Presented for Chofu Aerospace Center, JAXA
Organized by Japan Helicopter Society

Recent Development on Rotorcraft CSD (Comprehensive Structural Dynamics) Code at Konkuk University

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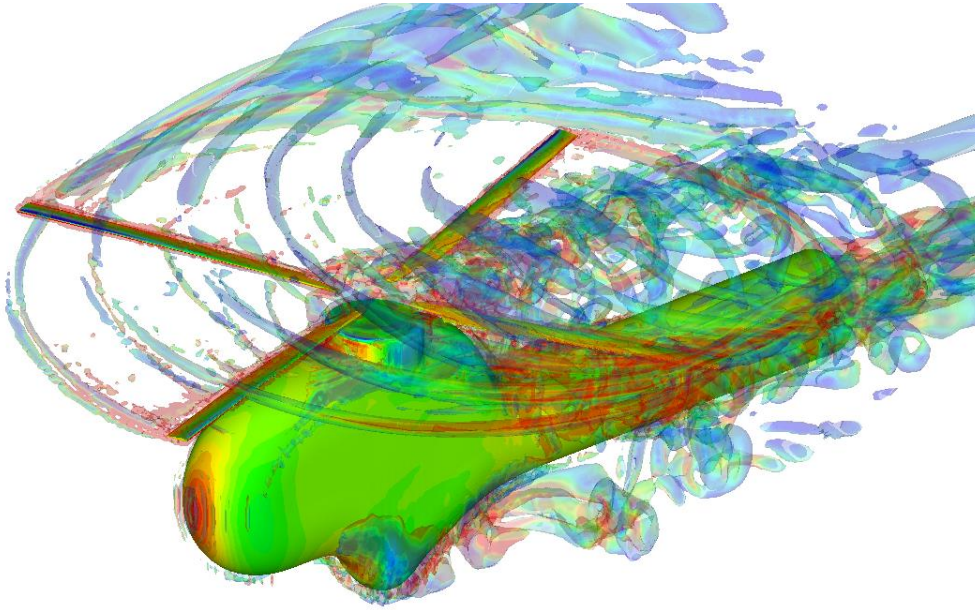
2/19/2024

Part I

Introduction



Intro: Speaker

- **Prof. Sung Nam Jung**
- **Research Interests:**
  - Rotorcraft Aeromechanics / Aircraft Structures / Optimum Design
- **Work Experience**
  - 2006 – Current, Professor, **Konkuk University**, Seoul
  - 2023 – 2023, Visiting Scientist, **KARI**, Daejeon
  - 2018 – 2018, Visiting Scientist, **DLR**, Braunschweig, Germany
  - 2011 – 2012, Visiting Scientist, **NASA Ames**, Moffett Field, CA
  - 1997 – 1999, Post Doctor, **Univ. of Maryland**, College Park
  - 1994 – 2006, Professor, **Jeonbuk National Univ.**, Jeonju
- **Professional Service**
  - AIAA Associate Fellow (Since 2014)
  - Associate Editor, Journal of the American Helicopter Society (2015 – 2022)
  - Associate Editor, Int. Journal of Aeronautical & Space Sciences (2011 – 2019)
  - President, Rotorcraft Systems Division, KSAS (2014 – 2015)
  - President, VFS Korean Chapter (2018 – 2021)
  - Tech Program Co-Chair/Chair, ARF 2012/2018, Rotor Korea 2007/2009

A doll in glasses (2000)

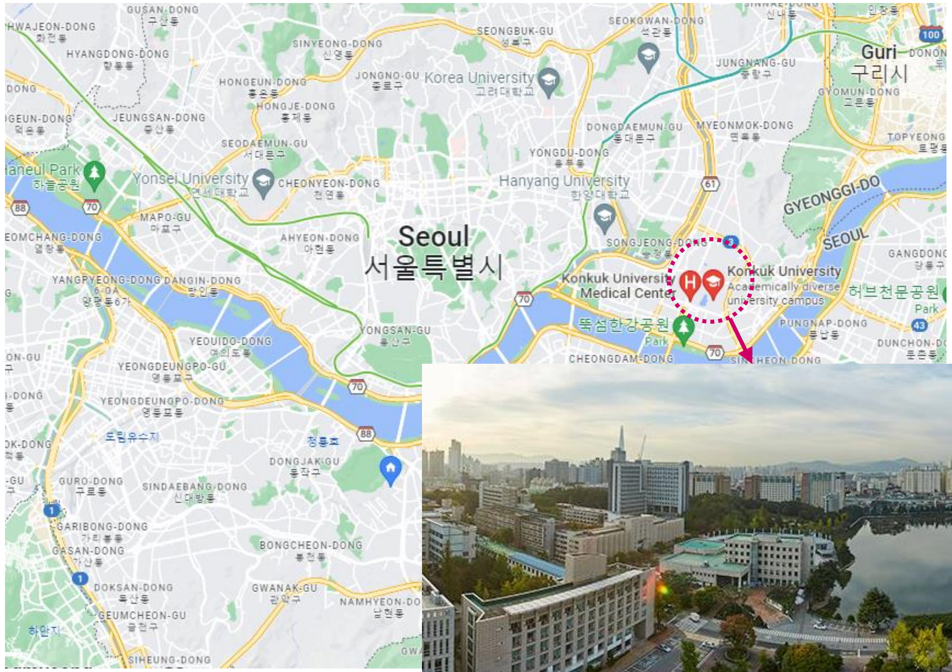
Intro: Konkuk University

Konkuk Univ., Seoul

KARI / ADD, Daejeon

Chonbuk National Univ.
Jeonju

Jeju Island (7^{th} ARF, 2018)

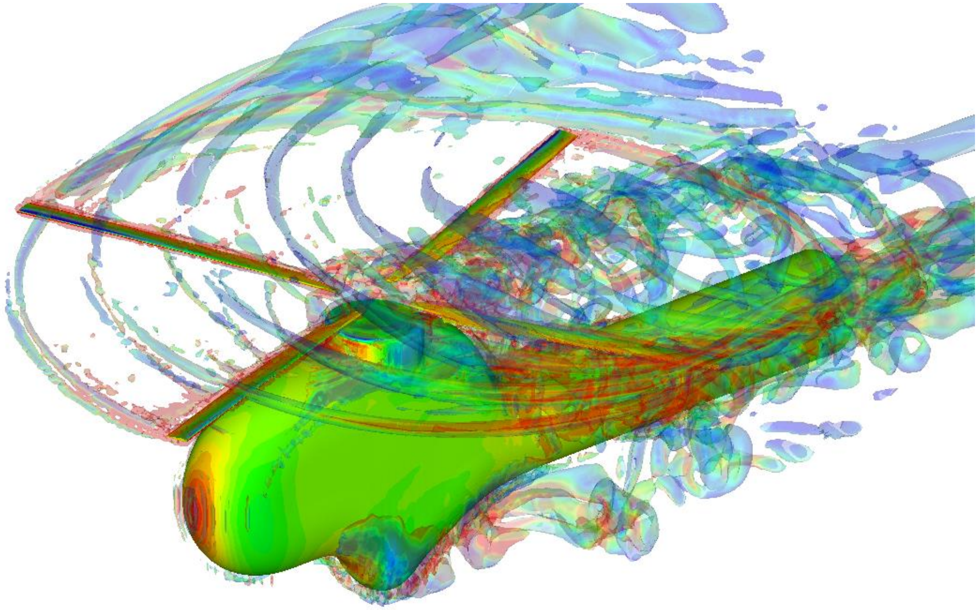


Konkuk Univ., Seoul

- **Konkuk University (KU):**
  - Located in the northeastern region of Seoul
  - About 30k undergraduate plus graduate students
  - Aerospace Eng. program started in 1990
  - Currently 12 faculty members at Aerospace Eng.

Part II

Rotorcraft CSD Code

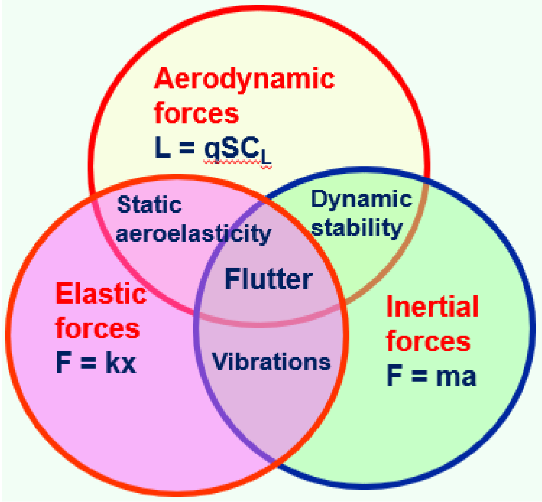


What Does the Rotorcraft CSD mean?

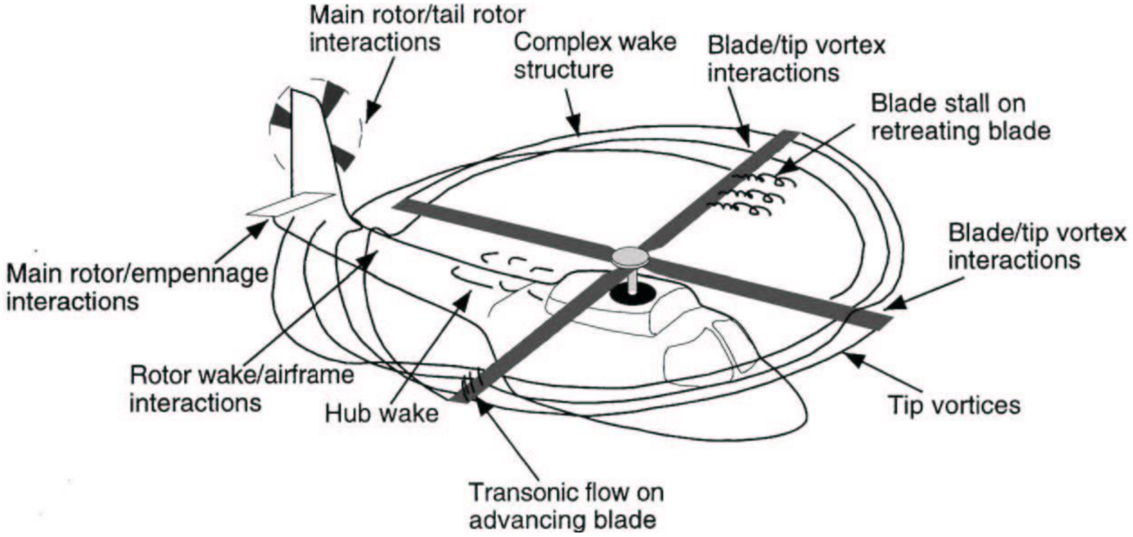
❖ **Rotorcraft CSD (Comprehensive Structural Dynamics): Disciplines related closely with "Aeromechanics" or "Aeroelasticity"**

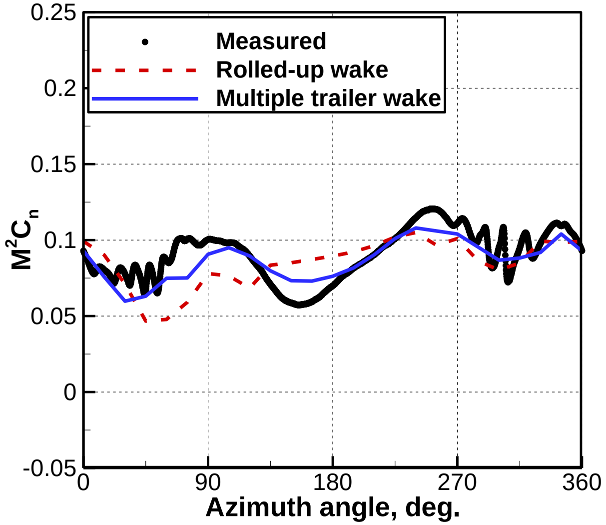
- **Aeroelasticity:** A branch of applied mechanics that studies the phenomena associated with the interactions between the inertial, elastic, and aerodynamic forces acting an elastic body
- **Aeromechanics:** The branch of aeronautical engineering science dealing with equilibrium, motion, and control of elastic rotorcraft in air (by W. Johnson)
- **Comprehensive:** Complete or broad covering (by Merriam-Webster)

