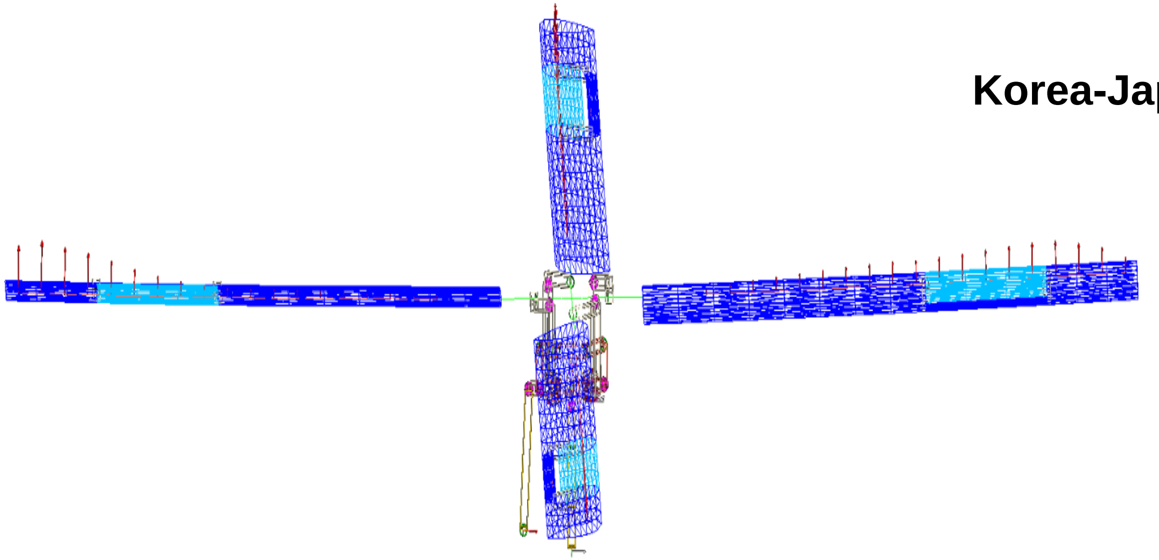
Hover Test of SNU Active Trailing Edge Flap for Rotor Vibration Reduction

SangJoon Shin

Seoul National University



Korea-Japan Joint Workshop on Rotorcraft

Yeosu, Republic of Korea

Session II Analysis & Test

February 10th 2023

13:00 – 13:20

Contents

Introduction

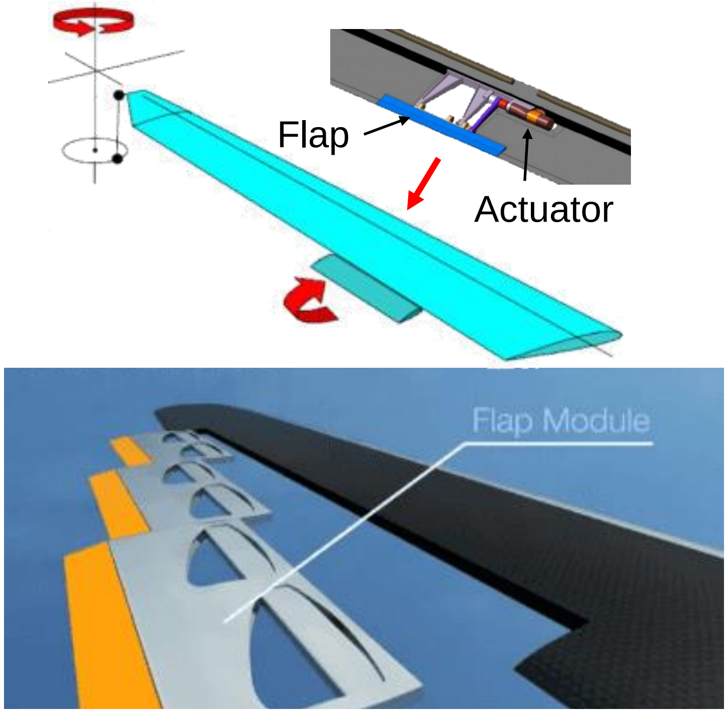
❖ Rotor blade with a trailing-edge flap

➢ Rotor vibration and noise control by active flap blades

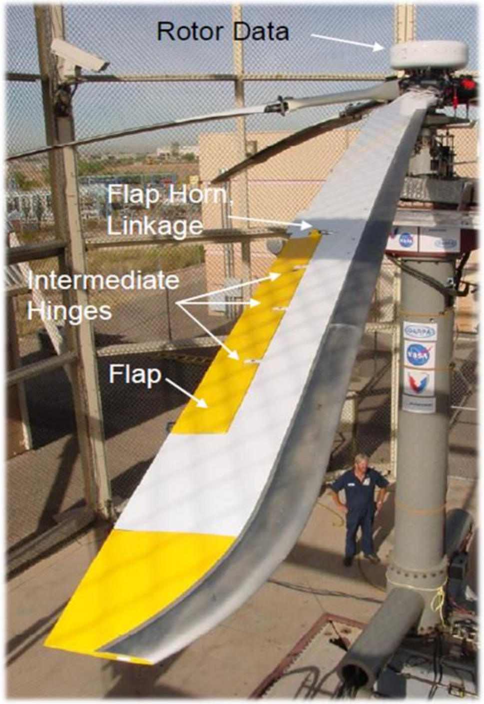
- Active rotor – numerous studies have been done*, and recently by DLR, JAXA, NUAA, SNU, …

  - Mechanism structural design, fluid dynamics, control, and wind-tunnel test

✓ **Underlying structural dynamics and aerodynamic features yet to be extracted**



▲ **Trailing-edge flap blade concept**



▲ **SMART rotor whirl stand test**

▲ **Sikorsky wind tunnel test**

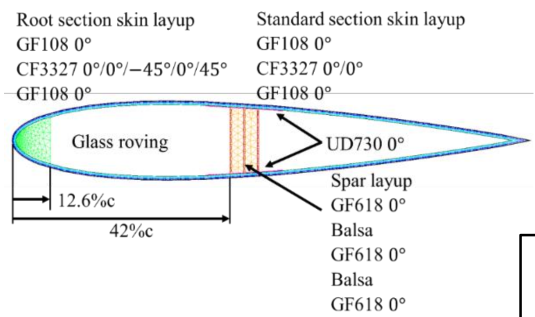
***Friedmann, P. P., "On-Blade Control of Rotor Vibration, Noise, and Performance: Just Around the Corner? The 33rd Alexander Nikolsky Honorary Lecture," American Helicopter Society 69th Annual Forum, Phoenix, AZ, May 2013.**

Introduction

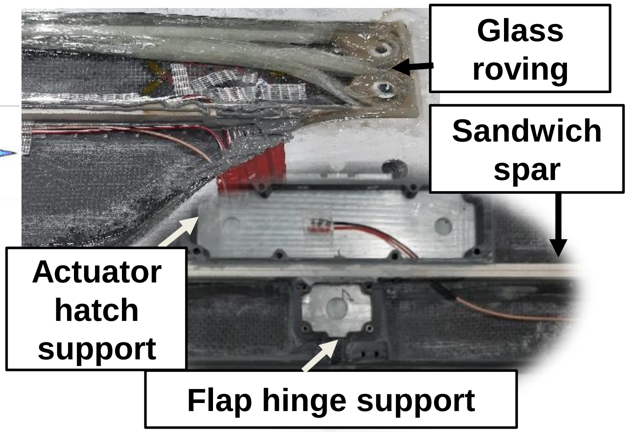
❖ SNUF (SNU Flap-blade) research objectives

➢ Baseline multi-disciplinary investigation

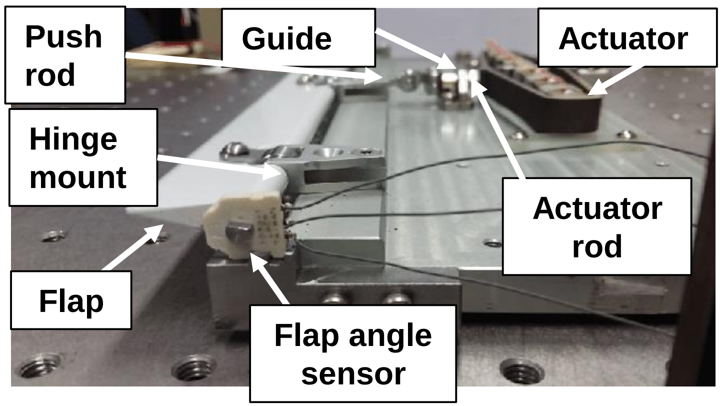
Composite blade structures



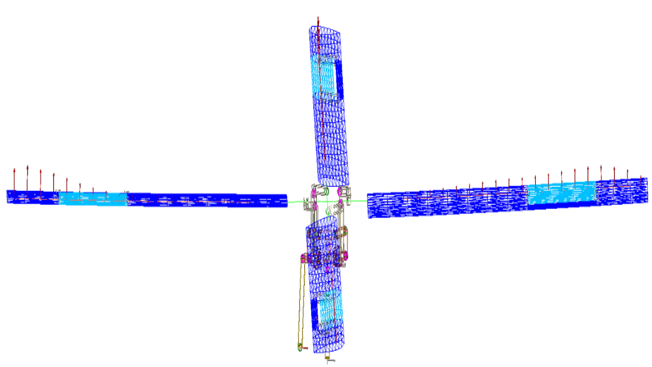
Cross-section optimization

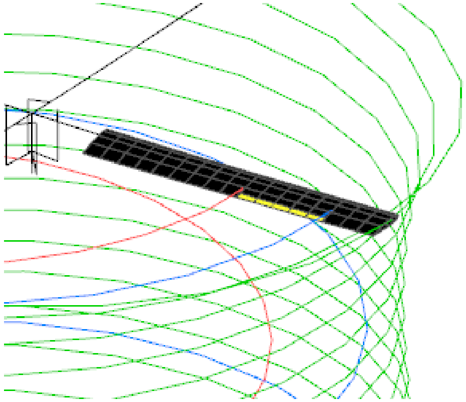


Flap driving mechanism



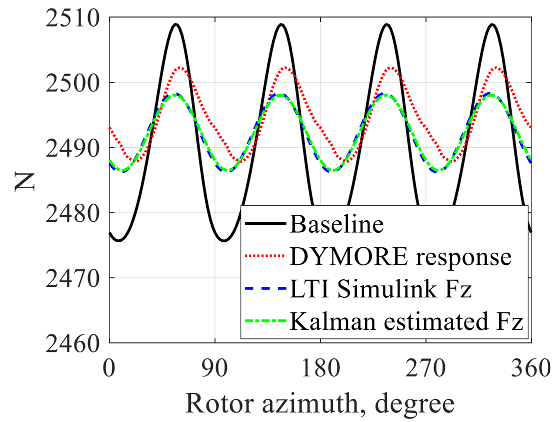
Multi-body comprehensive rotor aeromechanics





