DESIGN STUDY, PROTOTYPING AND PERFORMANCE EVALUATION FOR ON-BOARD BLADE PITCH CONTROL SYSTEM OF ROTORCRAFT CONSIDERING HIGH G ENVIRONMENT

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Abstract

The conventional blade pitch control of rotorcraft is performed by a swashplate mechanism driven by the actuators placed on a non-rotating frame. One of the drawbacks of the swashplate mechanism is the high life cycle cost deriving from its mechanical complexity. In order to cope with this problem, an active trailing edge flap based system is proposed and design studied considering an operation in the high centrifugal force acting environment. The proposed drive mechanism consists of a piezoelectric actuator, an amplifying mechanism and a linear/rotary movement converter to satisfy the design target which requires the trailing edge flap to deflect 6deg amplitude at 22Hz with 1,000G centrifugal force. A prototype of the drive mechanism is developed and statically evaluated by a bench test, then dynamically done by a spin test. Both tests demonstrate the enough operability of the developed drive mechanism on the high centrifugal force condition.

1. INTRODUCTION

The blade pitch control of rotorcraft is performed by a swashplate mechanism driven by actuators placed on a non-rotating frame, which has been a conventional method since the birth of helicopters as shown in Figure 1. On the non-rotating frame, the actuator output is transferred to the non-rotating swashplate which is tilted and/or heaved by the control rods around the rotor shaft. On the rotating frame, the scissors connected with the rotor shaft drives the rotating swashplate which is tilted and/or heaved corresponding to the non-rotating swashplate.

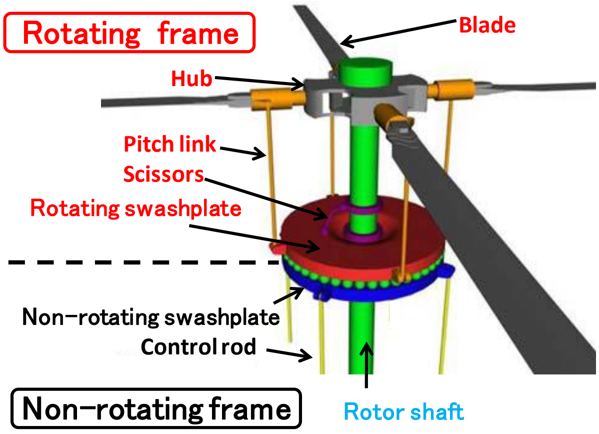

Figure 1: Generic blade pitch control system for conventional helicopters

Then, the pitch link rotates the blade around the pitch bearing to generate the collective and cyclic pitch angle variations with respect to the rotor azimuth.

One of the drawbacks of the swashplate mechanism is the high life cycle cost mainly arising from production and maintenance deriving from its mechanical complexity and the stringent safety requirements. Furthermore, the high speed compound helicopters which are being materialized recently require much lower drag and larger range of pitch angles.

In order to cope with this problem, some research activities utilizing active technologies, such as the active trailing edge flap, have been carried out [Refs.1, 2]. The merits of these active techniques are as follows;

1) Simple mechanism placed on the rotating frame

2) Enhancement of hover performance by variable twist

3) Improve high speed performance by mitigating stall on the retreating side

4) Noise and vibration reduction by higher harmonic control

The required compactness enough to be installed inside the thin rotor blade and the enough operability on a high centrifugal force condition

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(800-1,000G) are the main challenging points which have been researched so far.

JAXA has the history of the research activities for the on-board active techniques to reduce rotor noise and vibration for these decades, especially that for the active flap and the active tab [Refs. 3-12].

In this design study, the active flap is adopted as a test bed active technique for the system construction to demonstrate the blade pitch controllability. The design study is focused on the measures to assure the enough pitch controllability on a 1,000G environment which is representing the typical condition of the rotating blade of the conventional helicopters [Ref. 13]. The proposed on-board blade pitch control system is planned to examine the operating performance by a bench test and a spin test, which are also described.

2. SPIN TEST PLANNING

Figure 2 shows the schematics of the spin test set up utilizing the facility of Maruwa Electric Inc. [Ref.14].

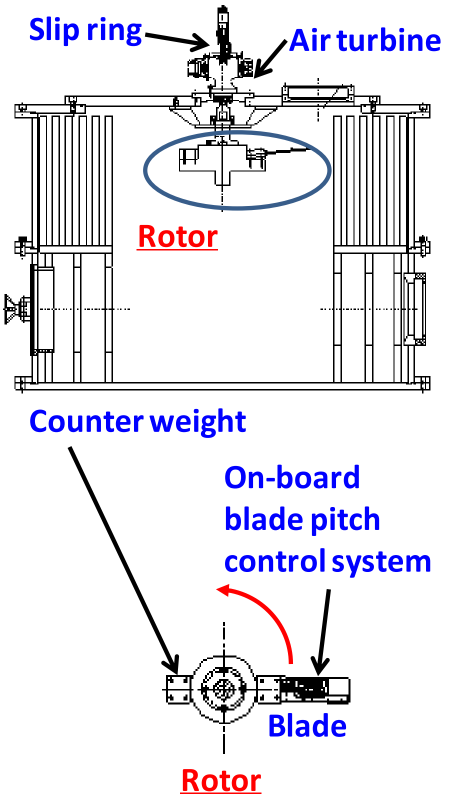


Figure 2: Assumed spin test set up

A 1-bladed rotor consisting of a blade and a counter weight is driven in the explosion-proof chamber by an air turbine equipped above the rotor. The blade contains the active flap based on-board blade pitch control system and is driven to generate 1,000G centrifugal force at the mid span of the flap.