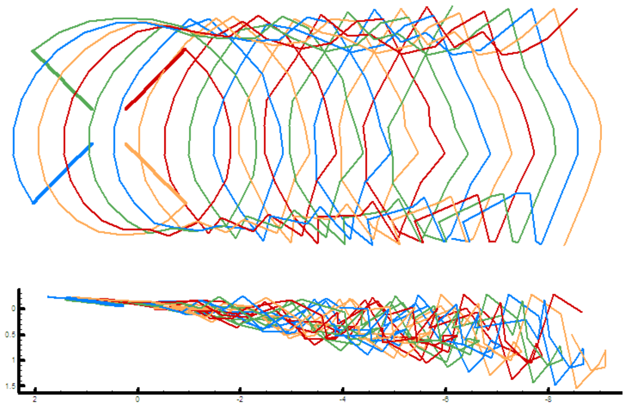
❖ **CSD code:** Key S/W dealing with rotorcraft aeromechanics analysis



Disciplines associate with Aeroelasticity







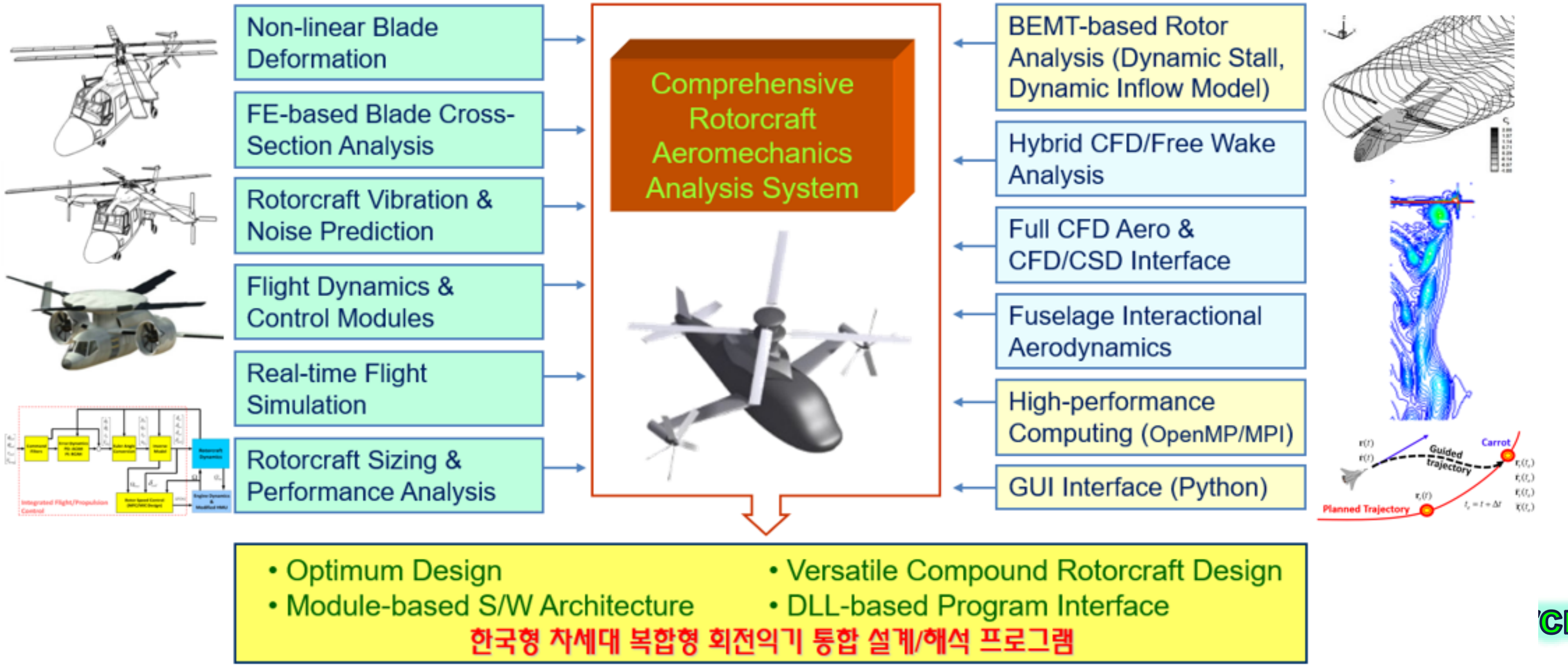
HART II validation (BL)

Source: J. G. Leishman, 2006

What Functions Needed for Rotorcraft CSD Codes?

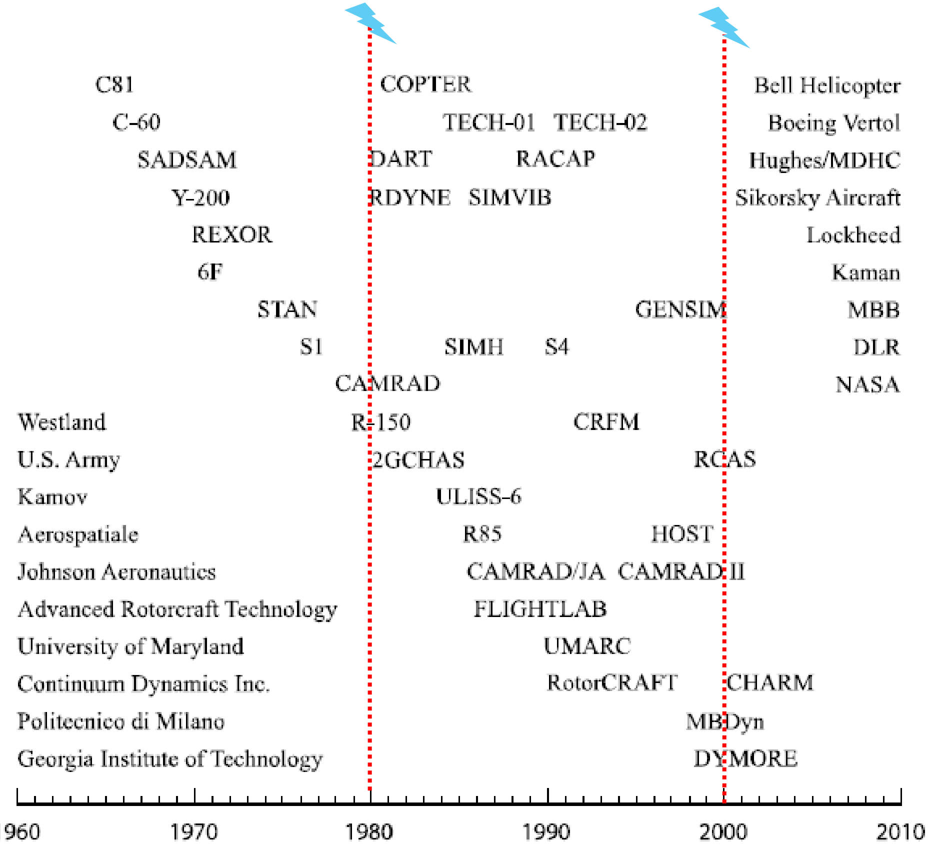
❖ Core features of generic rotorcraft CSD codes

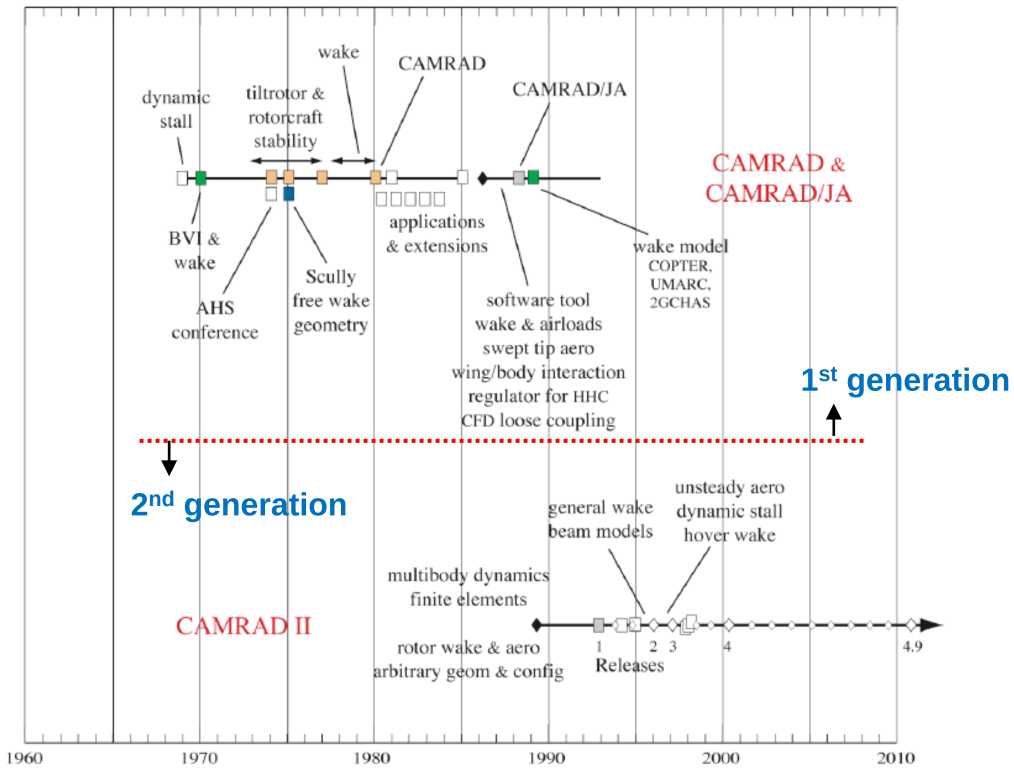
- Rotorcraft trim (wind tunnel, free flight) analysis
- Elastic plus rigid beams with large deformation (linear or nonlinear)
- Internal aerodynamics (quasi-steady or unsteady) with inflow models (uniform or prescribed/free wake)
- Multibody capability to model arbitrary rotor types, joints, linkages, dampers, and elastic bodies
- Loads (blade & hub loads) and vibration (airframe) prediction
- Aeroelastic or aeromechanical instability
- Link to external aerodynamics (e.g., CFD/CSD coupling)



How Rotorcraft CSD Codes Developed?

- ❖ **Rotorcraft CSD codes: Mostly developed by helicopter companies**
- ❖ **Technology drivers in CSD code developments**
  - **1970s: Blade elastic models (nonlinear); 1980s: Advanced inflow models (prescribed/free wake)**
  - **2000s: Multi-body formulations (joints, linkages)**





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Source: W. Johnson, 2012

What Rotorcraft CSD Codes Available?

❖ **Various rotorcraft CSD codes developed worldwide**

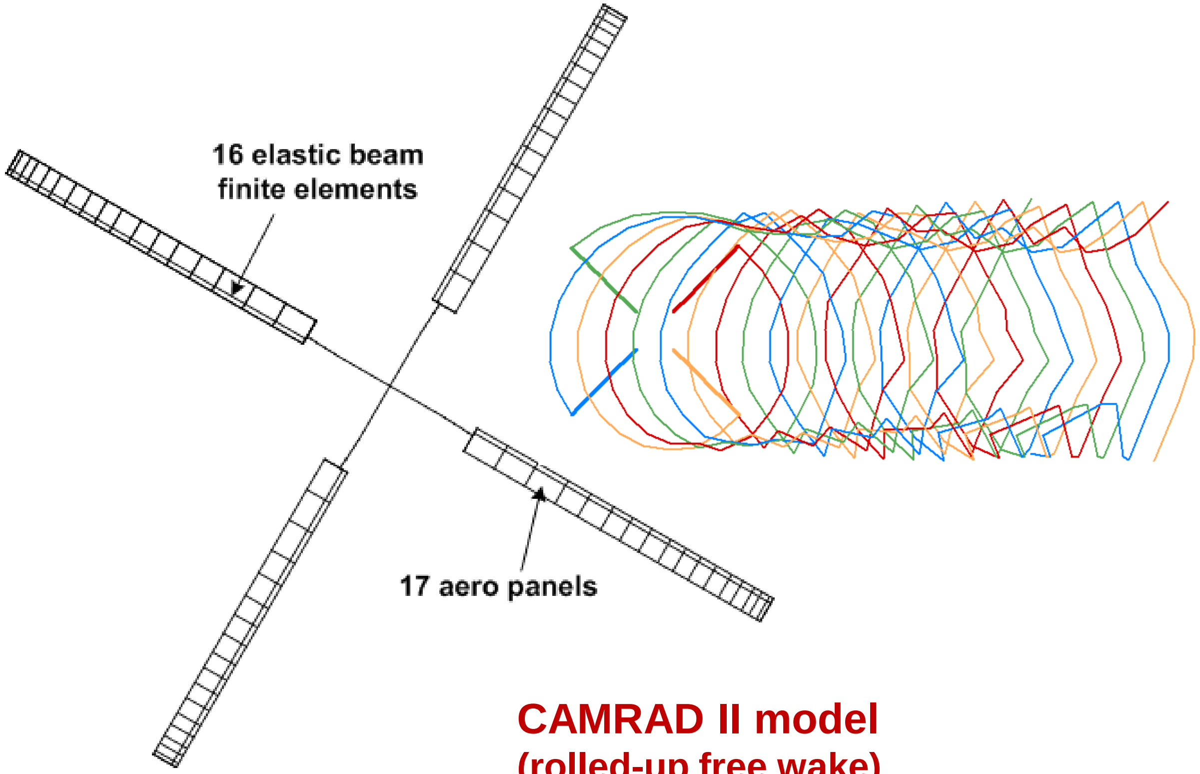
Program	Developer	Main Features	Beam Model
CAMRAD II	Johnson Aeronautics	Building block approach	FE-based multi-body, GEB (MLDB + Rigid)
DYMORE	Georgia Tech / Univ. of Maryland	Multi-body dynamics	FE-based GEB
RCAS	US Army / ART	Hierarchical FE	Nonlinear GEB (2GCHAS)
FLIGHTLAB	ART	Handling qualities & real time simulation	Nonlinear beam
UMARC	Univ. of Maryland	Non-profit (academic)	FE-based MLDB (Hodges-Dowel)
HOST	Eurocopter	FEM, Hierarchical inflow	Elastic
S4	DLR	FEM, Semiempirical	Linear elastic (Houbolt-Brooks)
rMode	JAXA	Structural dynamics	Linear elastic (Houbolt-Brooks)
RDYNE	Sikorsky	Substructure decomposition (rotor-body vibration)	Elastic (Arcidiacono, 1969)
Tech-01/02	Boeing	Modular approach	Elastic
…	…	…	…