Mid-fidelity aeromechanics analysis with full flap rotor

Active rotor controls

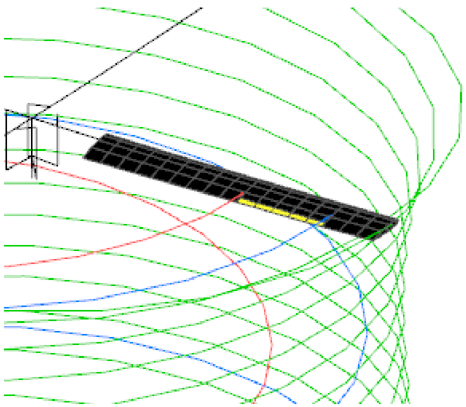


Closed-loop vibratory load control

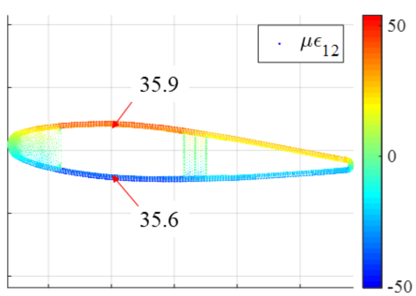
Introduction

❖ Hover test overview

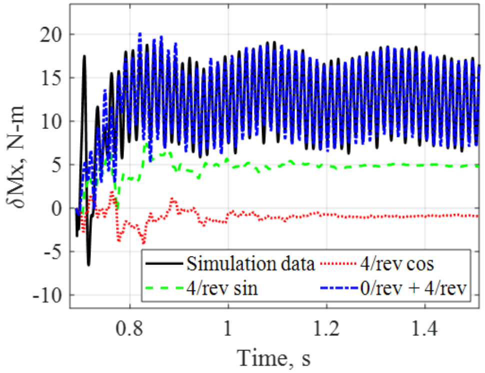
- ➢ Active flap blade **aeromechanics**, **composite blade integrity correlation**
- ➢ **Low-latency harmonic signal processing** for higher harmonic control
- ➢ **Time-periodic and multi-blade nature** w/ different collective
- ➢ **Hub load dynamics** w/ different **flap actuation mode**



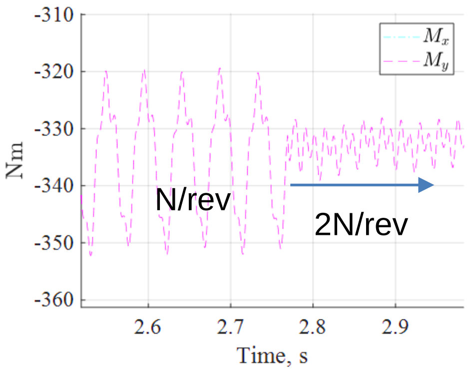
Aeromechanics



Composite blade analysis correlation



Harmonic signal processing



Time-periodic hub load

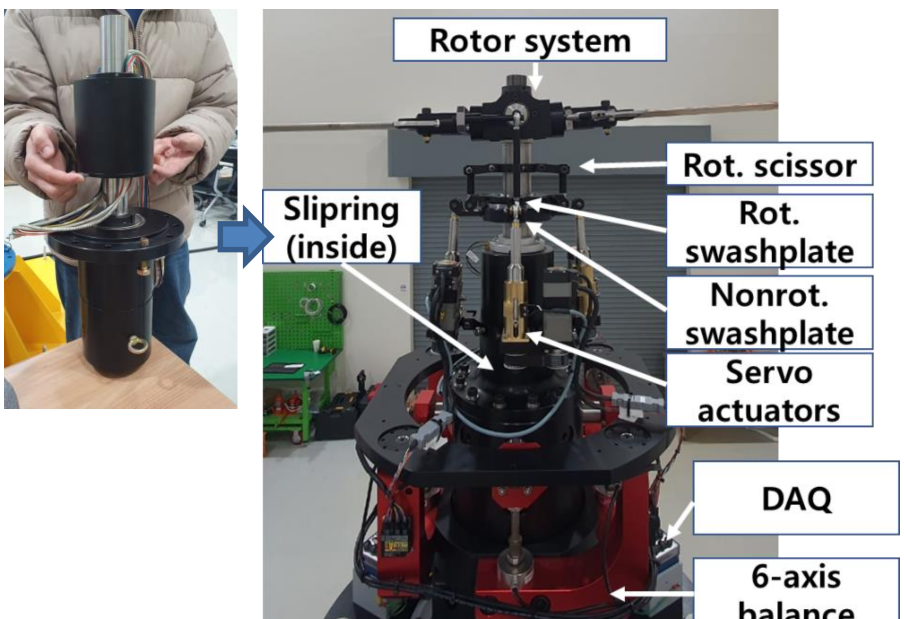
Contents

Test Preparation

❖ Hover test stand fabrication

➢ Seoul National University Rotor Test System (SNURTS)

- Siheung Campus test center: 9X12 m, 240 kW electric power capacity
- Collaboration w/ Chungnam National University: design/fabrication of the test stand
- 55kW AC motor direct drive, max. 2,000 RPM
- 6-axis balance: max. 2,000kgf thrust, 160kgf-m torque



▲ SNURTS components

▲ SNURTS control room

▲ SNURTS installed

Test Preparation

❖ Test stand fundamental mode identification

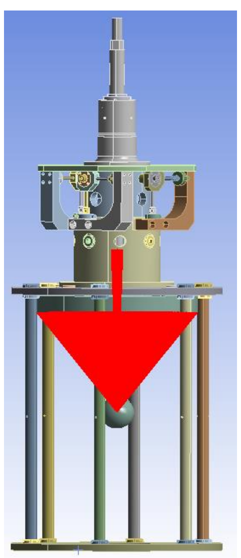
➢ Impact test and correlation

- Test stand structural analysis by ANSYS

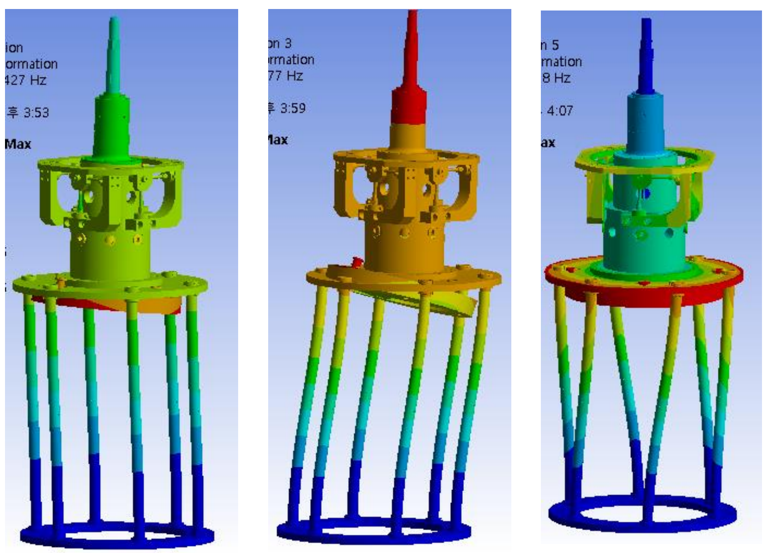
- Contact normal stiffness adjusted to match test results

- Major resonant speed identified: 300, 900RPM
- ISO-1940: satisfactory vibration level @ 1,100~1,300 RPM