3. DESIGN REQUIREMENTS

Considering the specification of the spin test facility (maximum rotor radius 775mm) and the active flap specification discussed in Refs.6 and 7, the requirements for the on-board blade pitch control system are set up as follows.

Test condition

Rotor speed 1500rpm (25Hz)

Operating performance:

Output deflection +/-6deg

Frequency 22Hz

Blade

Radius 644mm

Chord 150mm

Active flap

Span 100mm

Chord 22.5mm

Hinge line 85% blade chord

Radial station of the mid span 400mm

Instrumentations

Input voltage for on-board blade pitch control system

Displacement of actuator

Active flap deflection

4. DESIGN STUDY

Figure 3 shows the study path of the on-board blade pitch control system compromising among size, achievable active flap deflection and resonance frequency. Table 1 describes the features of each candidate.

Table 1: Features of each candidate

	Size	Deflection	Res. Freq.
1st	No	Yes	No
2nd	No	No	Yes
2nd_rev	No	No	No
3rd	Yes	No	No
4th	Yes	No	Yes
3rd_rev	Yes	Yes	Yes

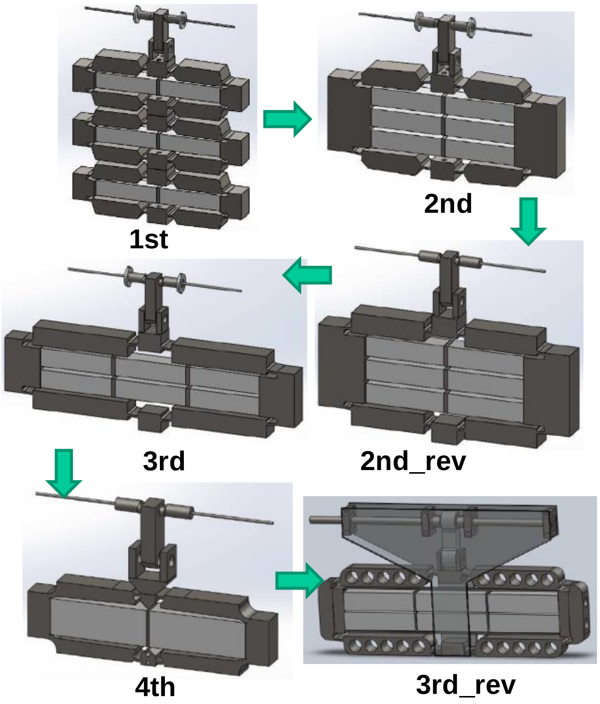
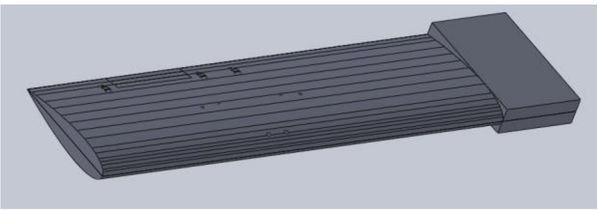


Figure 3: Study path of on-board blade pitch control system

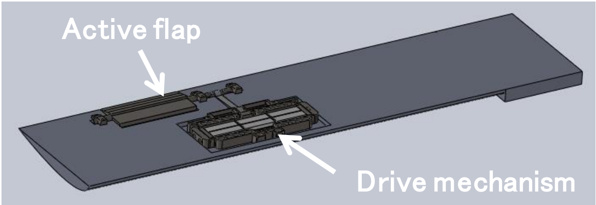
The finalized candidate is “3rd_rev” which can be designed within all the three limits defined to satisfy the design requirements mentioned above.

5. SYSTEM DESIGN

Figures 4 and 5 show the proposed on-board blade pitch control system to be installed inside the blade based on the design study.



(a) Blade assembly



(b) Arrangement inside blade

Figure 4: Blade with proposed on-board blade pitch control system

A drive mechanism utilizing a piezoelectric actuator is devised based on a preceding study applied to a helicopter blade [Refs. 8-12]. The entire blade assembly is shown in Figure 4 (a) and the inside arrangement of the blade is shown in Figure 4 (b).