MLDB: Moderately Large Deformation Beam
GEB: Geometrically Exact Beam

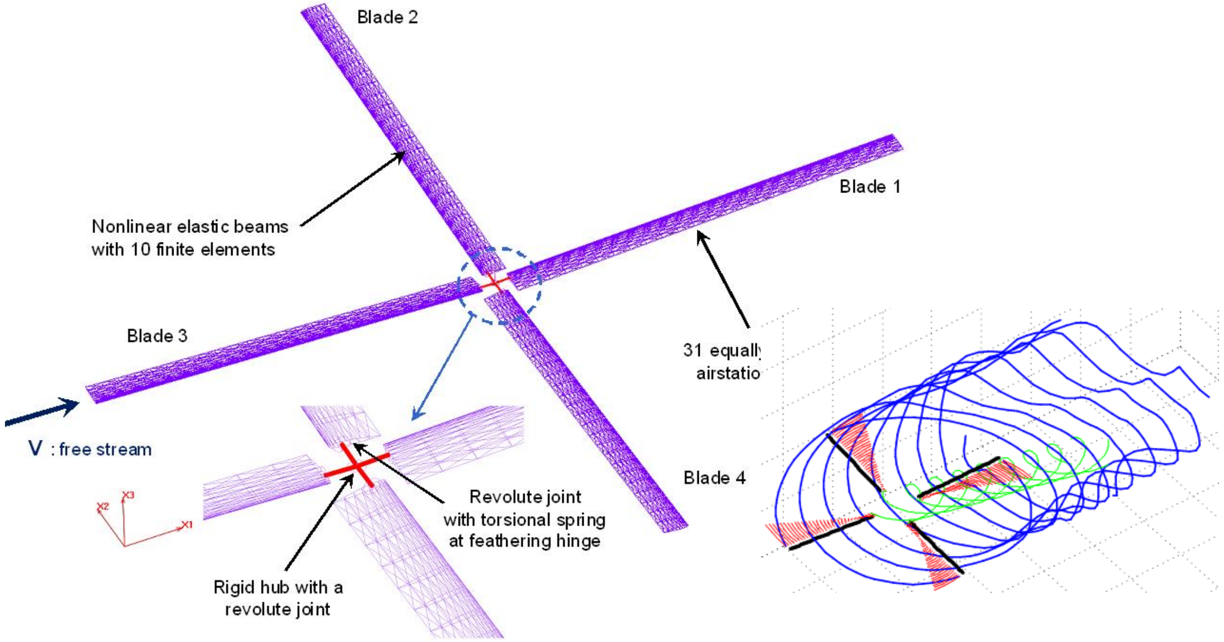
Sample CSD Results: HART II

❖ Application of sample CSD codes for the validation of HART II data

	No. of FEs	No. of aero panels	Time resolutions
DYMORE	10	31 (equally spaced)	15 deg.
CAMRAD II	16	17	1 deg.



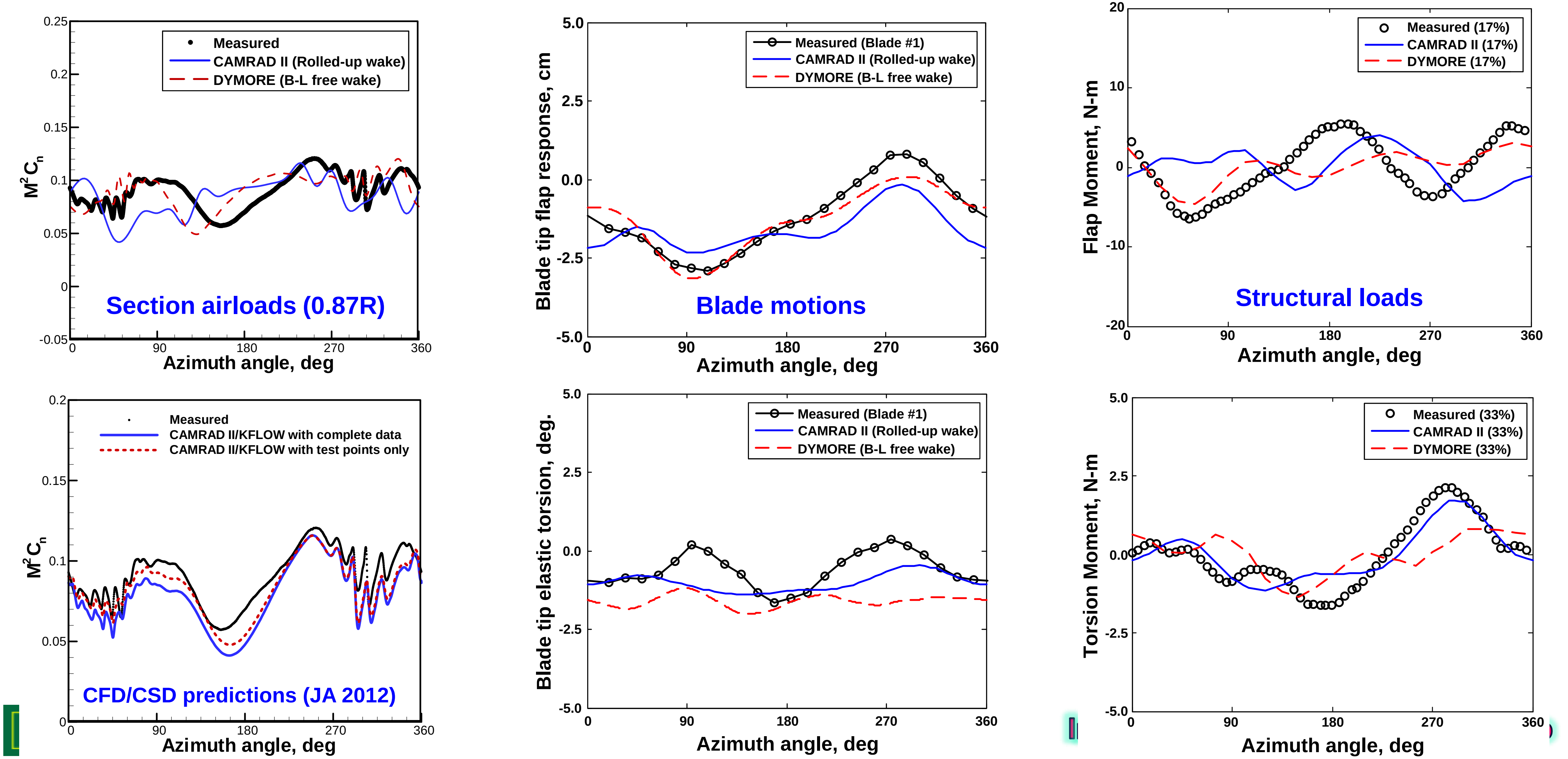
CAMRAD II model
(rolled-up free wake)



DYMORE model
(B-L free wake)

Sample CSD Results: HART II

❖ **Comparison of airloads, tip deflections, and structural loads (BL case)**



Development of K-CSD Code CoRAN

Goals:

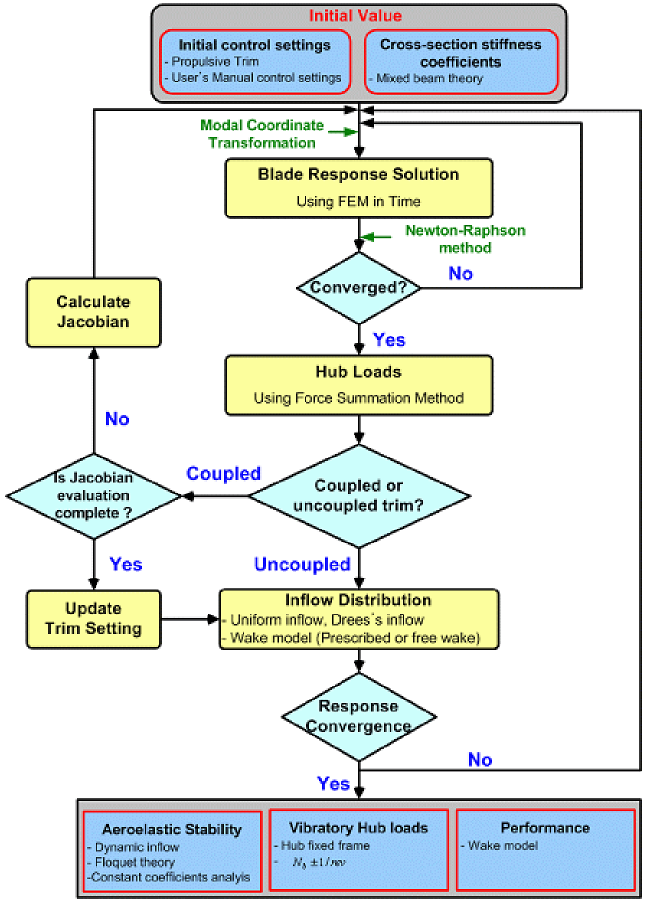
- Develop comprehensive aeromechanics analysis with the capability of predicting:
  - Rotating free vibration frequencies
  - Blade & hub loads
  - Trim, blade response, stability

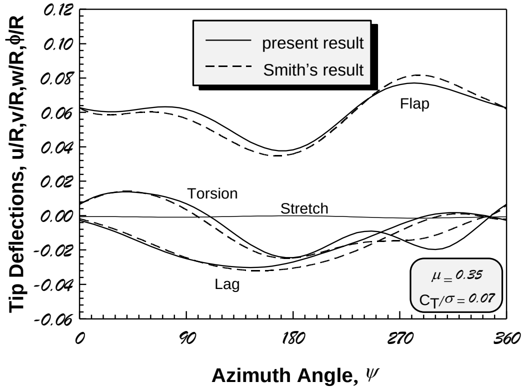
Approaches:

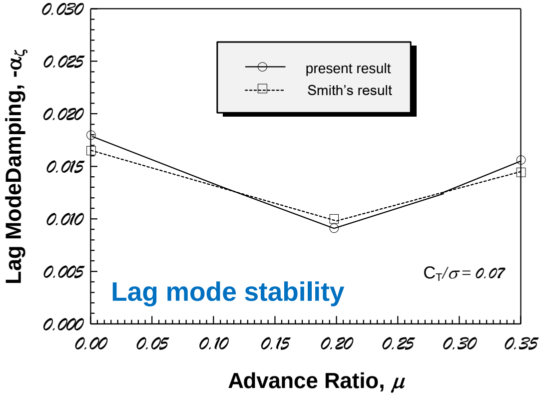
- Based on nonlinear beam theory (MLDB or GEB)
- Enabled multi-body modeling capability
- Quasi-steady or Leishman-Beddoes unsteady aerodynamic theory adopted
- Extension to free wake inflow model & loosely coupled CFD/CSD approach