▲ Test stand vibration level at 1,120 RPM

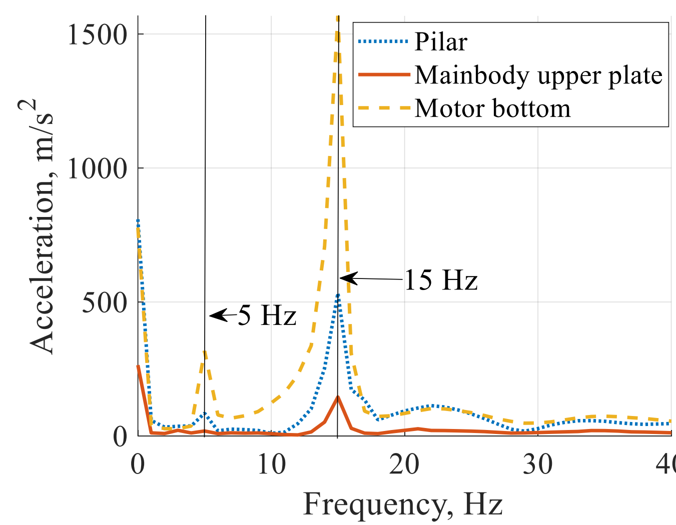


Concentrated motor mass



1st bending 4.8 Hz | 2nd bending 15 Hz | 1st torsion 22 Hz

▲ 3D FEM modal analysis correlation



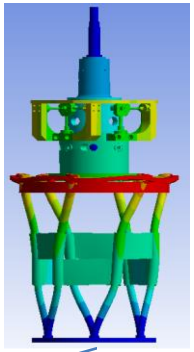
▲ Impact test result

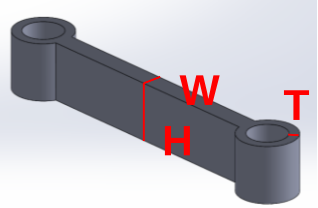
Test Preparation

❖ Test stand fundamental mode identification

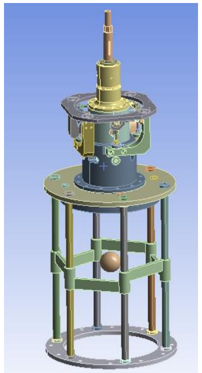
➢ Mode control by the stiffener

- Bending and torsion modes of the stand may be adjusted
- Bearing tower is structurally isolated with the test stand
- k/rev : 1300, 2600, 3900, 5200 … RPM avoided

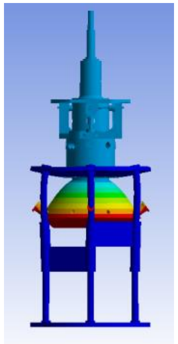


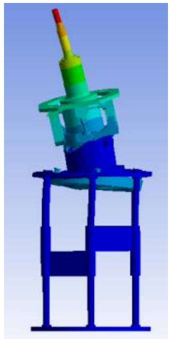


Stiffener



W mm	H mm	T mm	N	Support pillar 1st bending RPM (Hz)	Support pillar 2nd bending RPM (Hz)	Bearing tower 1st axial RPM (Hz)	Stand 1st torsion RPM (Hz)	Bearing tower 1st bending RPM (Hz)	Stand 2nd torsion RPM (Hz)
Baseline				295 (4.92)	924 (15.4)	1,532 (25.5)	1,320 (22)	4,022 (67.0)	5,120 (85.3)
20	60	10	3	336 (5.60)	1,059 (17.7)	-	1,448 (24.1)	-	-
20	60	10	6	362 (6.04)	1,227 (20.5)	1,538 (25.6)	1,558 (26.0)	4,084 (68.1)	5,358 (89.3)
20	120	10	6	383 (6.39)	1,474 (24.6)	1,538 (25.6)	1,714 (28.6)	4,154 (69.2)	5,580 (93.0)
20	150	10	6	388 (6.47)	1,560 (26)	1,539 (25.7)	1,776 (29.6)	4,188 (69.8)	5,706 (95.1)
20	180	10	6	392 (6.53)	1,638 (27.3)	1,540 (25.7)	1,830 (30.5)	4,218 (70.3)	5,874 (97.9)





▲ Isolated bearing tower mode

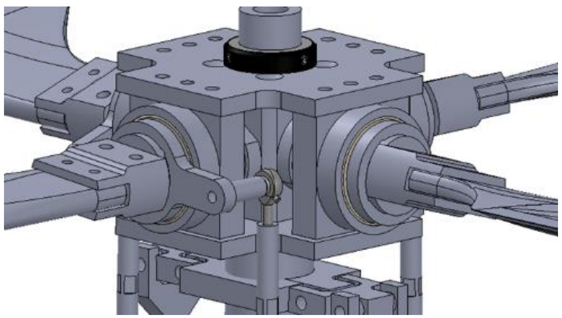
▲ Stiffener parametric examination

Test Preparation

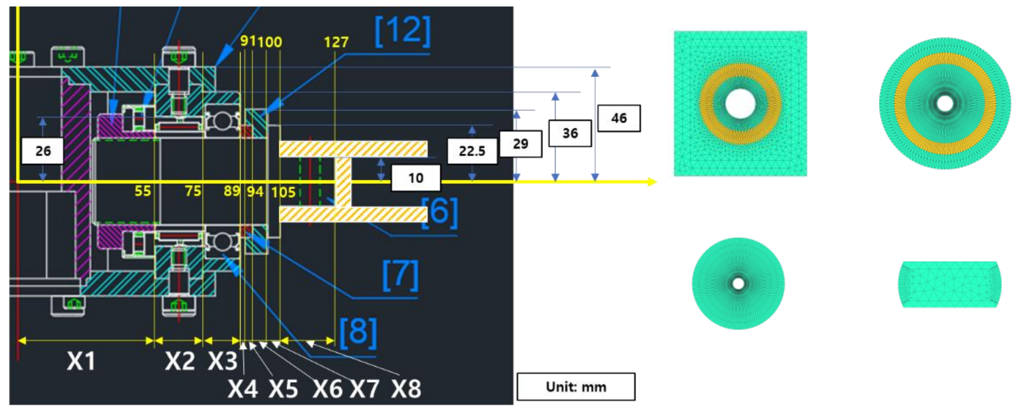
❖ Rigid 4-blade SNUF rotor hub

➢ Blade and grip structural integrity evaluation

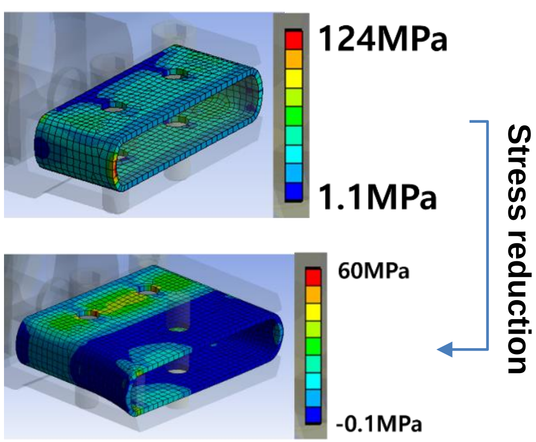
- Hingeless hub: grip structural analysis
- Rotor load from analysis: 39kN → applied load factor 1.5: 58kN centrifugal load
- Safety margin > 2