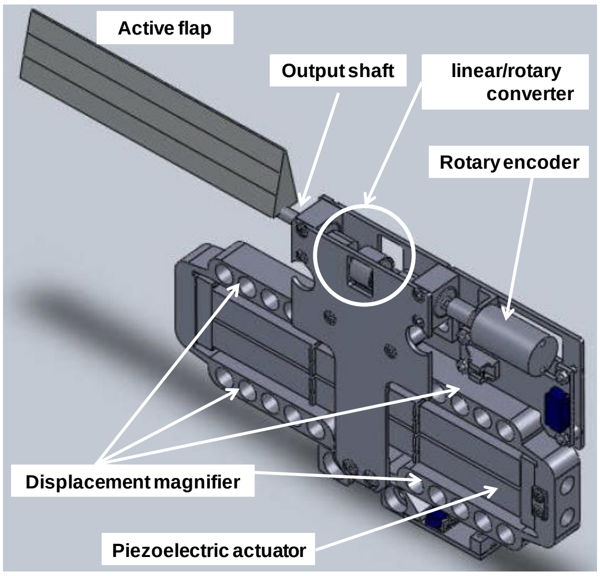
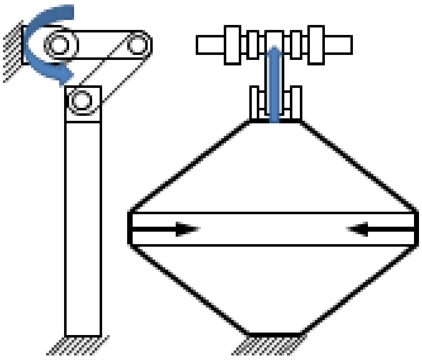


Figure 5: Proposed on-board blade pitch control system

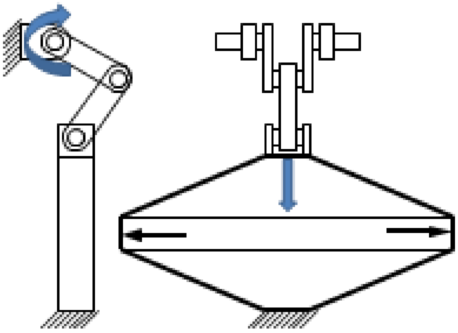
As shown in Figure 5, the six packs of the piezoelectric actuator generate a 144 μm linear reciprocal displacement which is magnified by a four-armed displacement magnifier by 9 times. This linear displacement is converted into a +/-6deg rotary reciprocal movement by the linear/rotary converter composed of the crank mechanism which is transmitted via the output shaft to the active flap as a drive force. The output deflection is measured and health monitored by the rotary encoder connected on the opposite side of the output shaft via the coupling.

The operating principle of the drive mechanism is shown in Figure 6. When the piezoelectric actuators are shrinking as shown in Figure 6 (a), the four-armed displacement magnifier is growing vertically. This input to the linear/rotary converter is transformed into the output shaft rotation. The opposite sequence of the movement of the drive mechanism happens in the actuator extending process as shown in Figure 6 (b).

Figure 7 shows the initial design of the drive mechanism of the on-board blade pitch control system and Figure 8 shows several counter measures for the drive mechanism enable to operate properly overwhelming the huge centrifugal force acting on vulnerable components and parts. The final design with the reinforcement of the drive mechanism is shown in Figure 8 (a). The support springs resist the radial centrifugal force acting on the push-pull rod of the linear/rotary converter which is strengthening the stiffness. The thrust bearings are placed near the ends of the output shaft and the end of the rotary encoder side and the both ends of the push-pull rod. The mass balance is put on the opposite side of the flap across the hinge in order to place the center of gravity of the flap on the hinge to almost nullify the hinge moment increment by the centrifugal force as shown in Figure 8 (b). The outboard side of the flap hinge end is connected to the thrust bearing to assure the proper movement of the active flap by supporting the severe centrifugal force as shown in Figure 8 (c).



(a) Actuator shrinking



(b) Actuator extending

Figure 6: Operating principle of drive mechanism

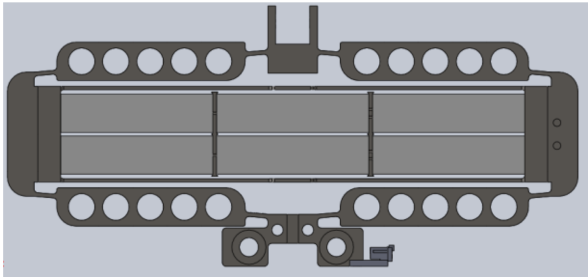
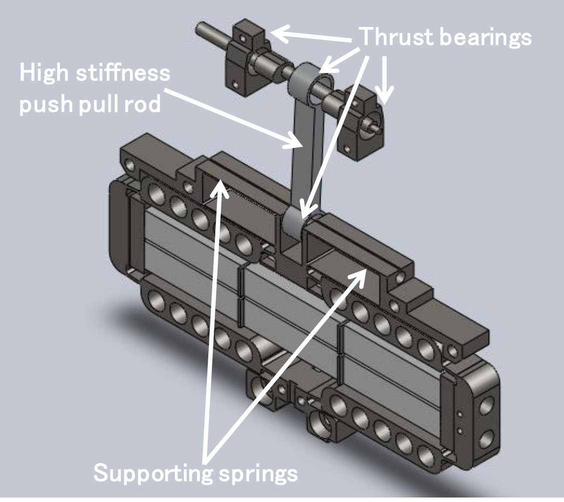
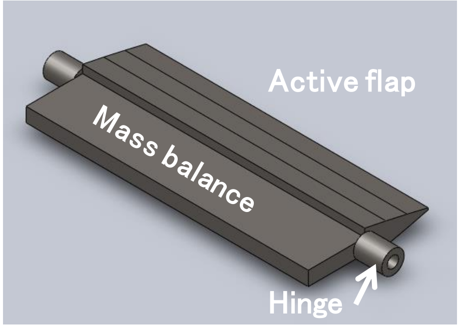