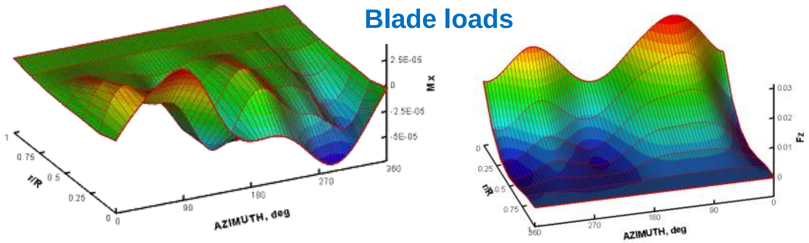
Outcomes:

- General purpose rotorcraft CSD program
- Integration into rotorcraft M&S (modeling and simulation) system
- Possible applications for new helicopter developments in Korea

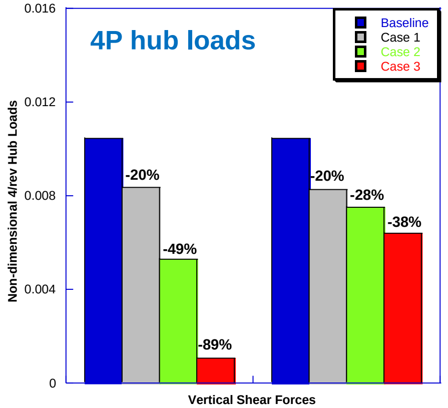








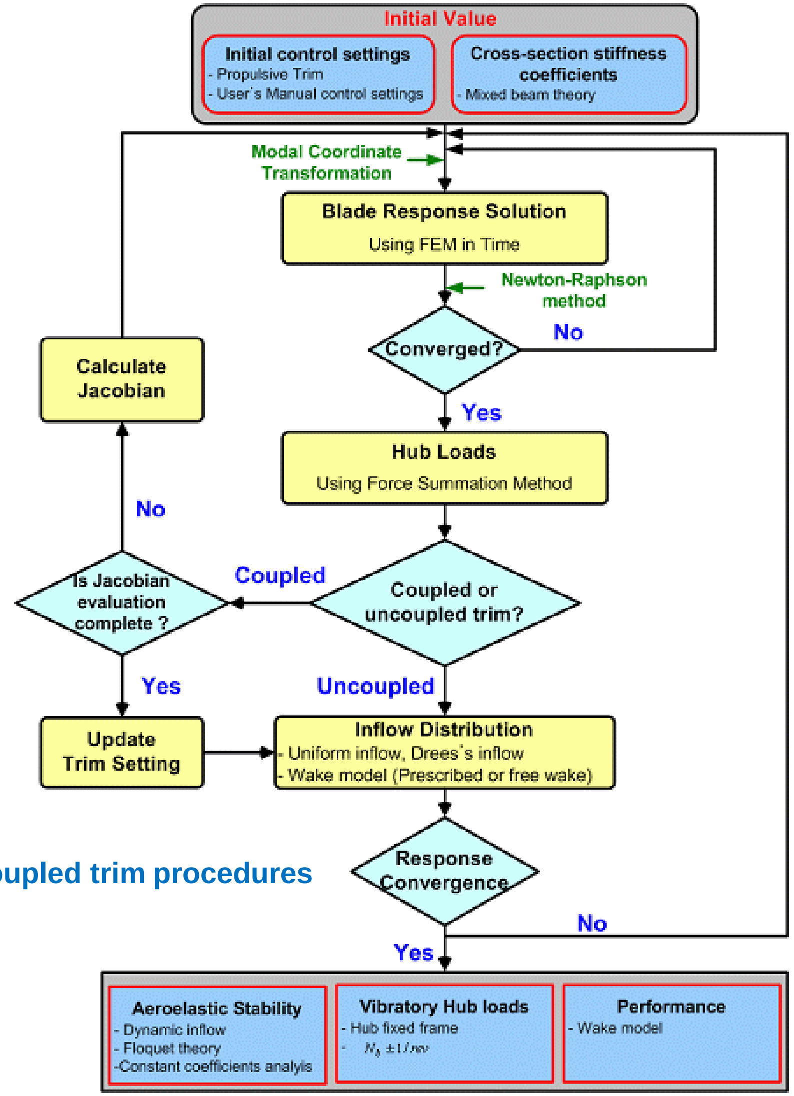
Jung et al., AIAA J, 2002



Intro: K-CSD Code CoRAN

❖ **Flow diagram of K-CSD code CoRAN (Comprehensive Rotorcraft Aeromechanics aNalysis) System**

Code under development with the collaboration of KU & JBNU



Coupled trim procedures

Free flight / Wind tunnel trim
Autopilot trim

Nonlinear beam (MLDB or GEB)
Multi-body formulation (control linkages, lag damper, *rotor-rotor, rotor-wing*)
Single or *multiple load path* blades (articulated, hingeless, bearingless rotor)

External interface: Blade section properties
Ksec2D

Blade response: steady & transient
Blade & hub loads
Rotor-body coupled vibration

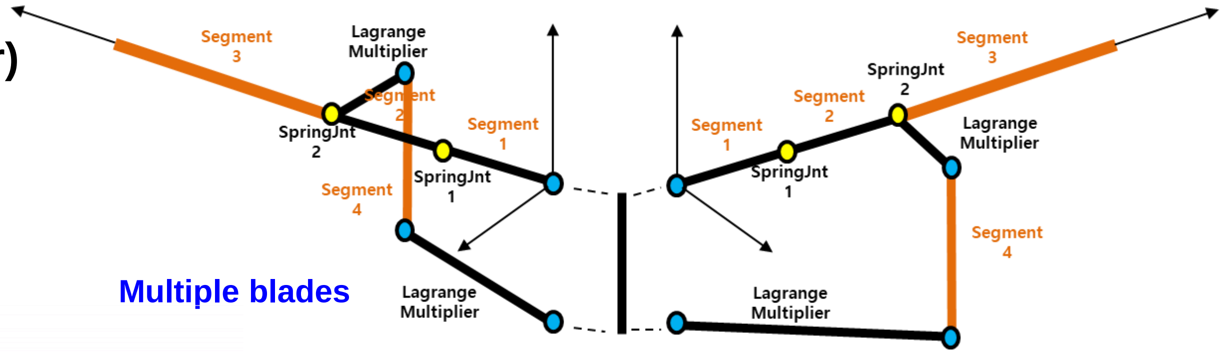
Analytic / C-81 table
Inflow models: Uniform / Linear / *Free wake*
Peters-He dynamic inflow
External aero interface
CFD/CSD coupling

Aeroelastic instability (Flutter)

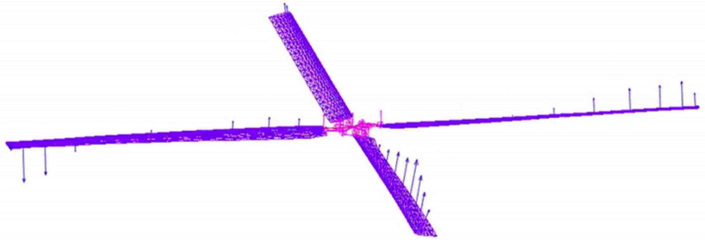
K-CSD Code CoRAN: An Overview

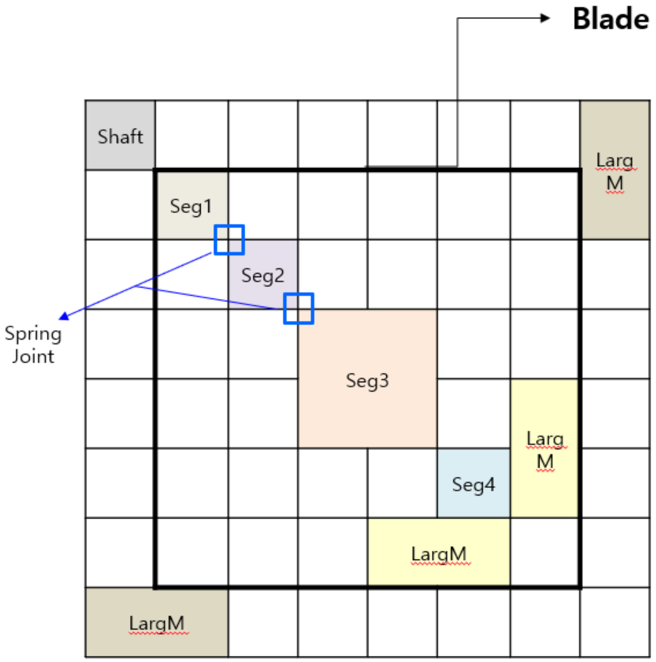
❖ Multi-body formulation

- **Multi-body models (e.g., control linkages, lag damper)**
- **Multiple load paths (e.g., bearingless rotor)**
- **Multiple rotors (e.g., coaxial, tilt rotors)**
- **Rotor-body coupled vibration analysis (MSC.NASTRAN, ICARUS)**
- **Rotor-wing coupling**

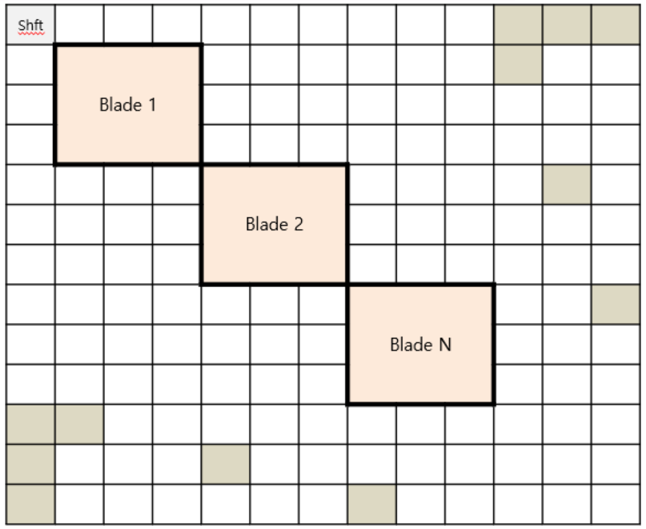


Multiple blades

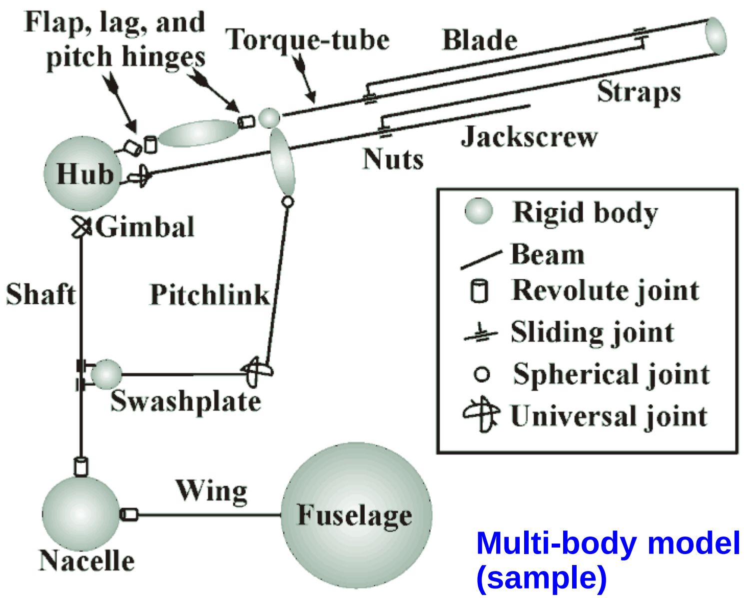




Single blade



Multiple blades/rotors



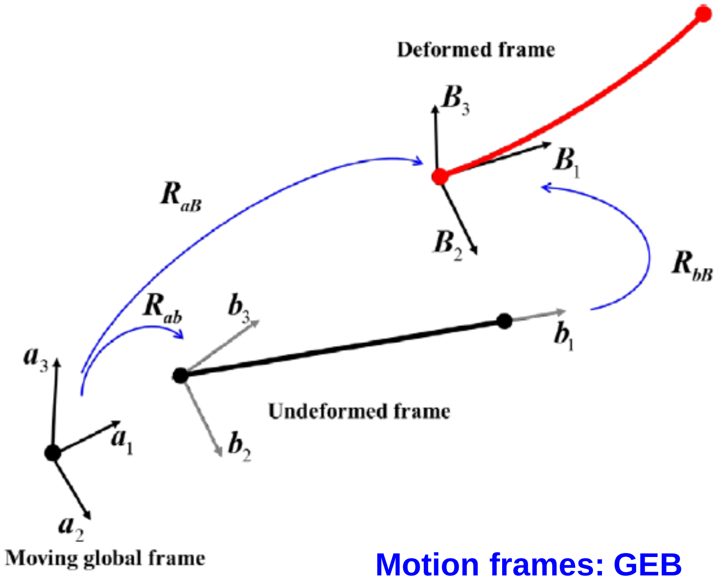
Multi-body model (sample)