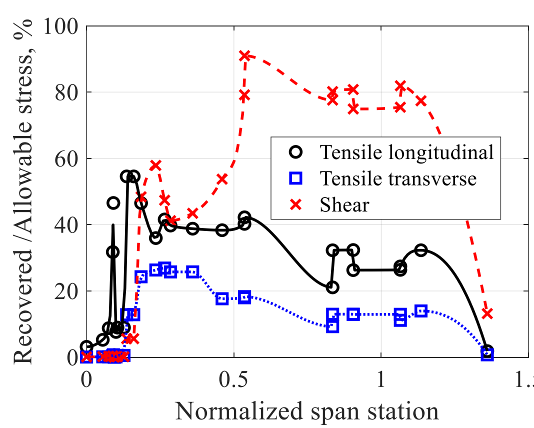
▲ SNURTS rigid hub



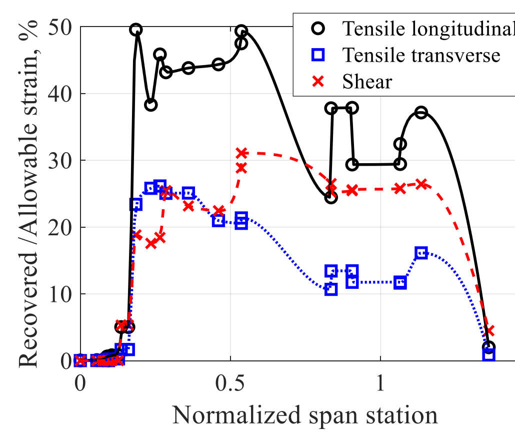
▲ VABS cross sectional modeling



▲ Grip M6-bolt reinforcement



▲ Stress recovery



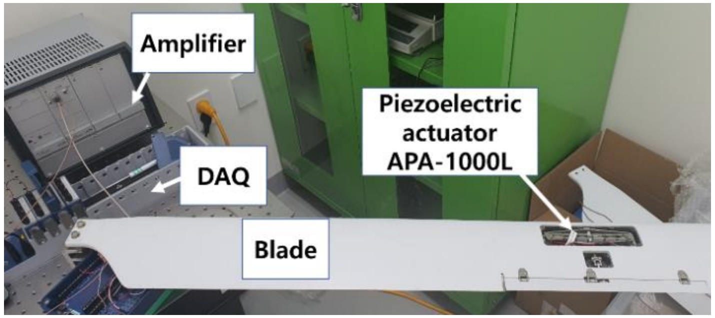
▲ Strain recovery

Test Preparation

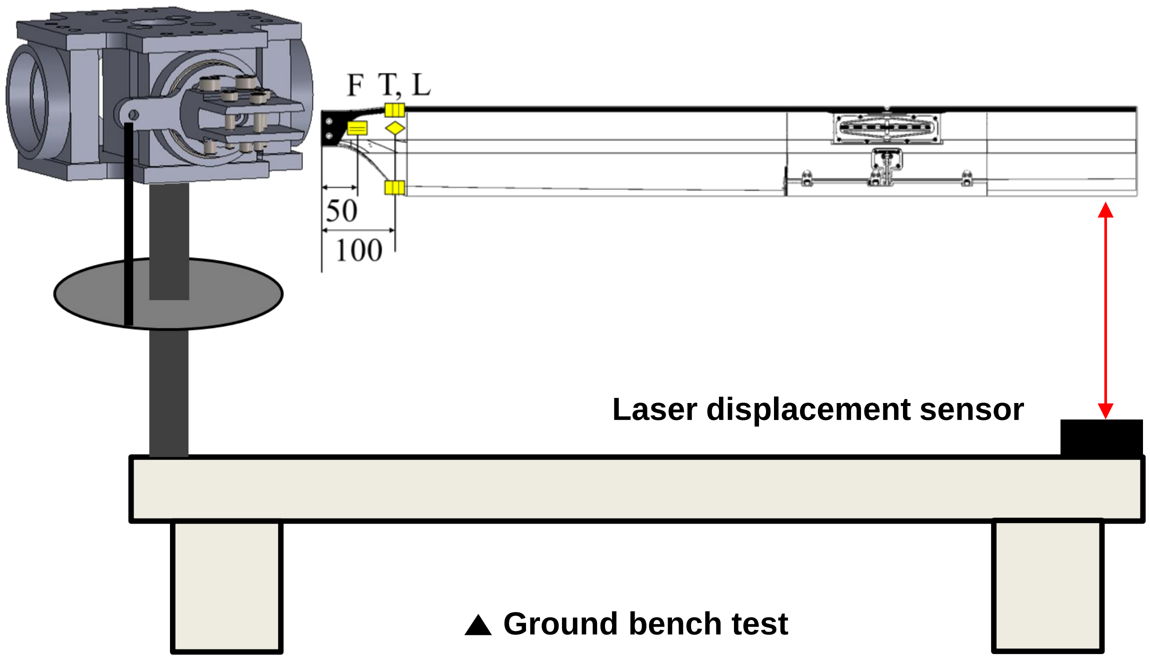
❖ SNUF blade ground-test

➢ Ground bench test (scheduled ~March 23')

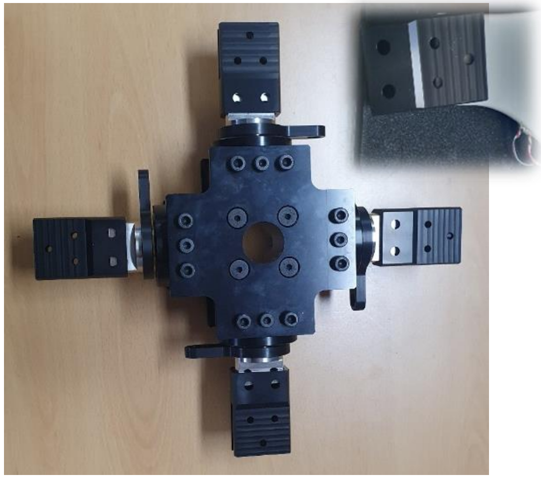
- Strain gauge calibration by the tip displacement (flap, lag, torsion)
  - Tip displacement measure sensor for the test stand
- Measurement and control program test
- Actuator inner-loop position control test



▲ SNUF blade ground test



▲ Ground bench test



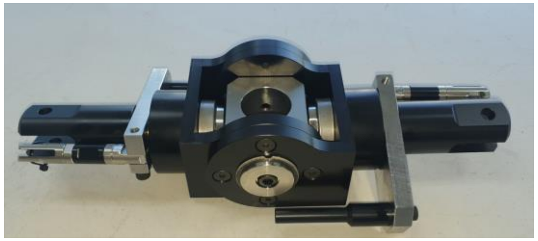
▲ Fabricated grip and SNUF rotor hub assembly

Test Preparation

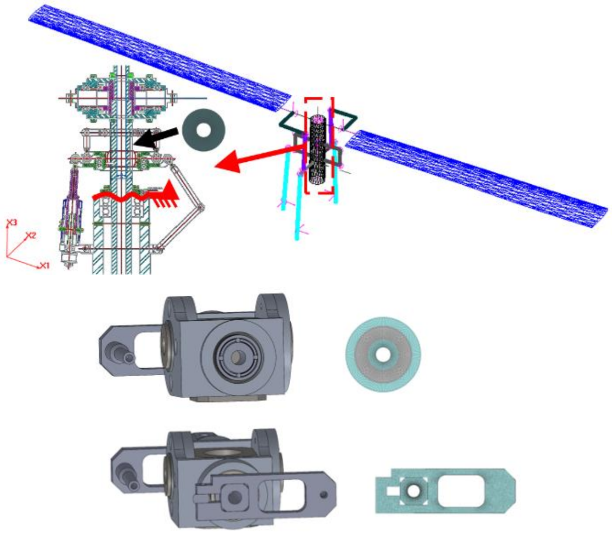
❖ SNURTS evaluation

➢ Reference OLS rotor from NASA test*

- 2-m diameter, NACA0012, no twist, no taper
- To evaluate the functionality of SNURTS
- Validate against the present prediction



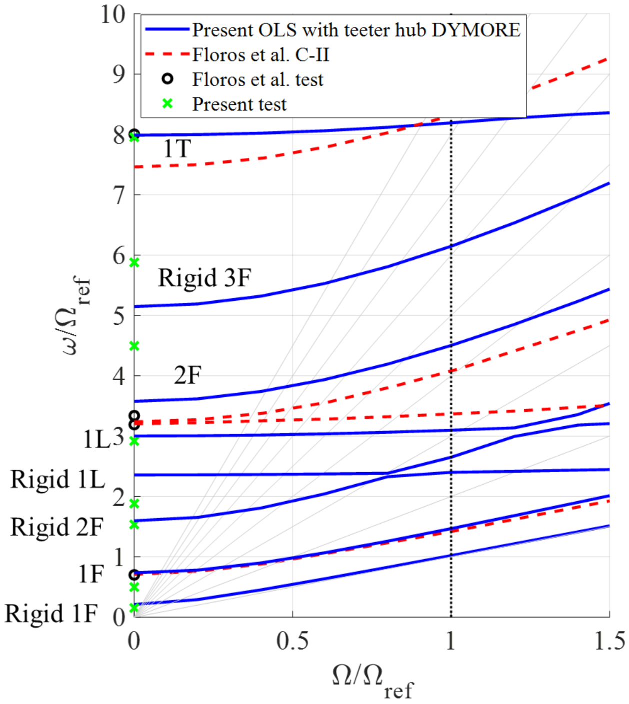
▲ Present OLS hub



▲ Present DYMORE configuration of the SNURTS-OLS rotor

▲ Blade modal test

▲ Rotor hub modal test



▲ Fan plot from the present hub test result

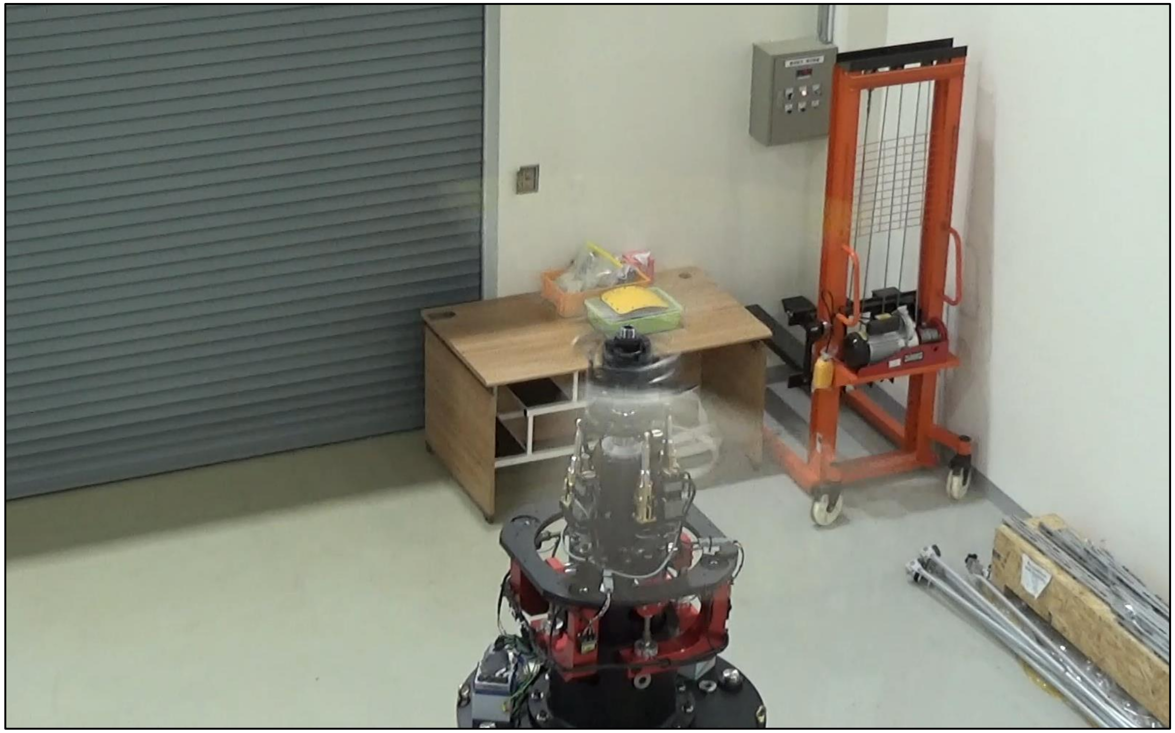
*Floros, M. W., Gold, N. P., and Johnson. W., "An Exploratory Aerodynamic Limits Test with Analytical Correlation", American Helicopter Society 4th Decennial Specialists' Conference, Jan 2004.