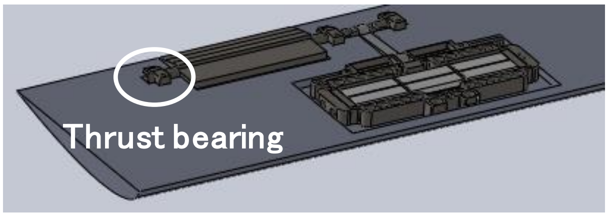
Figure 7: Initial design of drive mechanism



(a) Final design of drive mechanism



(b) Active flap mass balance



(c) Active flap thrust bearing

Figure 8: Counter measures for high G

6. PROTOTYPING AND BENCH TEST

Figure 9 shows a prototype of the developed drive mechanism for the on-board blade pitch control system. Figure 10 illustrates the similar example of the set up of a bench test [Refs. 15 and 16]. This test is carried out to evaluate the operability of the drive mechanism with an isolated configuration on a non-rotating condition, therefore without the simulated centrifugal force. The prototype of the drive mechanism is installed with the loadings of simulated inertia, dynamic and static forces of the active flap during the spin test. The inertia of the active flap is simulated by the mass with the equal inertia moment around the output shaft. The dynamic force is done by a piano wire with the equal torsional stiffness. The static force is done by the initial torsion deflection added to the piano wire.

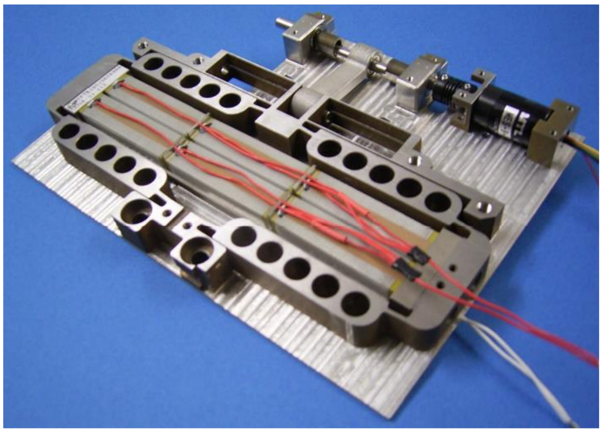


Figure 9: Prototype of drive mechanism for on-board blade pitch control system

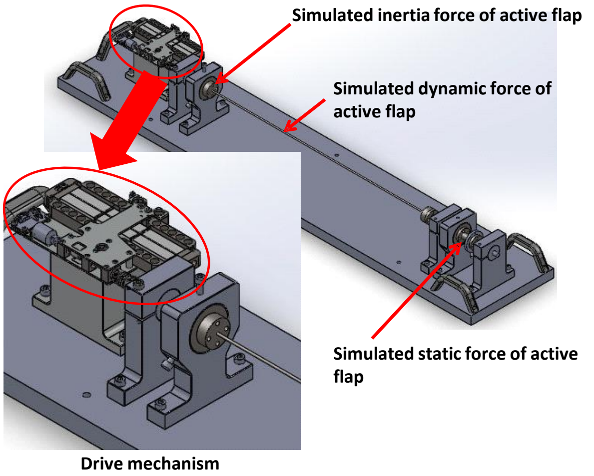
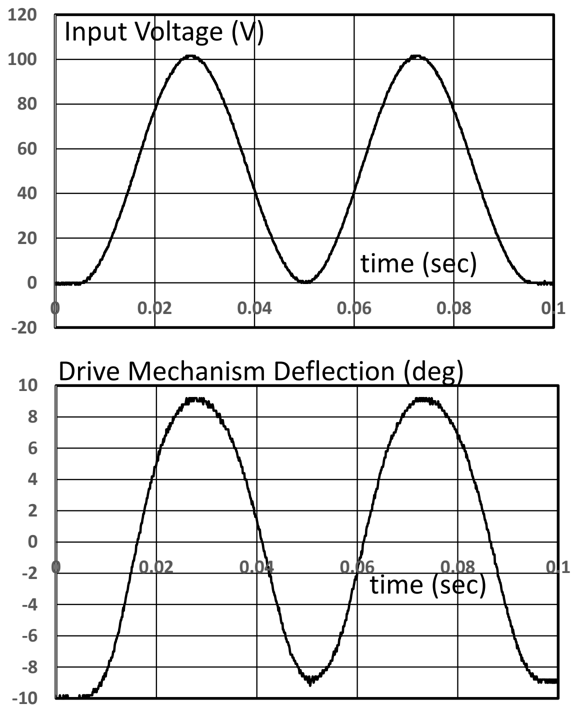