K-CSD Code CoRAN: An Overview

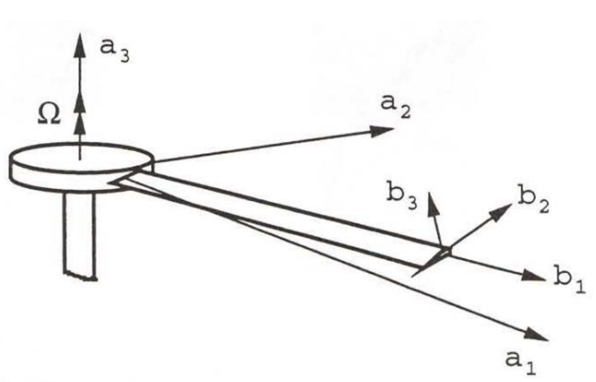
- ❖ **Nonlinear beam kinematic models: Two-track approach**
- ❖ **Large deformation GEB (geometrically exact beam) model**
  - **Based on Hodges' (1990) mixed variational beam formulation**
  - **Initial code developed from the work of Im et al. (2020)***
- ❖ **Moderately large deformation beam (MLDB) model**
  - **Based on Hodges & Dowell's (1974) 2nd order geometric nonlinearity**
  - **Initial code developed from the work of Jung et al. (2002)****

* Im, B., Cho, H., Kee, Y., & Shin, S. (2020). Geometrically exact beam analysis based on the exponential map finite rotations. *Int. Journal of Aeronautical and Space Sciences*, *21*(1), 153-162.

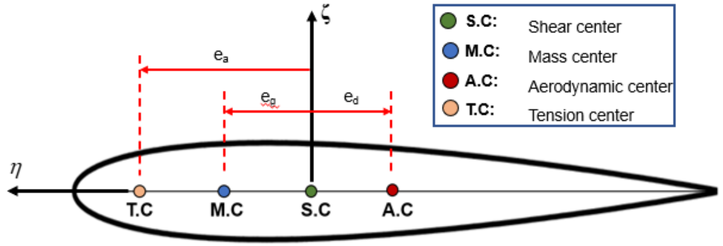
** Jung. S. N., Kim. K. N., and Kim. S. J., "Forward Flight Stability Characteristics for Composite Hingeless Rotor Rotors with Transverse Shear Deformation", AIAA Journal, 40(9), 2002



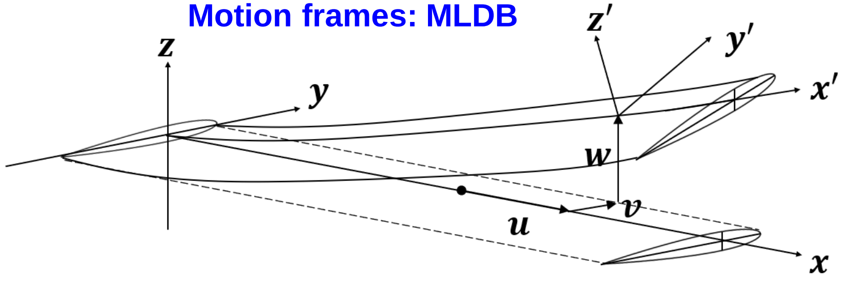
Motion frames: GEB



a : rotating global frame
b : blade's undeformed reference frame
B : blade's deformed reference frame



Motion frames: MLDB

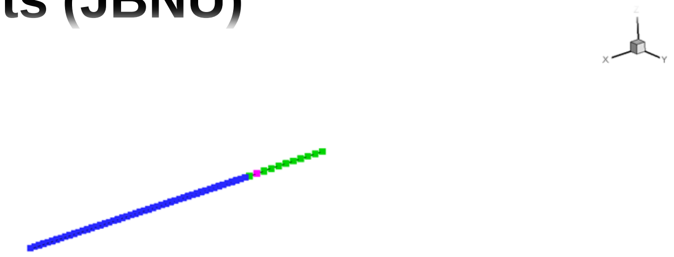


Undeformed coordinate system

K-CSD Code CoRAN: An Overview

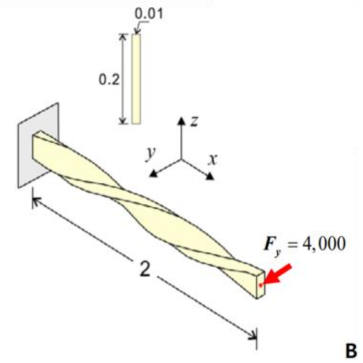
❖ **Large deformation, nonlinear GEB model: Validation of results (JBNU)**

Governing equation: $$\int_{t_1}^{t_2}\int_0^l \left[\delta(K-U)+\overline{\delta W}\right]dx_1 dt = \overline{\delta \mathcal{A}}$$

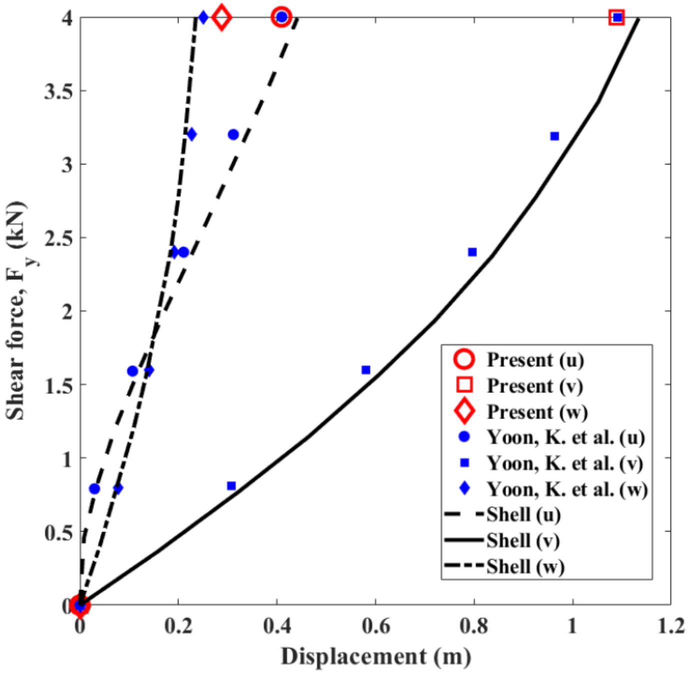


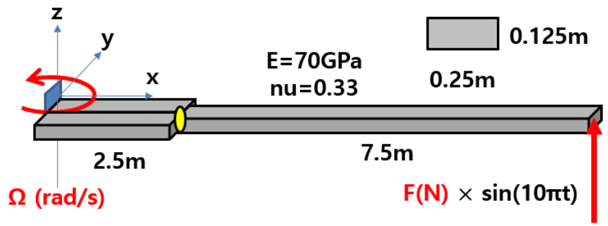
$$\int_{t_1}^{t_2} \delta X^T\left[F_S(X,\dot{X}) - F_L\right]dt = 0$$

$$X = \left[\hat{F}_1^T\ \hat{M}_1^T\ u_1^T\ \theta_1^T\ F_1^T\ M_1^T\ P_1^T H_1^T \ldots u_N^T\ \theta_N^T\ F_N^T\ M_N^T P_N^T\ H_N^T\ \hat{u}_{N+1}^T\hat{\theta}_{N+1}^T\right]^T$$

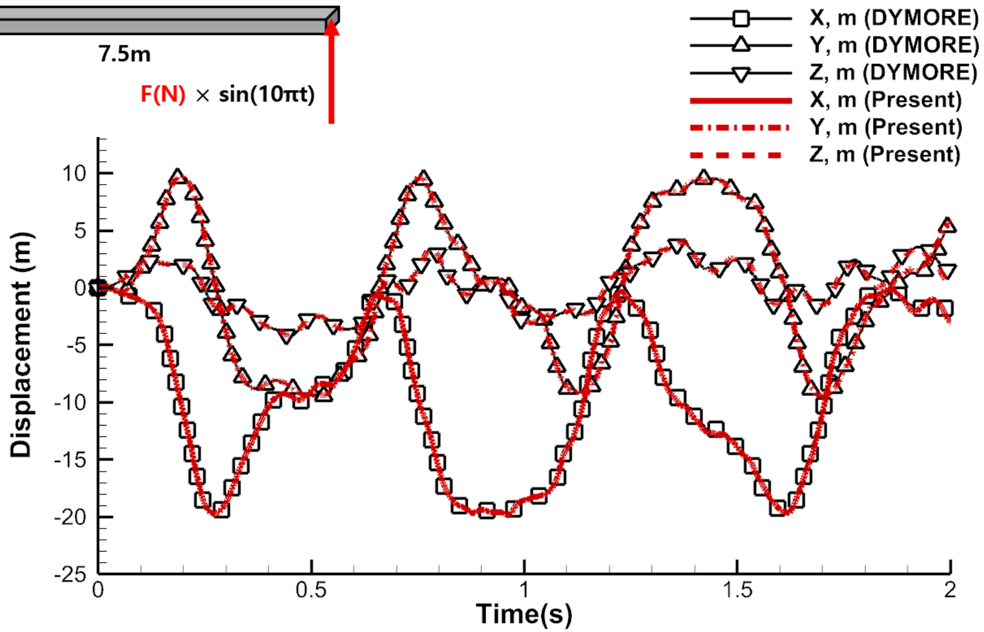


Twisted cantilevered beam (GEB)





Dynamic response analysis (GEB)



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K-CSD Code CoRAN: An Overview

❖ Nonlinear MLDB model: Validation of results (KU)

- **Governing equation:** $\delta\Pi = \int_{t_1}^{t_2} (\delta U - \delta T - \delta W) dt = 0$

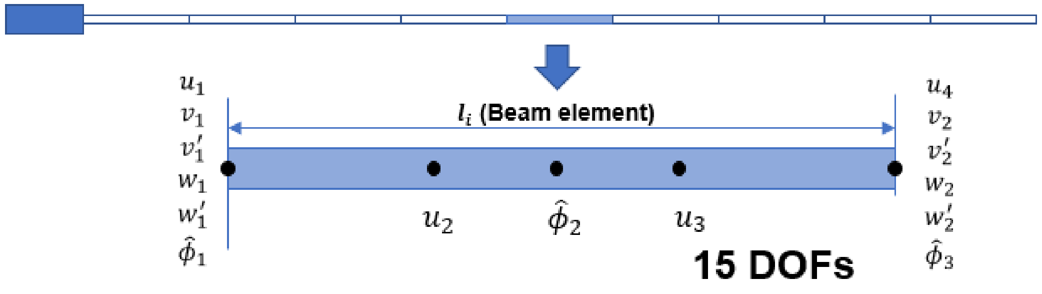
where

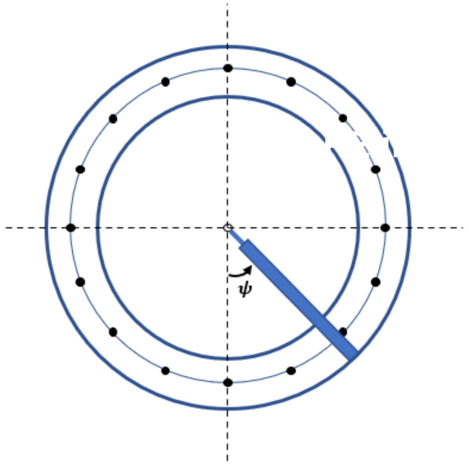
$$\delta U = \frac{1}{2}\int_0^R \iint_A (\sigma_{xx}\delta\varepsilon_{xx} + \sigma_{x\eta}\delta\varepsilon_{x\eta} + \sigma_{x\zeta}\delta\varepsilon_{x\zeta}) d\eta d\zeta dx$$

$$\delta T = \int_0^R \iint_A \rho_s \vec{V}\cdot\delta\vec{V} d\eta d\zeta dx$$

$$\delta W = \int_0^R (L_u \delta u + L_v \delta v + L_w \delta w + M_{\hat{\phi}} \delta\hat{\phi}) dx$$