Test Preparation

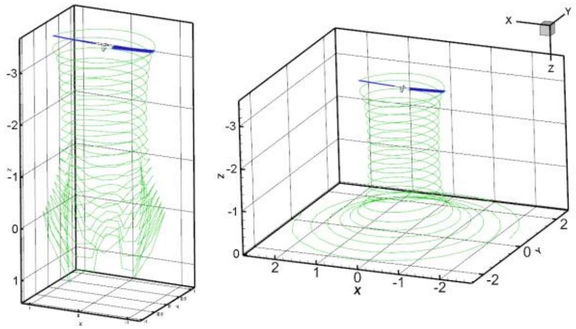
❖ OLS rotor hover test

➢ Collective pitch sweep test

- Test repeated 3 times and one open-door test
- Sufficient ground height for OLS rotor
- Functionality of SNURTS verified (run, collective, stop command)



▲ **Closed-door test (@ free run stop)**



▲ **Ground effect wake analysis**

→ No ground effect

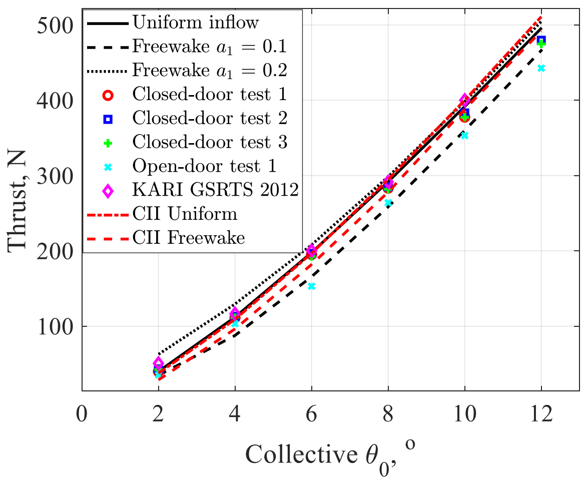
Test Preparation

❖ OLS rotor hover test

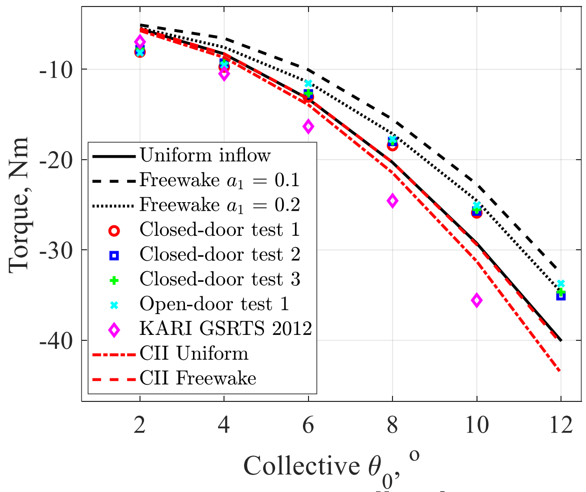
➢ Collective pitch sweep test

- 98% ↑ reproducibility for the measured thrust and torque
- Measured unrealistic figure of merit: 2012 KARI test as a reference
- Present momentum theory inflow analysis gives good correlation to the reference test
- Free-wake viscous influence should be carefully correlated
- Balance designed for SNUF rotor 400 N-m rated torque

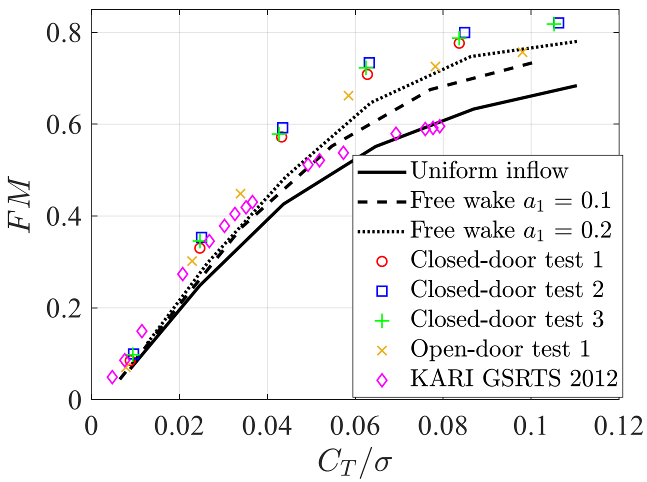
  → torque resolution unmatched for max torque 40 N-m OLS rotor



▲ Thrust-collective



▲ Torque-collective



▲ Figure of merit

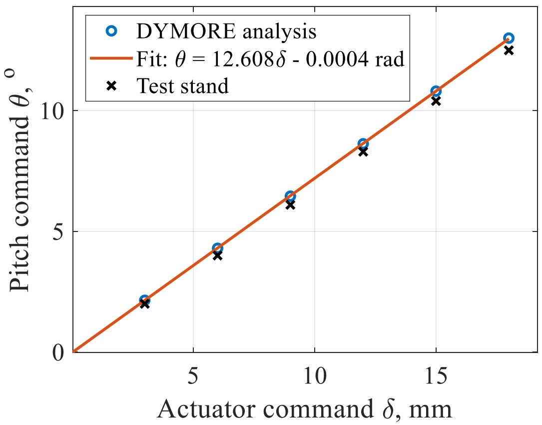
Contents

Pre-test Prediction

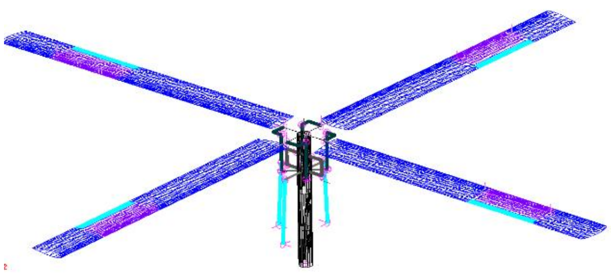
❖ Correlation against the comprehensive analysis

➢ Multi-body dynamic analysis: DYMORE and CAMRAD-II

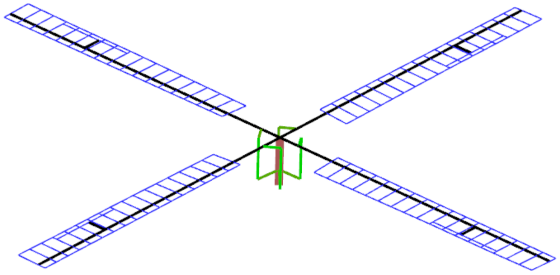
- Incorporate SNURTS pitch link, servo actuators, shaft, trailing-edge flaps
- Code-to-code comparison and evaluation
- Time-marching free-wake analysis with the multiple-trailer wake
- DYMORE-Simulink coupled simulation for the control



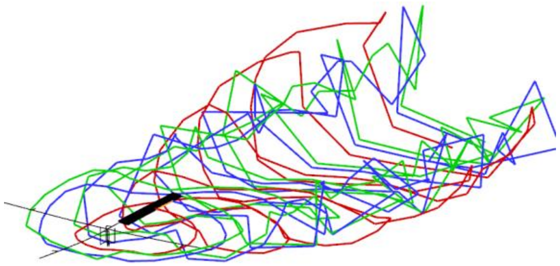
▲ Servo-pitch test and prediction



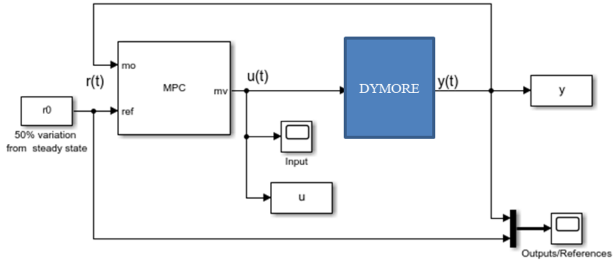
▲ SNUF DYMORE configuration



▲ SNUF CAMRAD-II configuration



▲ Free-wake analysis

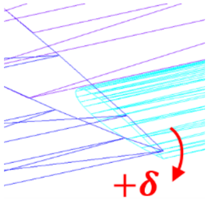


▲ DYMORE-Simulink coupled simulation

Pre-test Prediction

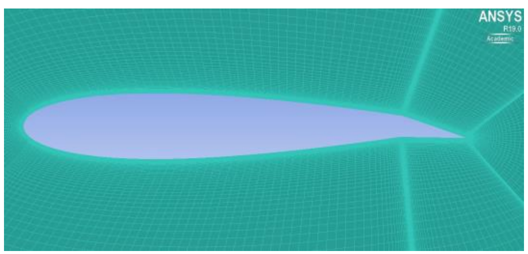
Seoul National University
Active Aeroelasticity and Rotorcraft Lab.

❖ Additional accuracy for the lifting-line theory

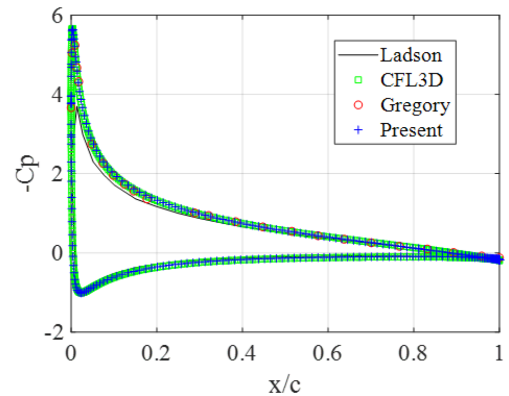


➢ C81 table for an airfoil w/ a flap

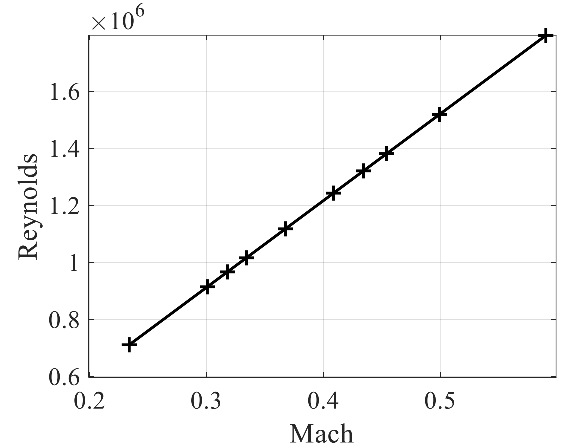
- Improved aerodynamic load prediction at the flap station
- RANS (k-ω SST) by using FLUENT, matched y+=1 for all the cases
- Advance ratio μ = 0 ~ 0.16 → Mach 0.3~0.5