Figure 10: Bench test set up [Refs. 15 and 16]

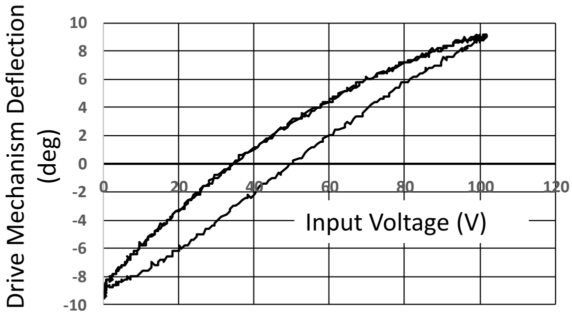
For this objective, the drive mechanism is operated with input voltage 0 to 100V at 22Hz without the simulated applied loads.

Figure 11 shows the bench test result. This figure denotes the dynamic behavior of the drive mechanism measured by the encoder with the simultaneously measured input voltage to the actuator. As shown in Figure 11 (a), 8.5deg output deflection of the drive mechanism at 22Hz is obtained, which satisfies the requirement mentioned above. Figure 11 (b) shows the hysteresis of the drive mechanism output deflection with respect to the input voltage. This hysteresis can be coped with the feedback controls to eliminate during the practical use of the drive mechanism.



Input voltage and drive mechanism deflection

(a) Time history



(b) Hysteresis

Figure 11: Bench test result :

Without simulated loads

Rotor speed=0rpm

Actuator frequency = 22Hz

Achieved active flap deflection=8.5deg

7. SPIN TEST

7.1. Dynamic balancing

Figure 12 shows the set up for the dynamic balance adjustment in order to avoid the harmful vibration during the spin test caused by the misalignment between the rotational axis and the principal axis. The adjustment was carried out by measuring the phase locked vibration and by adding the compensation mass to cancel out the vibration repeatedly by trial and error.

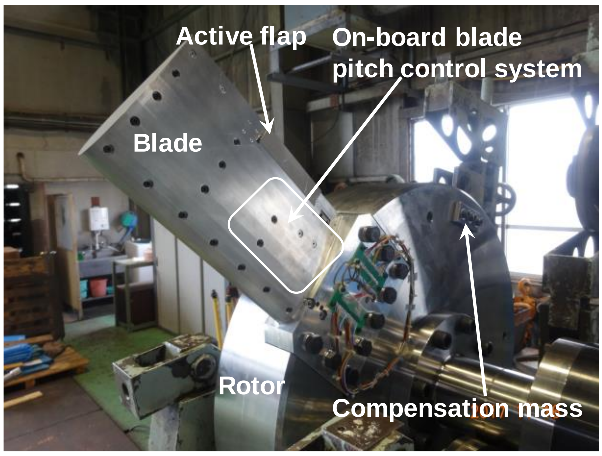


Figure 12: Set up for dynamic balancing

7.2. Set up for spin test

Figure 13 shows the spin test set up in the air turbine drive spin tester.