- **FE responses in space & time (x, ψ):**





$$H_1(s) = \frac{2}{3}(s^4 - s^3 - 0.25s^2 + 0.25s)$$

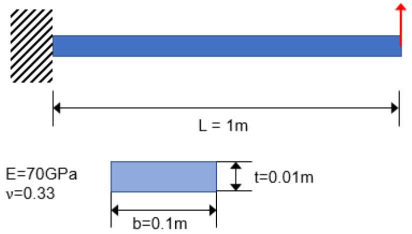
$$H_2(s) = -\frac{8}{3}(s^4 - 0.5s^3 - s^2 + 0.5s)$$

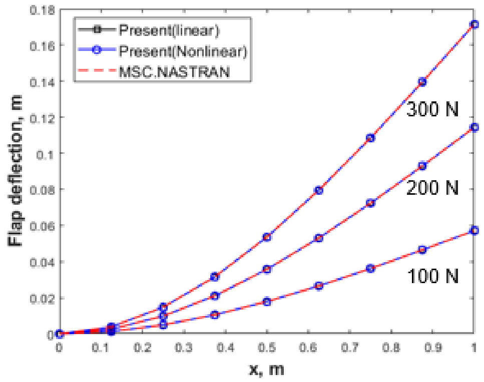
$$H_3(s) = 4(s^4 - 1.25s + 0.25)$$

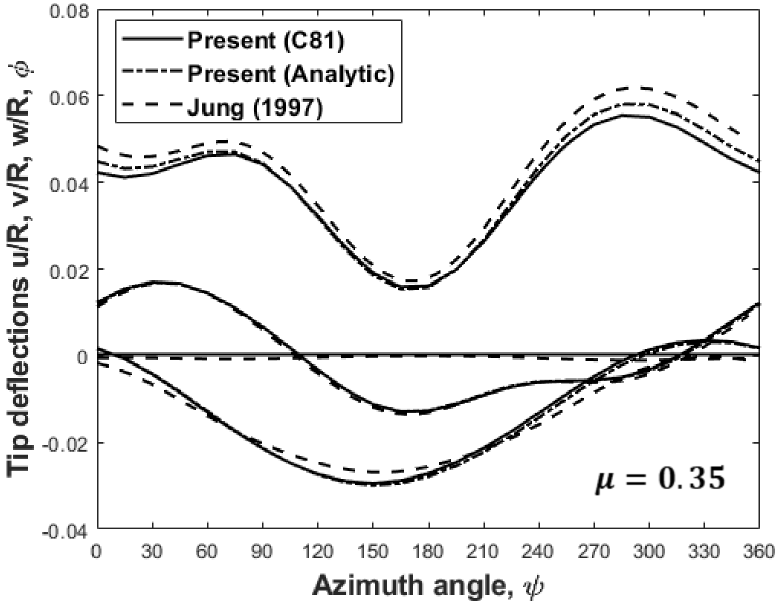
$$H_4(s) = -\frac{8}{3}(s^4 + 0.5s^3 - s^2 - 0.5s)$$

$$H_5(s) = \frac{2}{3}(s^4 + s^3 - 0.25s^2 - 0.25s)$$

ψ : 4th order shape function







Comparison of blade response solutions

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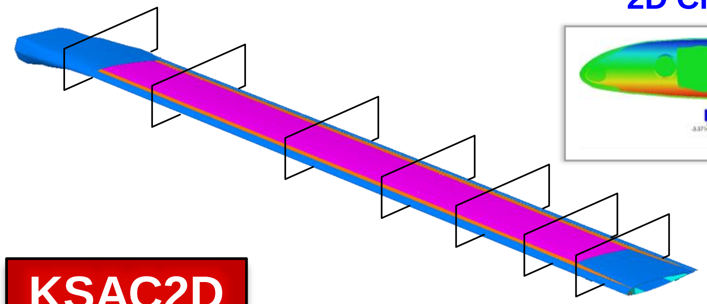
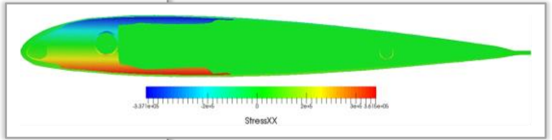
K-CSD Code CoRAN: An Overview

❖ Interface with a general blade cross-section analysis program KSAC2D

3D geometry of rotor blades

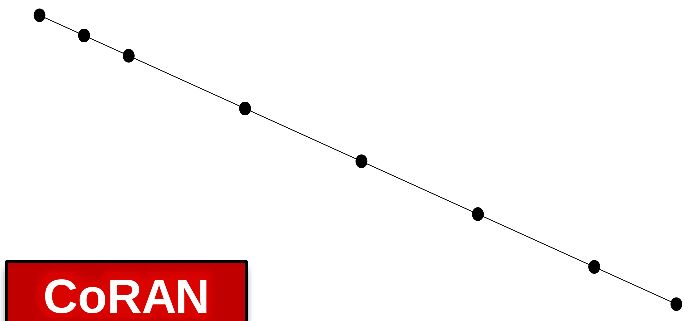


2D Cross-section FE model



KSAC2D

1D blade FE model



CoRAN

MLDB or GEB model

Interface

KSAC2D output

- **Stiffness/inertia matrices in Euler-Bernoulli level (4x4):**

$$\mathbf{K} = \begin{bmatrix} EA & & EAe_{a2} & EAe_{a1} \\ & GJ & & \\ & & EI_y & \\ sym & & & EI_z \end{bmatrix} \qquad \mathbf{M} = \begin{bmatrix} m & & me_{g2} & me_{g1} \\ & mk_m^{\;2} & & \\ & & mk_{m_1}^{\;2} & \\ & & & mk_{m_2}^{\;2} \end{bmatrix}$$

with the section constants:

$$EA = E\iint_A dydz \qquad EAe_{a1} = EA\iint_A ydydz$$

$$GJ = G\iint_A (y^2+z^2)dydz \qquad EAe_{a2} = EA\iint_A zdydz$$

$$EI_y = E\iint_A z^2 dydz \qquad k_A^{\;2} = \iint_A (y^2+z^2)dydz = I_y + I_z$$

$$EI_z = E\iint_A y^2 dydz \qquad me_{g1} = \iint_A \rho y\, dydz$$

$$m = \iint_A \rho\, dydz \qquad me_{g2} = \iint_A \rho z\, dydz$$

$$mk_{m1}^{\;2} = \iint_A \rho z^2 dydz$$

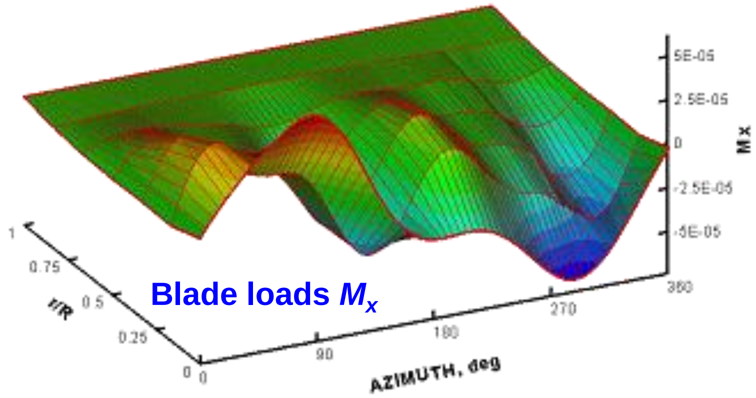
$$mk_{m2}^{\;2} = \iint_A \rho y^2 dydz$$

$$mk_m^{\;2} = \iint_A \rho (y^2+z^2)dydz = mk_{m1}^{\;2} + mk_{m2}^{\;2}$$

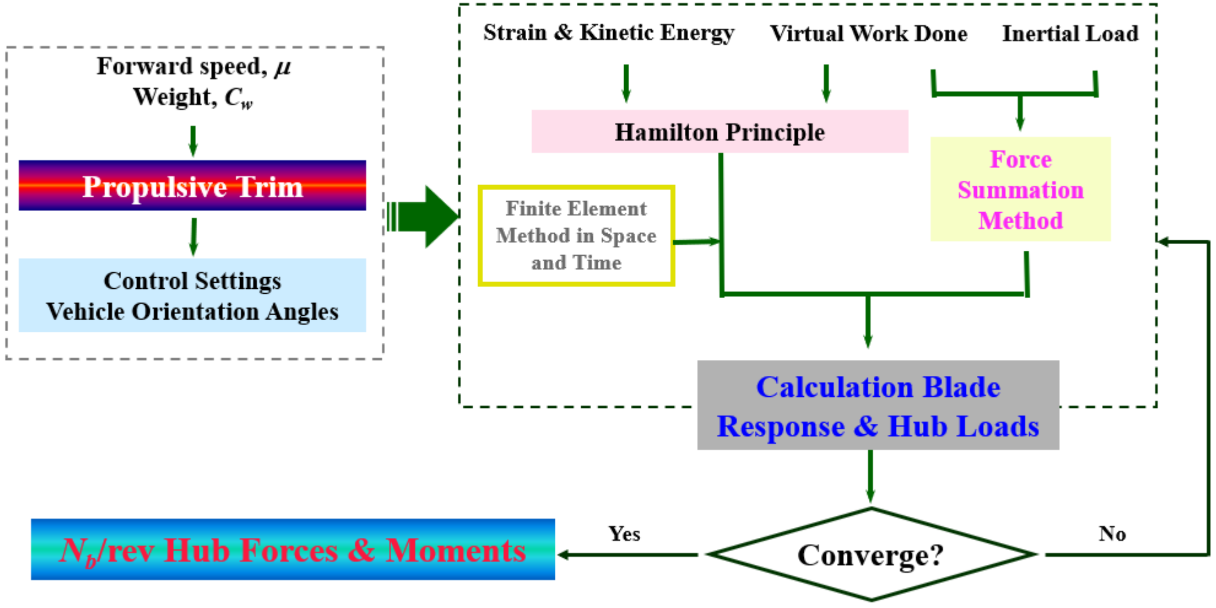
K-CSD Code CoRAN: An Overview

❖ Evaluation of blade & hub loads

- Blade loads (rotating frame): Force summation method
- Hub loads: Fourier coordination transformation
- Hub vibration: nN_b/rev (blade passage freq.) components



Blade loads M_x



Hub forces:

$$F_x(\psi)=\sum_{m=1}^{N_b}(F_x\cos\psi_m - F_y\sin\psi_m - F_z\cos\psi_m\beta_p)$$

$$F_y(\psi)=\sum_{m=1}^{N_b}(F_x\sin\psi_m + F_y\cos\psi_m - F_z\sin\psi_m\beta_p)$$

$$F_z(\psi)=\sum_{m=1}^{N_b}(F_z + F_x\beta_p)$$

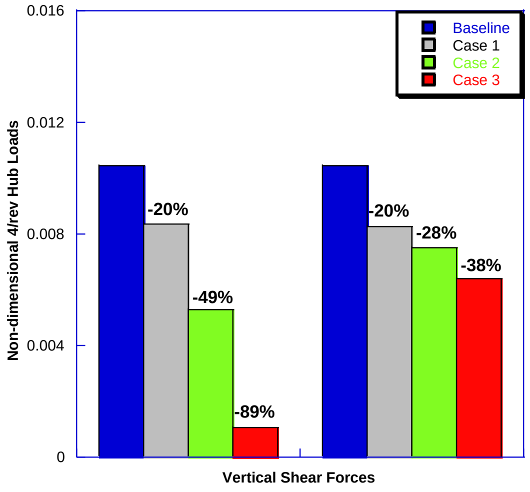
Hub moments:

$$M_x(\psi)=\sum_{m=1}^{N_b}(M_x\cos\psi_m - M_y\sin\psi_m - M_z\cos\psi_m\beta_p)$$

$$M_y(\psi)=\sum_{m=1}^{N_b}(M_x\sin\psi_m + M_y\cos\psi_m - M_z\sin\psi_m\beta_p)$$

$$M_z(\psi)=\sum_{m=1}^{N_b}(M_z + M_x\beta_p)$$

Hub vertical shear F_z



N_b/rev hub loads:

$$f(\psi)=f_0+\sum_{n=1}^{\infty}(f_{nc}\cos n\psi + f_{ns}\sin n\psi)$$

KU KONKUK UNIVERSITY

Intelligent Rotorcraft Structures Lab

K-CSD Code CoRAN: An Overview

❖ Rotor aeroelastic stability analysis

- **Governing equation:** $M\ddot{q}+C(q,\psi)\dot{q}+K(q,\psi)q=F(q,\dot{q},\psi)$
- **Linearized perturbation equation:** $M\delta\ddot{q}+\left(C-\frac{\partial F}{\partial \dot{q}}\right)\delta\dot{q}+\left(K-\frac{\partial F}{\partial q}\right)\delta q=0$
- **State-form equations:** $\delta\dot{X}=A(\psi)\delta X$

$$A(\psi)=\begin{bmatrix}0 & I\\ -\bar{M}^{-1}\bar{K} & -\bar{M}^{-1}\bar{C}\end{bmatrix} \qquad \delta X=\begin{Bmatrix}\delta p\\ \delta\dot{p}\end{Bmatrix}$$