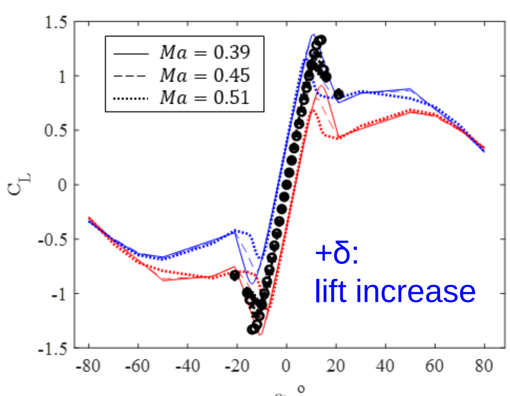
▲ CFD grid of NACA0015 15% flap



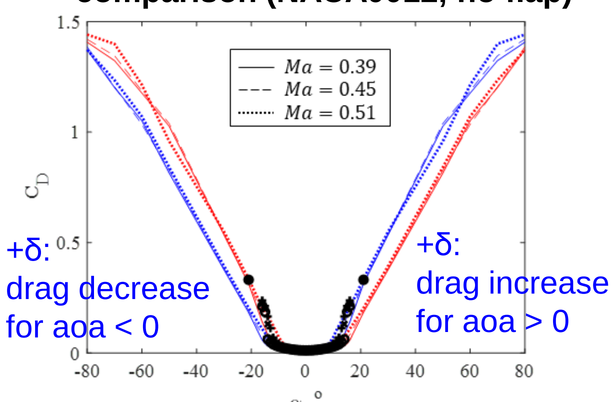
▲ Present CFD grid accuracy comparison (NACA0012, no flap)



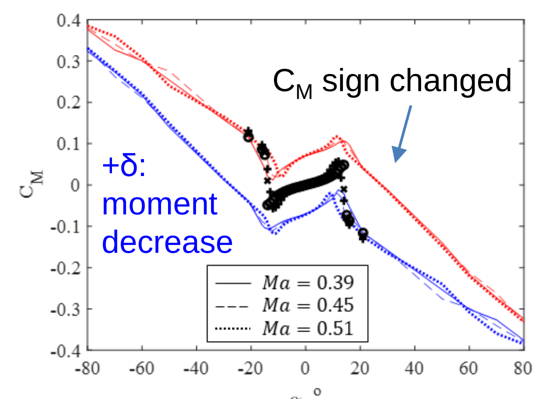
▲ Present rotor operating condition



▲ Lift coefficient



▲ Drag coefficient



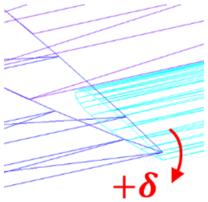
▲ Moment coefficient

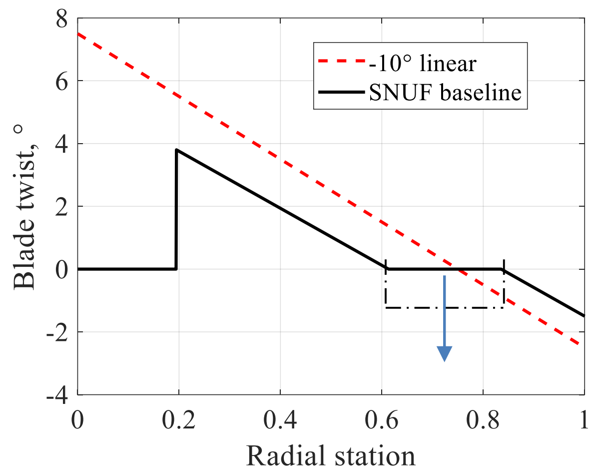
Pre-test Prediction

❖ Hover test prediction

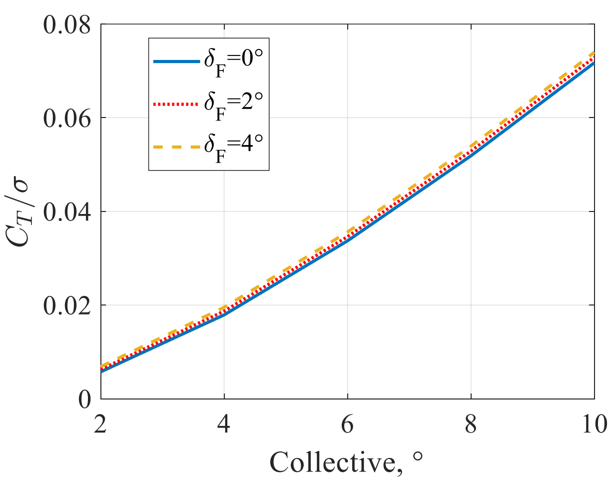
➢ Flap rotor test

- Baseline rotor performance
- Far wake 5 ages, 2˚ azimuth, 10˚ spatial step
- Flap deflection (steady and harmonic)
- Nonlinear blade twist achieved by the steady flap deflection (2˚, 4˚, 6˚, 8˚, 10˚)
- Positive flap deflection:
  thrust and torque slightly increase, no FM variation

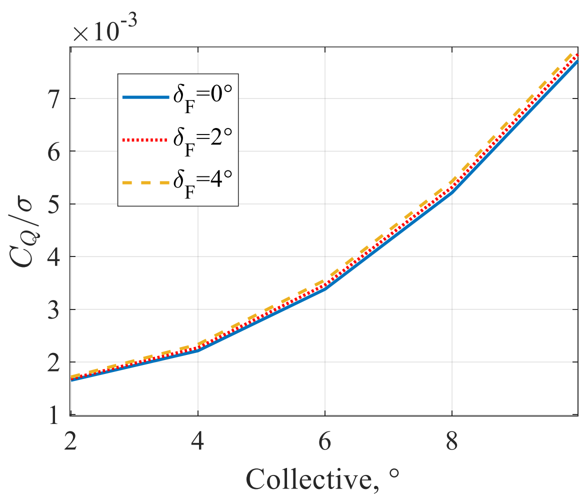




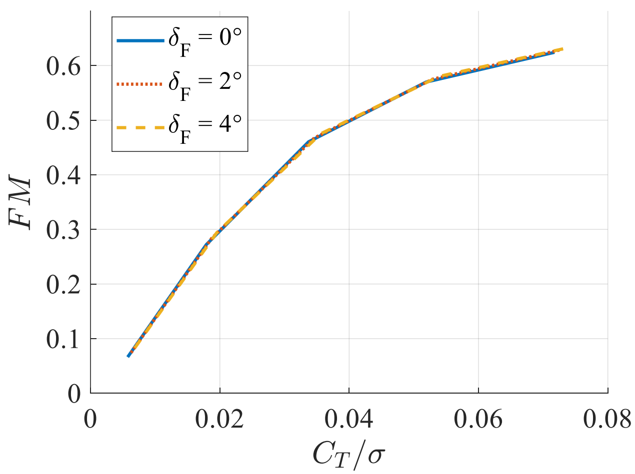
▲ SNUF blade effective twist due to the steady flap deflection



▲ Blade loading vs collective



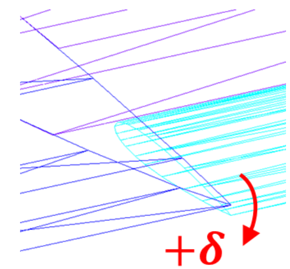
▲ C_Q/σ vs collective



▲ Steady flap sweep F.M.

Pre-test Prediction

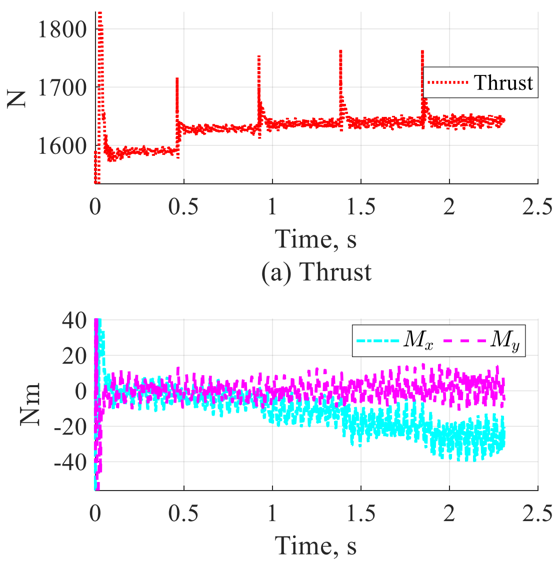
❖ Wind-tunnel test prediction



➢ Isolated rotor in the forward flight, fixed collective

- Wind-tunnel speed 30 m/s ($\mu = 0.162$), shaft angle $\alpha_s = -6°$
- Steady collective mode flap deflection sweep (2˚, 4˚, 6˚, 8˚, 10˚)
- Thrust increased most when 0˚ → 2˚
- Control authorities: rolling moment > pitching moment
- **Flapped section pitching moment drives the entire blade to the opposite AOA**
- A soft in-plane blade responds in a ‘control reversal’ mode