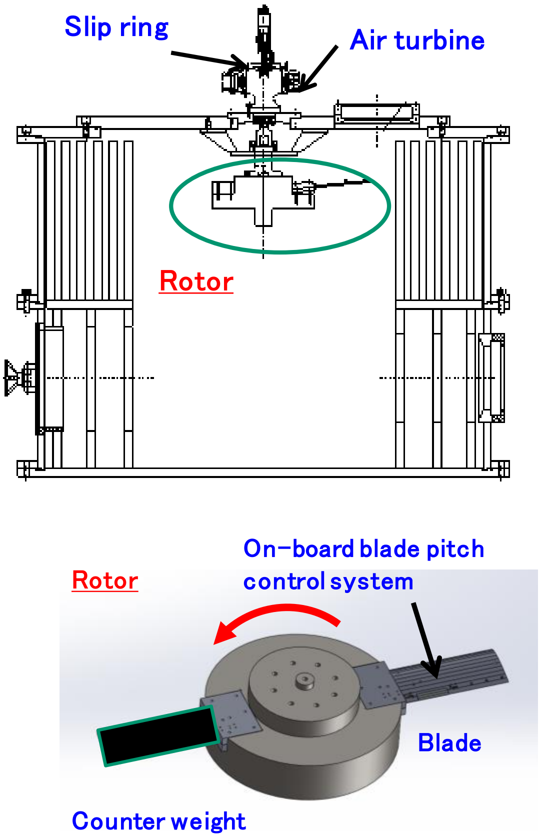


Figure 13: Set up in air turbine drive spin tester

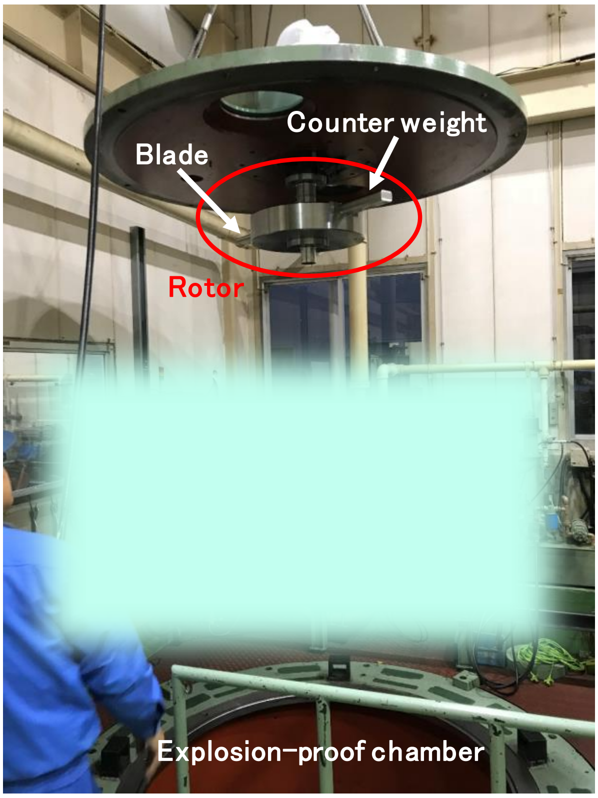


Figure 14: Actual installation

The actual installation of the rotor is shown in Figure 14. The active flap deflection and the actuator displacement are measured by a data acquisition system outside the chamber. The data are transmitted via 36ch slip ring placed on top of the air turbine. The electric power to the drive mechanism is also transmitted via this slip ring.

Figure 15 shows the on-board blade pitch control system installed in the blade and the rotor assembly consisting of the blade with the active flap, the counter weight and the compensation mass added for securing the dynamic balance of the rotor assembly is shown in Figure 16.

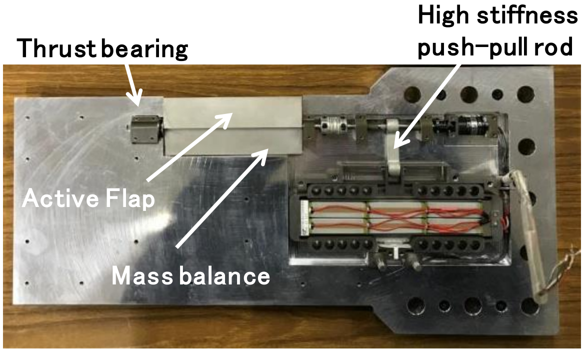


Figure 15: On-board blade pitch control system installed in blade

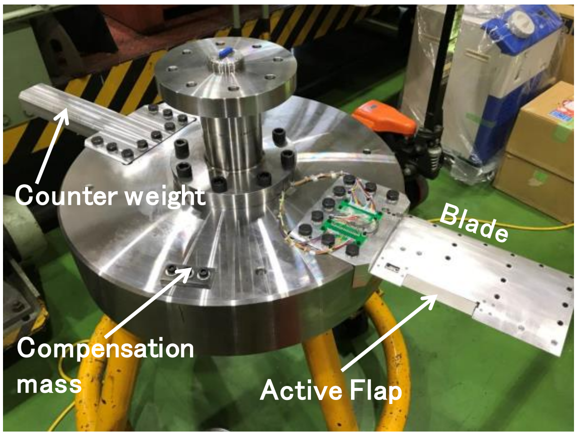


Figure 16: Rotor assembly

7.3. Spin test results

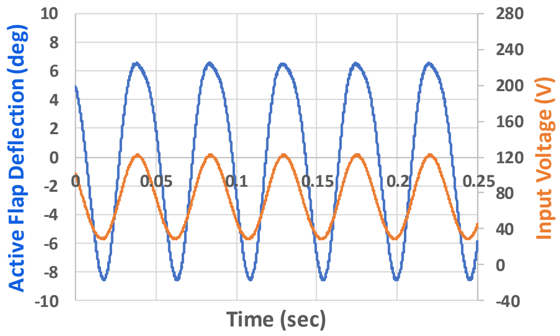
Figures 17 to 22 show the result of the spin test with the rotor speed 0 to 1500rm for the performance evaluation for the on-board blade pitch control system.

As a general, it is demonstrated that the developed system satisfied the design requirement of the active flap deflection 6deg at 22Hz on 1000G condition. The deformation in the active flap deflection near the top and bottom dead centers is observed, which is the future challenging to be solved.

