressure Fig.9 shows that the correlation between the compound ΔCpmax and SPL can be seen better than that of the single pressure sensor ΔCpmax as shown in Fig.8 and that SPL and ΔCpmax converges to the target values obtained by the open loop test. The converging history also has a good property to make fully use of the noise reduction capability of the active flap.
the sound pressure are measured on a BVI condition. The correlation between the compound ΔCpmax and the sound pressure is examined in order to make use the former as BVI detection index.

Summarizing the results of this study, the followings are concluded:

1. The closed loop control law is proposed and developed utilizing the compound ΔCpmax processed by the multiple blade surface pressure sensor signals as an input in order to better represent the BVI phenomenon on the blade and to enhance the convergence of the control law comparing with ΔCpmax generated by a single pressure sensor signal.
2. The proposed control law is evaluated by the wind tunnel test using the 1-bladed rotor system equipped with active flap as a test bed for noise reduction active technique. It is demonstrated by the test results that the proposed closed loop control law with the compound ΔCpmax successfully functioned with sufficient convergence better than that with ΔCpmax generated by a single pressure sensor signal.
3. One example procedure for generating the compound ΔCpmax by selecting pressure sensors and by arithmetically averaging them is proposed in this study. Establishing the methodology to obtain the better compound ΔCpmax theoretically and physically is one of the future works.

7 ACKNOWLEDGEMENTS

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