→ Additional control phase lead or lag will be induced

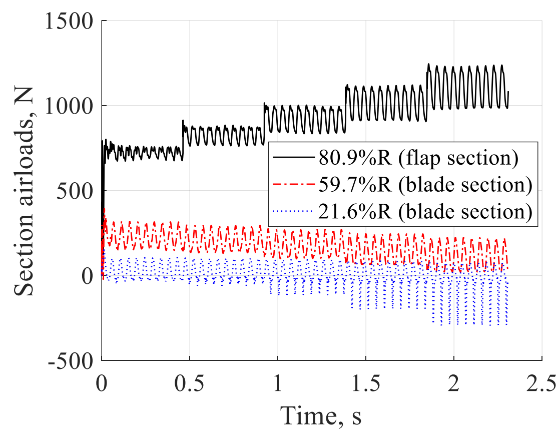


(a) Thrust

(b) Rolling and pitching moment

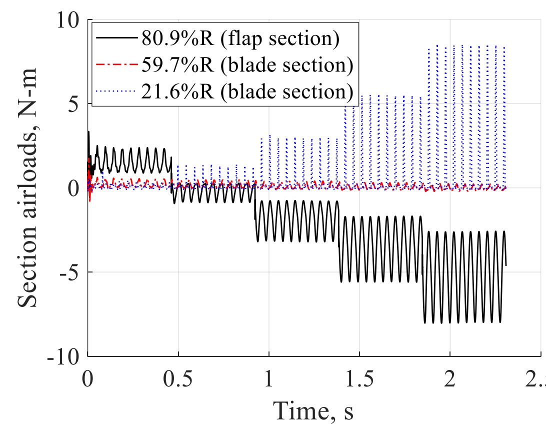
▲ **Propulsive loads control authorities**

+δ:
lift increase



▲ **Sectional lift**

+δ:
moment
decrease



▲ **Sectional pitching moment**

Contents

Conclusion

❖ Conclusion and test schedule

➢ Conclusion

- SNUF blade design: blade structural design, test and analysis
- SNURTS preparation: 3m-diameter 75HP class Mach-scaled rotor test stand

➢ Test schedule and future works

- **Hover test schedule: April ~ May 2023**
- SNUF baseline rotor test (passive flap)
  - RPM: 1,100 ~ 1,300 RPM
  - Collective sweep: 2°~12°
- 1- active flap actuation test
- 4- active flap actuation test
- Future work: 5-hole fast response probe for wake measurement
- Wind-tunnel tests on ROKAFA

Thank you

Appendix

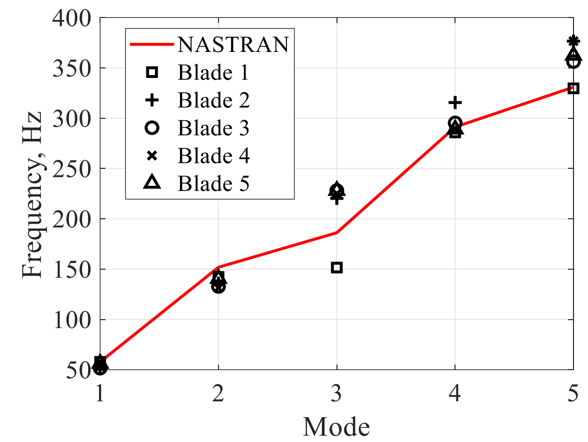
❖ Blade preliminary structural test*

➢ Tensile test

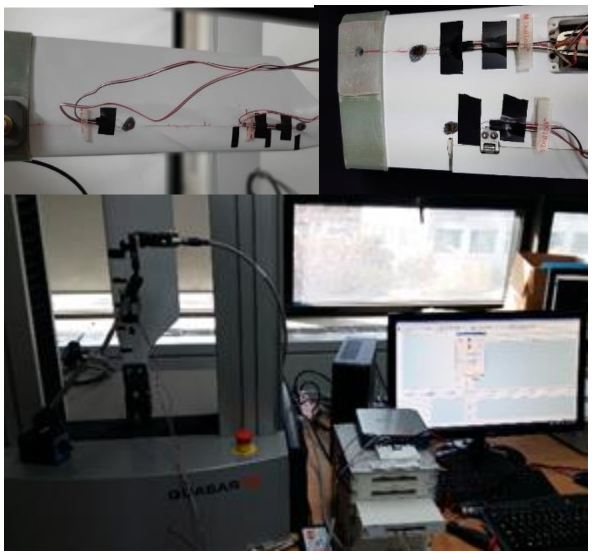
- Root and flap component safety margin > 2

➢ Blade modal test

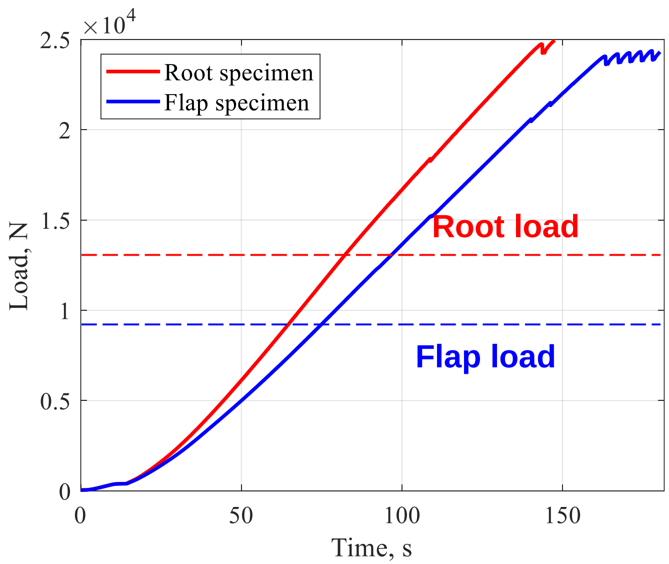
- Blade No. 1 has 20% lower torsional frequency
- Blade Nos. 2~5: within 10% frequency difference



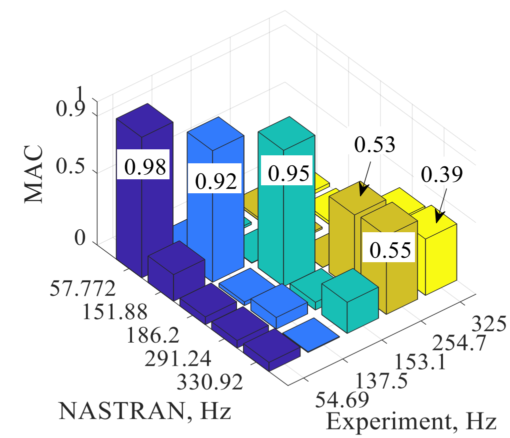
▲ Blade modal test



▲ Tensile test



▲ Root and flap component tensile load



▲ MAC plot for Blade #1

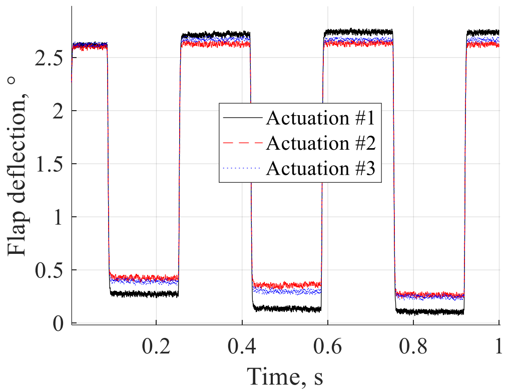
*Im, B. U., Lee, C. B., and Shin, S. J., "Experimental Evaluation on a Mach-scaled SNUF Blade for Active Vibration Control," 45th European Rotorcraft Forum, Poland, 2019

Appendix

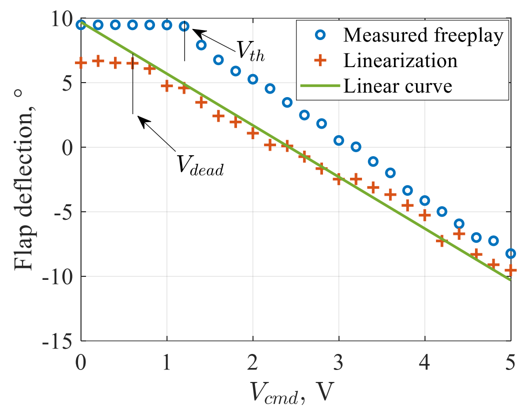
❖ Flap rotor blade dynamics measurement

➢ Bench test

- Flap deflection: measured by the potentiometer and calibrated by the digital protractor
- DAQ: 0 ~ 5 V → 0 ~ 100 V by amplifier
- Linearization of the flap driving mechanism

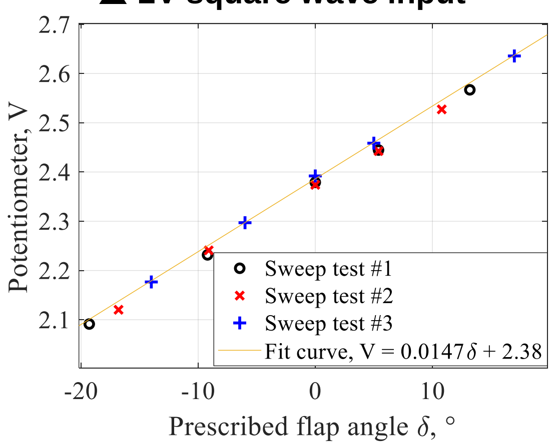


▲ 2V square wave input

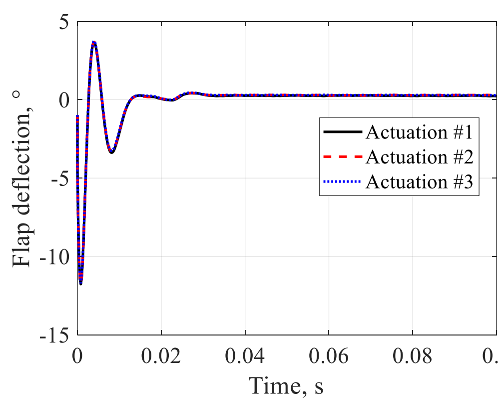


▲ Linearization of the flap driving voltage

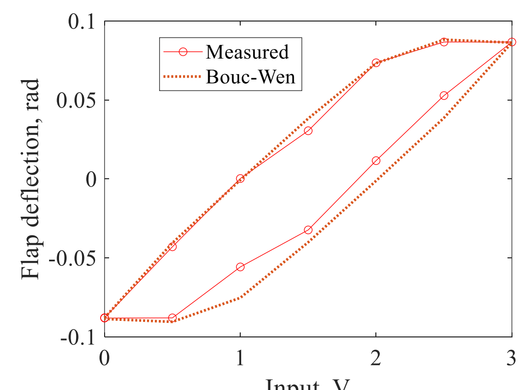
$$V_{cmd}^{*} = \frac{V_{sat} - V_{th}}{V_{sat} - V_{dead}}(V_{cmd} - V_{dead}) + V_{th}$$