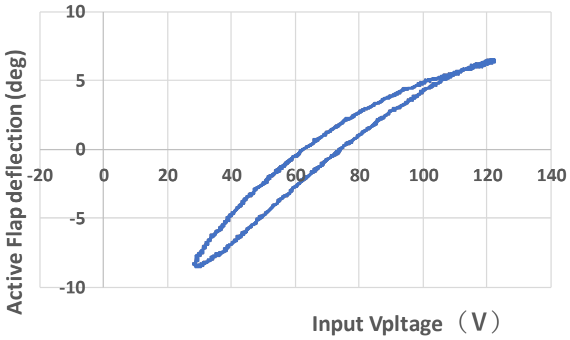
Comparing Figure 11(Bench test) and Figure 17(Spin test at rotor speed 0rpm), although there is no centrifugal force on both cases, the achieved active flap deflection of the bench test is larger than that of the 0rpm spin test. It is supposed that the difference is caused by the installation loss. The bench test was carried out with the isolated drive mechanism without any loads such as simulated inertia, dynamic and static forces of the active flap. On the other hand, the drive mechanism is installed inside the blade and connected with the active flap during the spin test, which degrades the operability of the drive mechanism.

As shown in Figures 18 to 20 (b) Hysteresis, all the cases with rotation have “fish tailed” overshoots at the maximum active flap deflection stroke (the most lower position of the active flap trailing edge), which is supposed that the friction of the thrust bearing on the outboard side of the active flap hinge end (as shown in Figure 8 (c)) developed by the centrifugal force prevents the smooth movement of the active flap.

Figures 21 and 22 show the drive mechanism operation properties with rotor speed 1500rpm at the lower active flap frequencies 5.5Hz and 11Hz, respectively to be able to study the active flap frequency influence.

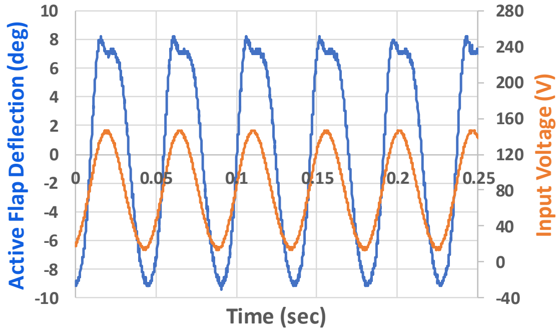


(a) Time history

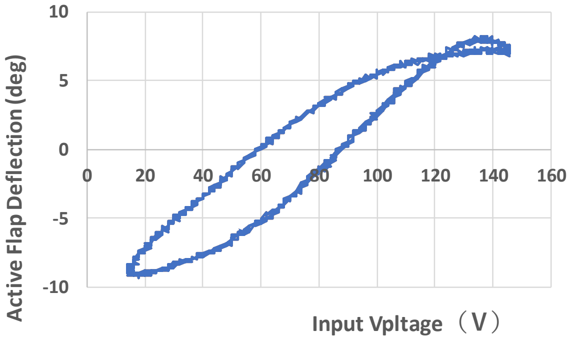


(b) Hysteresis

Figure 17: Spin test result :
Rotor speed=0rpm, Active flap frequency=22Hz
Achieved active flap deflection=7.6deg

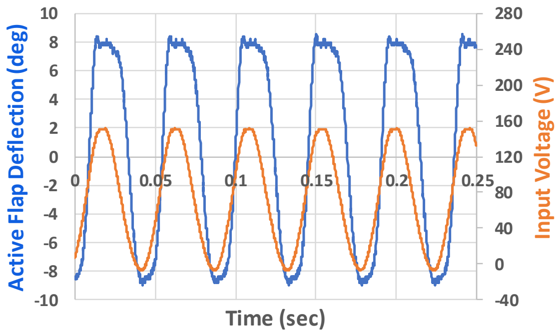


(a) Time history

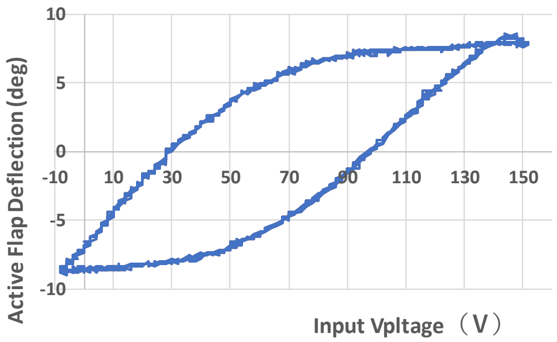


(b) Hysteresis

Figure 18: Spin test result :
Rotor speed=600rpm, Active flap frequency=22Hz
Achieved active flap deflection=8.7deg

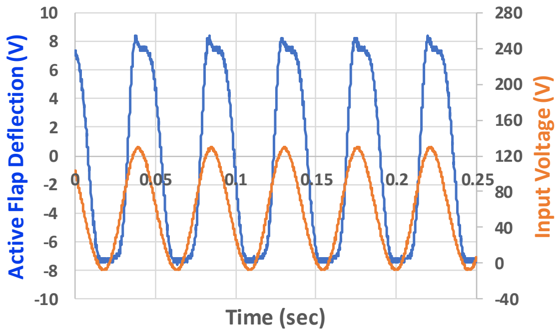


(a) Time history

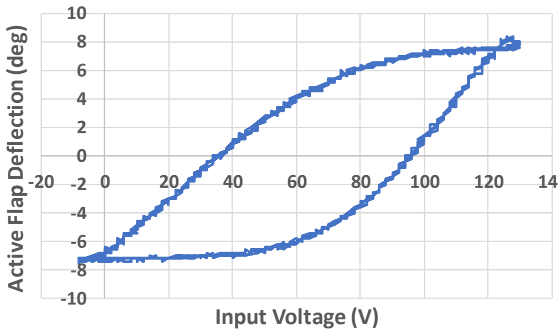


(b) Hysteresis

Figure 19: Spin test result :
Rotor speed=900rpm, Active flap frequency=22Hz
Achieved active flap deflection=8.4deg