- **Modal flutter equations:** $\bar{M}\delta\ddot{p}+\bar{C}\delta\dot{p}+\bar{K}\delta p=0$

$$\bar{M}=\phi^T M\phi \qquad \bar{C}=\phi^T\left(C-\frac{\partial F}{\partial \dot{q}}\right)\phi \qquad \bar{K}=\phi^T\left(K-\frac{\partial F}{\partial q}\right)\phi$$

- **Flutter solutions: Constant coefficient / Floquet transition matrix solutions**

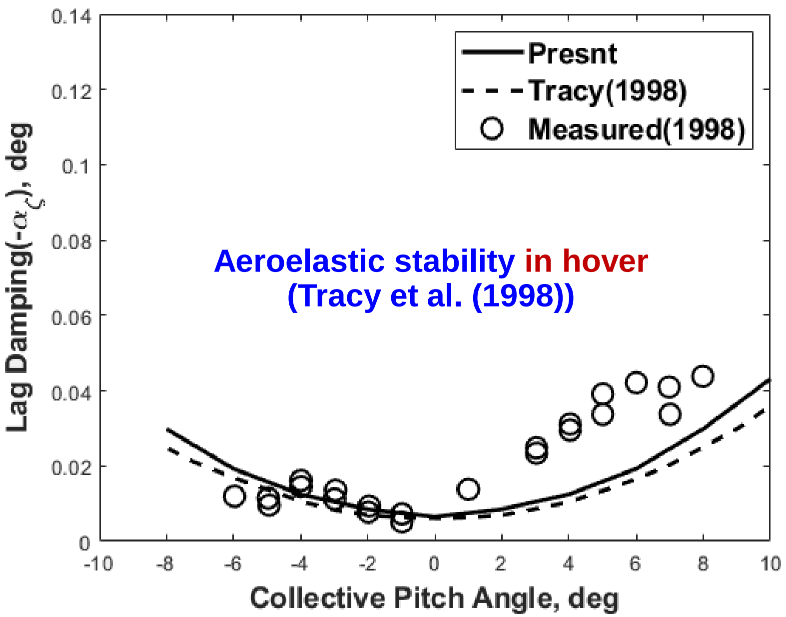
$$P_k=\frac{1}{T}\ln\lambda_k=\alpha_k+i\omega_k \qquad \alpha_k=\frac{1}{T}\ln|\lambda_k|=\frac{1}{2T}\ln\left((\lambda_k)_R^{\ 2}+(\lambda_k)_R^{\ 2}\right)$$

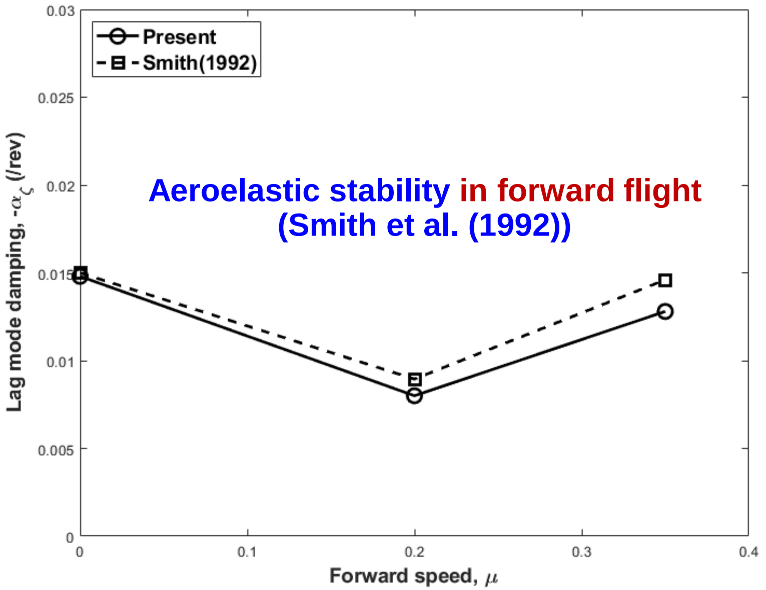
- **Stability criteria:**

$\alpha_k>0$ **: Unstable**

$\alpha_k<0$ **: Stable**

$$\omega_k=\frac{1}{T}\tan^{-1}\left(\frac{(\lambda_k)_I}{(\lambda_k)_R}\right)$$

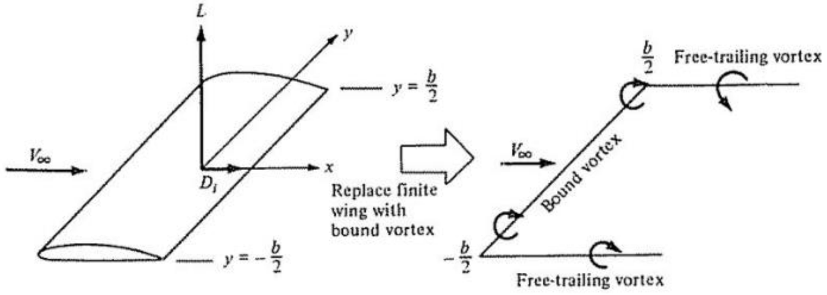


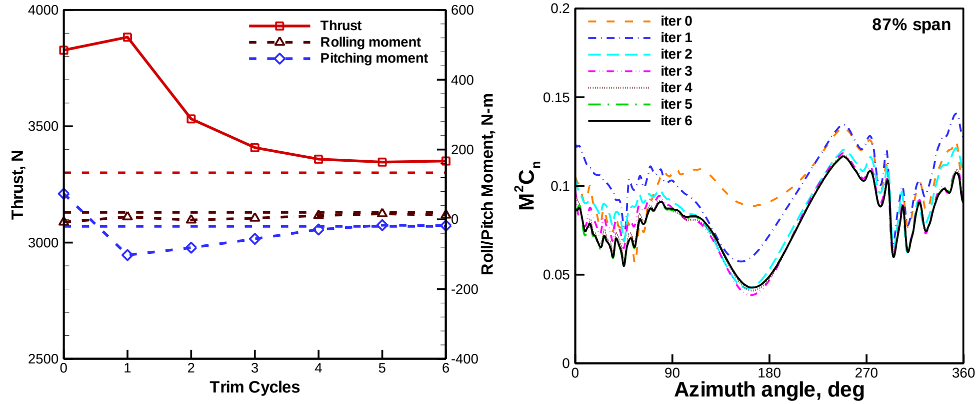


K-CSD Code CoRAN: An Overview

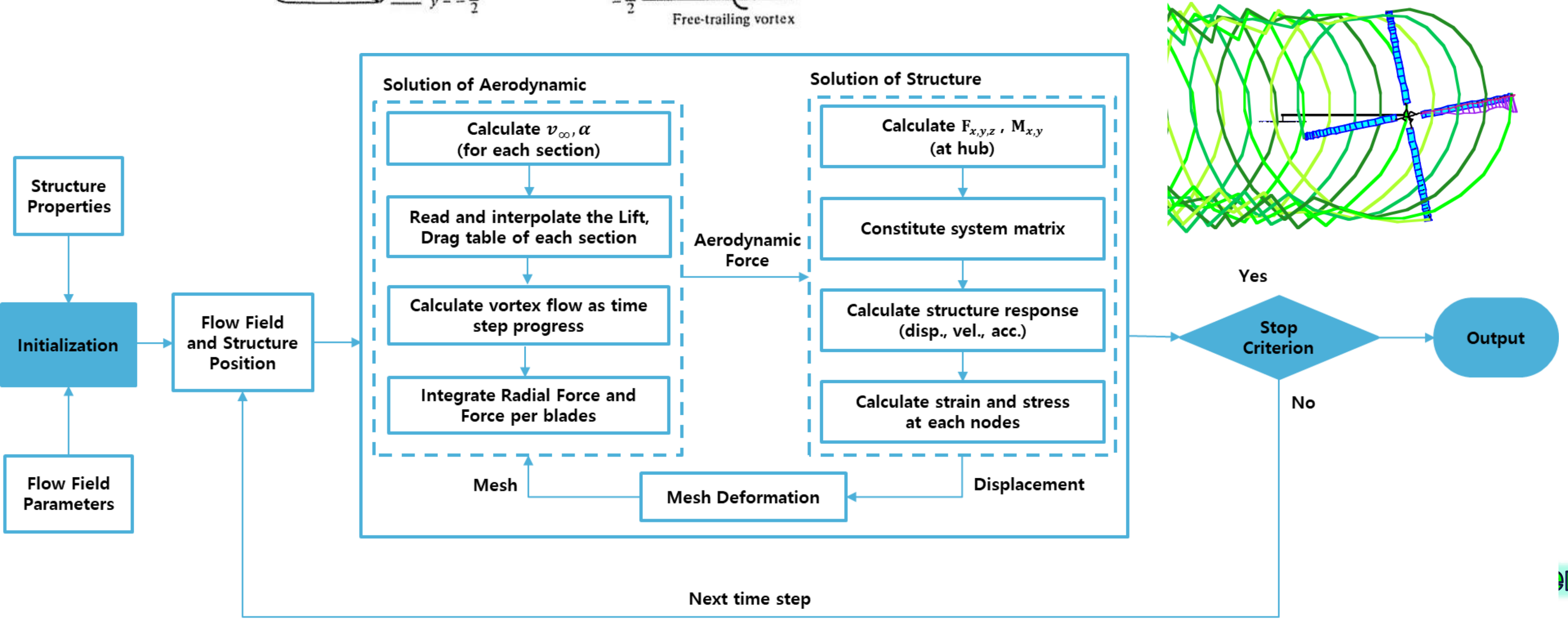
❖ **Interface with external aerodynamics: Future work**

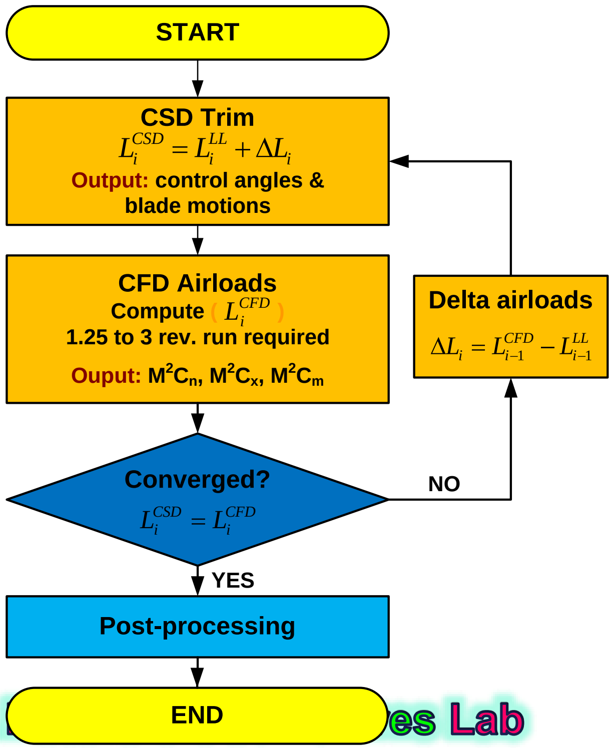
- **Tight coupling with prescribed or free wake model**
- **Loose coupling with RANS CFD code (KFLOW)**