▲ Flap deflection calibration



▲ 2V step input responses



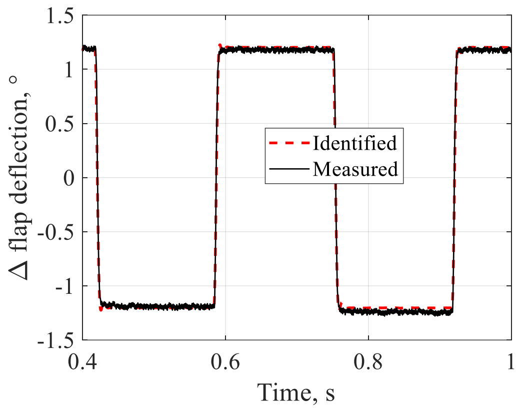
▲ Bouc-Wen hysteresis modeling

Appendix

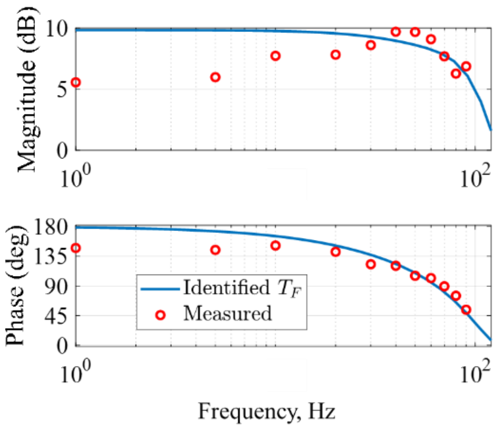
❖ Flap rotor blade dynamics measurement

➢ Bench test

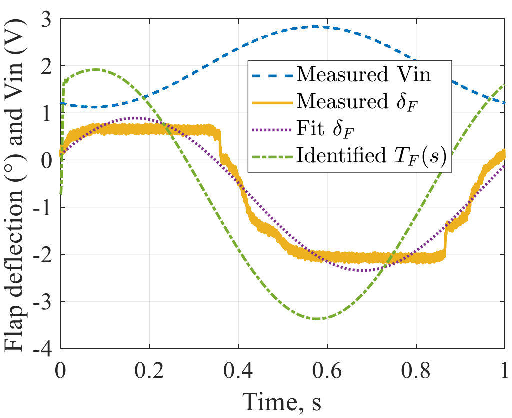
- 3rd order flap deflection/command voltage transfer function identified



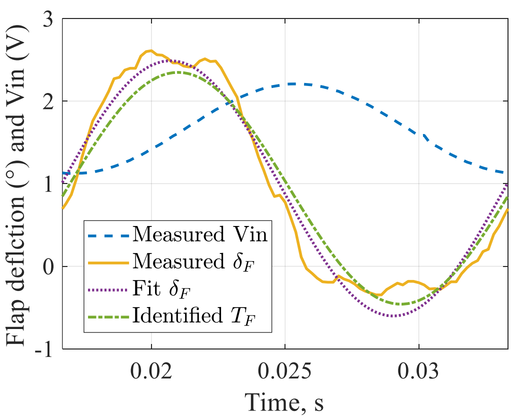
▲ Transfer function identification in time-domain



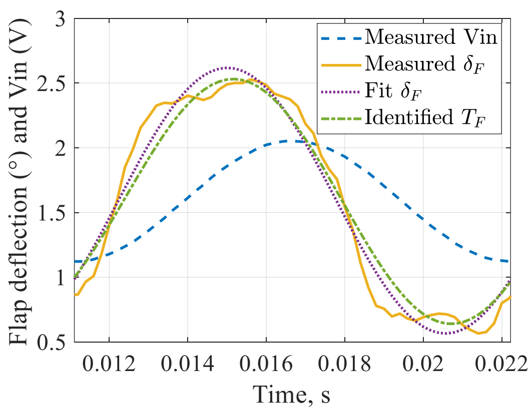
▲ Frequency response



▲ 1 Hz



▲ 60Hz



▲ 90Hz

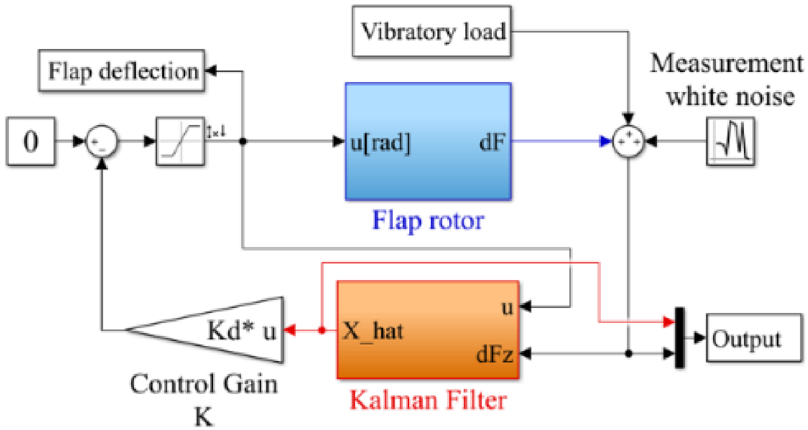
Appendix

❖ IBC control design and simulation

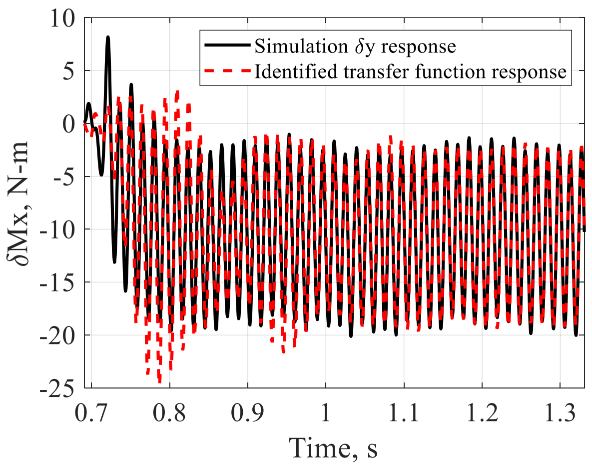
➢ Controller design

- Sub-optimal LQR/LQE-observer baseline*
- LTI system identification using the dedicated $\mathrm{N}, \mathrm{N} \pm 1/\mathrm{rev}$ input by the discrete Fourier filter**
- Output regulation:

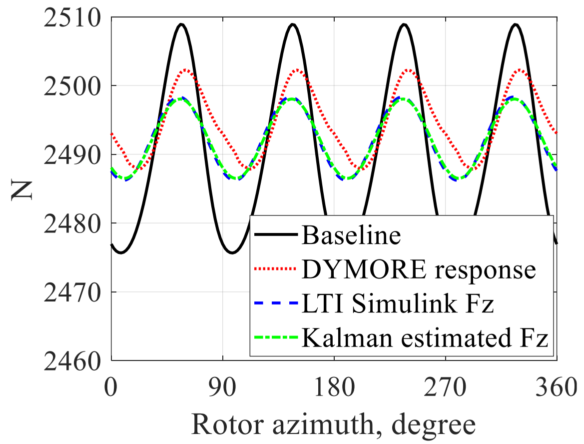
$$J = \frac{1}{2}\int_0^\infty y^T Q y + u^T R u \, dt = \frac{1}{2}\int_0^\infty x^T C^T Q C x + u^T R u dt$$



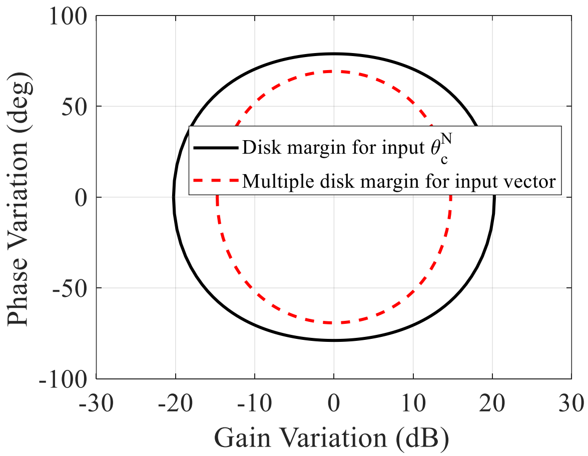
▲ LQG rotor vibration reduction control design



▲ Flap rotor system identification



▲ Closed-loop simulation



▲ Relative stability analysis

*Im, B., Lee, C., Kee, Y., and Shin, S.J., "Investigation of Linear Higher Harmonic Control Algorithm for Rotorcraft Vibration Reduction", Journal of Dynamic Systems Measurement and Control, Vol. 143, (1), 2021, pp. 011008-1 - 011008-12.
**Im, B., Kang, S., Kong, G., Park, S., Cho, H., and Shin, S. J., "Improved Higher Harmonic Control Analysis for HART-II Rotor", The Vertical Flight Society's 77th Annual Forum & Technology Display, May 2021