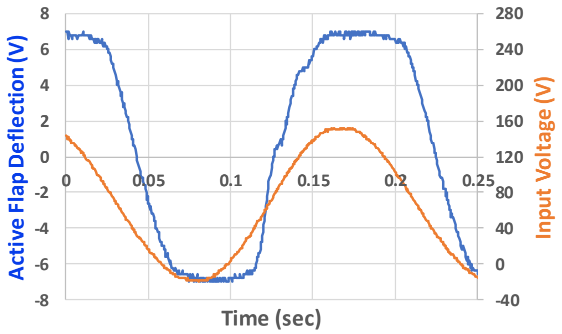


(a) Time history

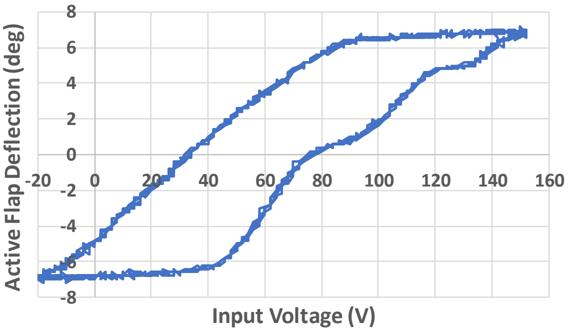


(b) Hysteresis

Figure 20: Spin test result :
Rotor speed=1500rpm, Active flap frequency=22Hz
Achieved active flap deflection=7.9deg

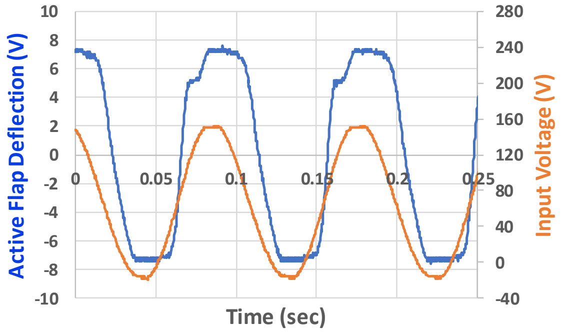


(a) Time history

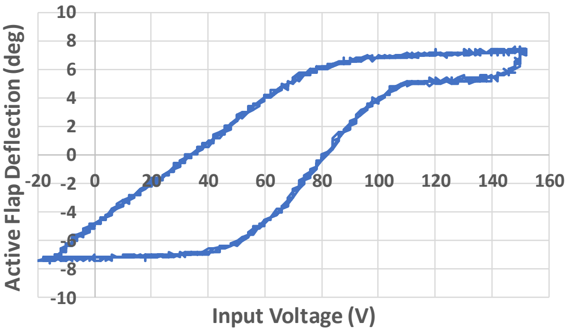


(b) Hysteresis

Figure 21: Spin test result :
Rotor speed=1500rpm, Active flap frequency=5.5Hz
Achieved active flap deflection=7.0deg



(a) Time history



(b) Hysteresis

Figure 22: Spin test result :
Rotor speed=900rpm, Active flap frequency=11Hz
Achieved active flap deflection=7.4deg

Comparing Figure 20 to 22, 5.5Hz and 11Hz cases have the different type of the hysteresis from 22Hz case. The slower movement of the active flap is much more prevented from smooth operation because lack of enough inertia to overcome the friction acting at the thrust bearing on the outboard side of the active flap hinge end (as shown in Figure 8 (c)).

CONCLUSIONS

Summarizing the study results, the followings are concluded by this study.

1. An on-board blade pitch control system complying of a piezoelectric actuator, an amplifying mechanism and a linear/rotary movement converter is proposed based on a design study to satisfy the requirements for the spin test and a blade with the active flap is also designed in which the drive mechanism is installed.
2. Several counter measures for the drive mechanism enable to operate properly overwhelming the huge centrifugal force acting on vulnerable components and parts are also proposed. The thrust bearings, supporting springs and the mass balance are efficiently arranged on the primary components and parts.
3. The developed drive mechanism for the on-board blade pitch control system is evaluated by the bench test which demonstrates that the drive mechanism achieves 8.5deg output deflection at 22Hz successfully.
4. After the dynamic balance adjustment, the developed drive mechanism demonstrated by the spin test to satisfy the design requirement of the active flap deflection more than 6deg. at 22Hz on 1000G condition.

FUTURE WORKS

The deformation in the active flap deflection near the top and bottom dead centers is observed, which is the future challenging to be solved.

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