CFD/CSD LC trim histories

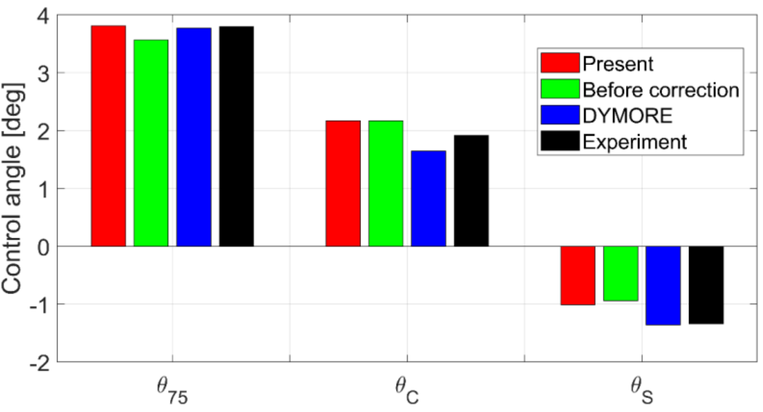




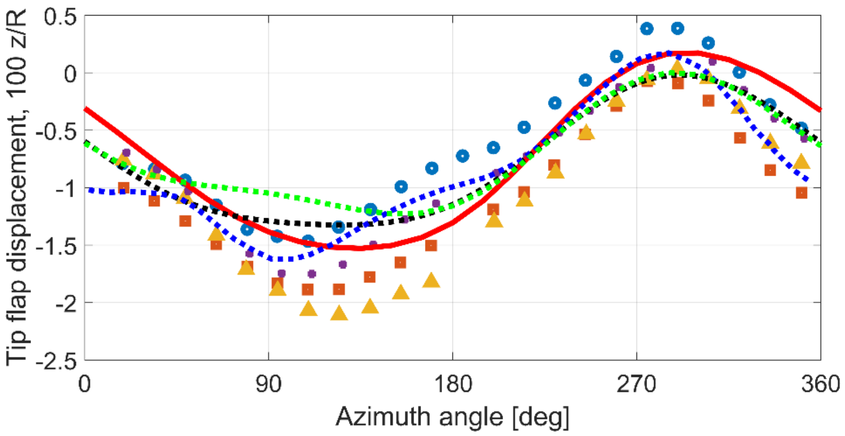
K-CSD Code CoRAN: Sample Results

❖ **Sample results of CoRAN: Validation of HART II BL data**

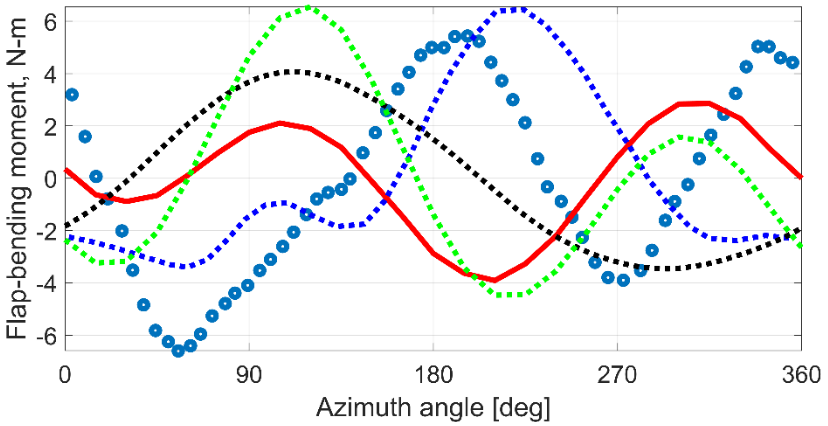
Trim control angles

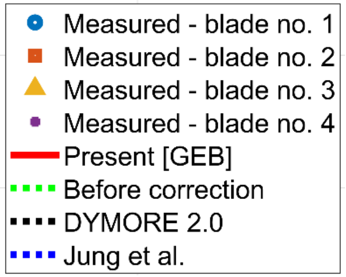


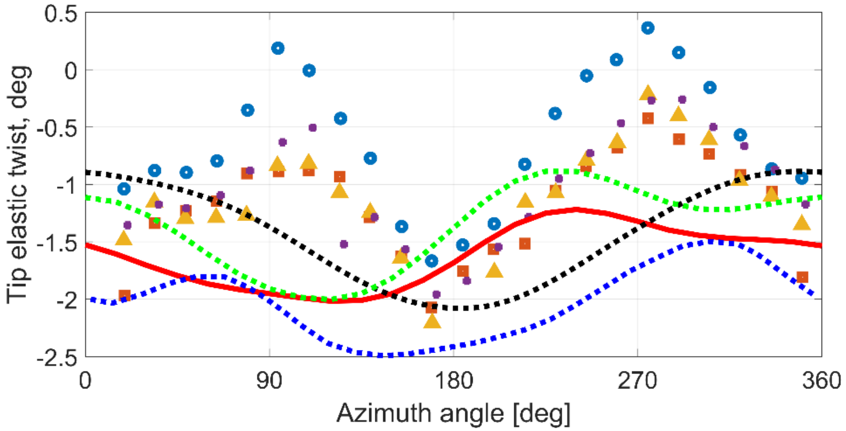
Blade tip deflections

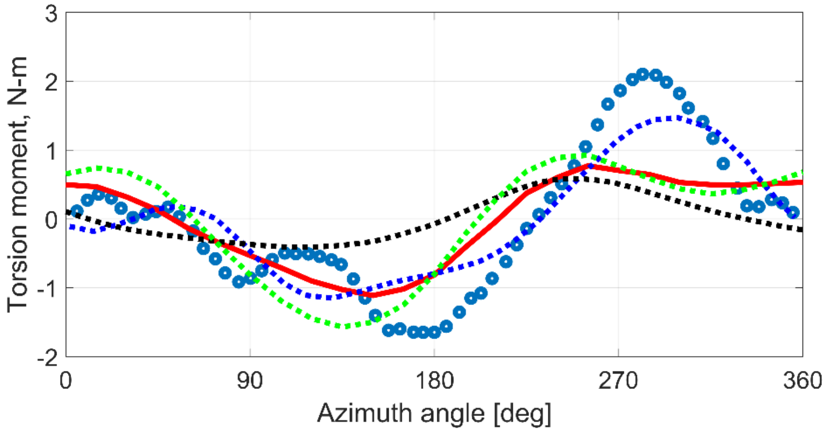


Blade structural moments





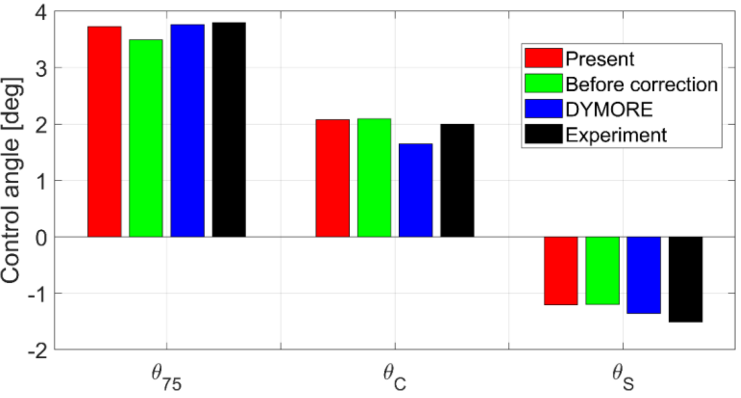


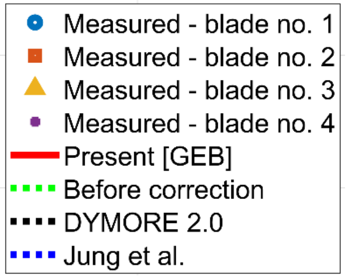


K-CSD Code CoRAN: Sample Results

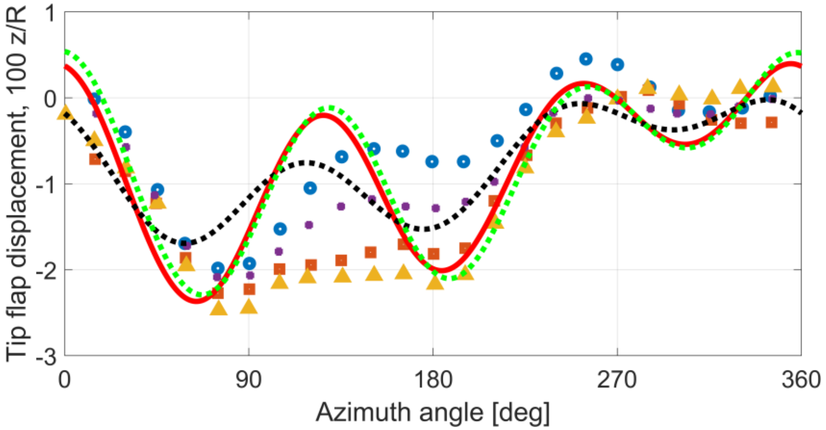
❖ **Sample results of CoRAN: Validation of HART II MV data**

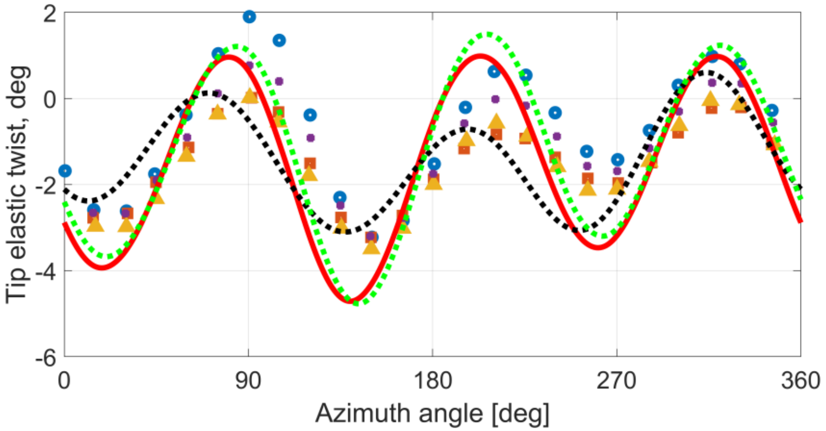
Trim control angles



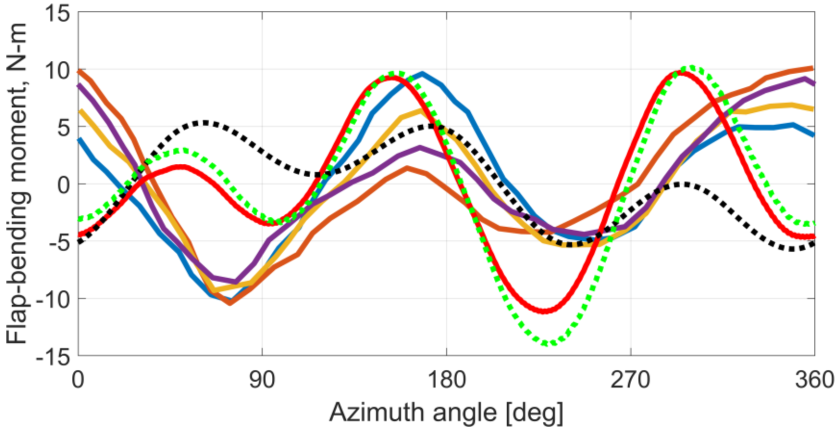


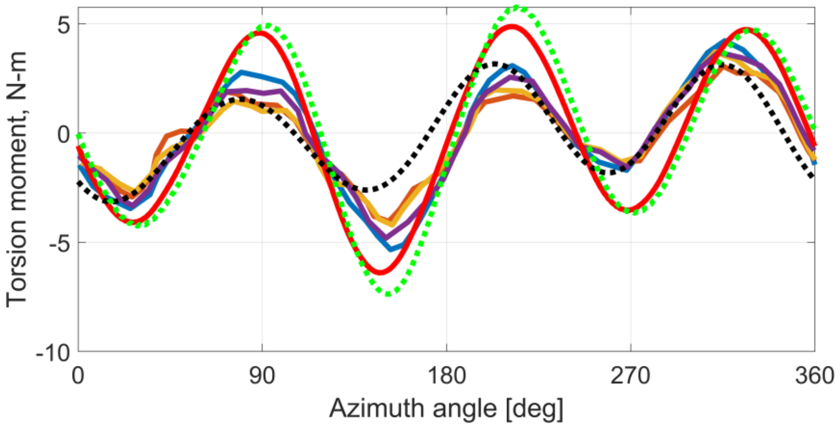
Blade tip deflections





Blade structural moments





Summary

- Current status of rotorcraft CSD codes briefed
- Ongoing work on CSD code development at KU introduced. Key features of the *so-called* CoRAN include:
  - Flexible multi-body formulation
  - Nonlinear beam kinematics modeling (MLDB or GEB)
  - Prediction of trim, blade response, blade & hub loads, and aeroelastic stability
  - Interface with a general section analysis program KSAC2D
  - Pipeline to external aerodynamics (free wake, CFD solver)
- Some benchmark comparison results demonstrated
- Future work: Long way to go… (wake models, CFD/CSD coupling)

Q & A

Thank you!

Contact: snjung@konkuk.ac.kr