Prediction of Helicopter Blade-Vortex Interaction Noise using Motion Data from Experiment

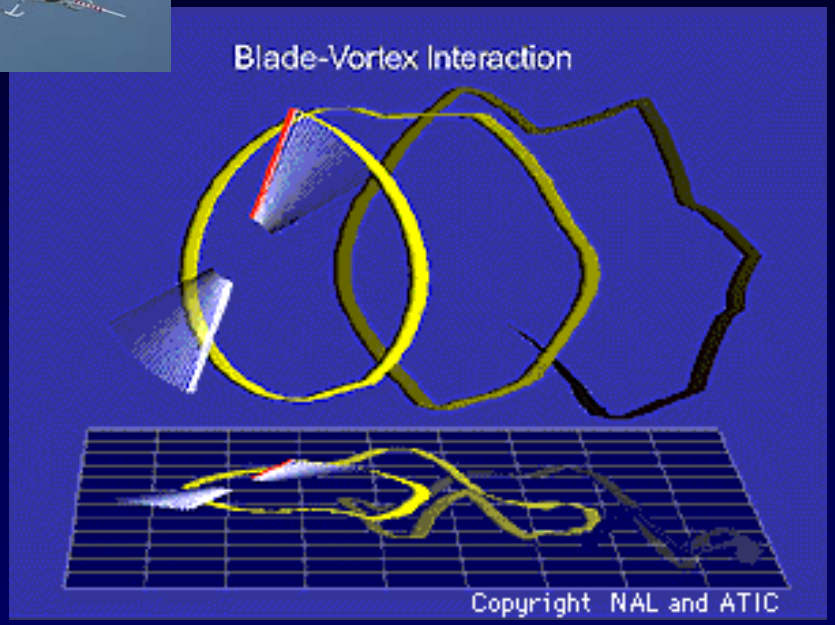
Yoshinobu Inada, Choongmo Yang, and Takashi Aoyama

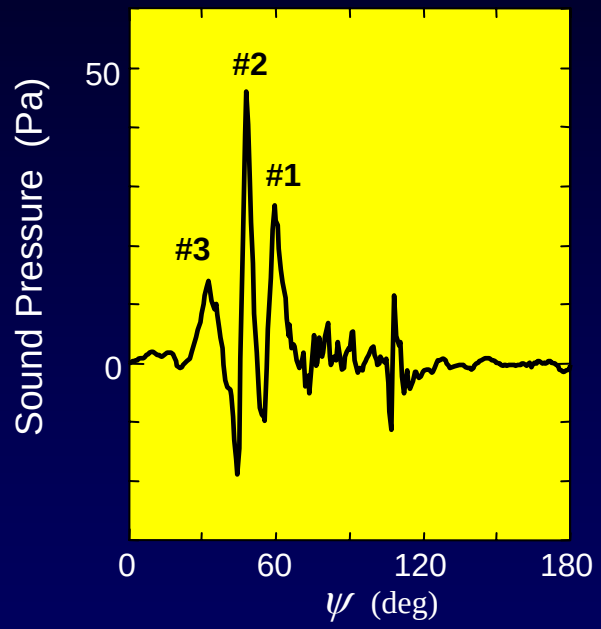
Computational Science Research Group (CSRG)
Institute of Aerospace Technology (IAT)
Japan Aerospace Exploration Agency (JAXA)

Outline

1. Introduction
   - Background and Objectives
2. Methods and Results
   - Single Blade Calculation
   - Full CFD Calculation (Overlapped grid method)
   - Acoustic Analysis
3. Conclusion

Helicopter BVI Noise



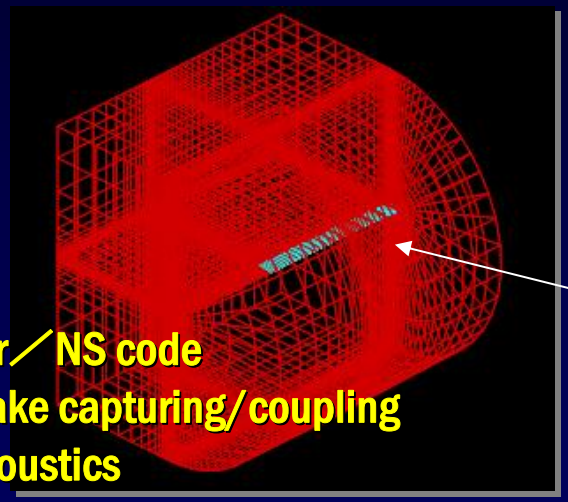


Large impulsive noise caused by the blade and vortex interaction, inhibiting a flexible operation of helicopter

Background

CFD analysis for helicopter aerodynamics

Single Grid Model



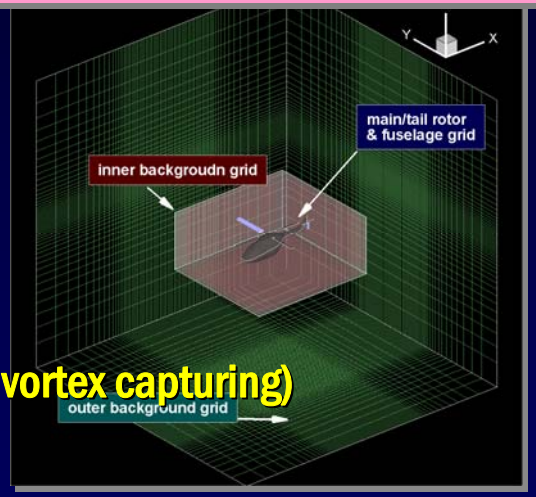
Rotor Blade

Euler／NS code
+ Wake capturing/coupling
+ Acoustics

"MENTOR"

Multidisciplinary
Euler/Navier-Stokes
Tool for Rotorcrafts

Full CFD Model (Overlapped Grid Model)



Euler (direct vortex capturing)
+ Acoustics

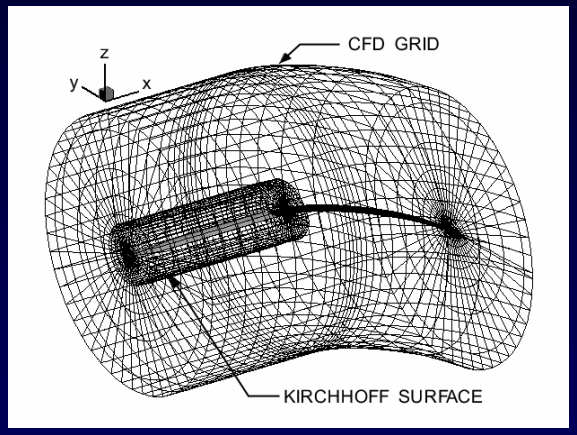
Grid Type	Single grid	Overlapped grid
Grid points	0.5~5 millions	20~60 millions
Computing time	1~10 hr/case	100~500 hr/case
Accuracy	moderate	excellent
Purpose	Design/Industry	Academic

Background

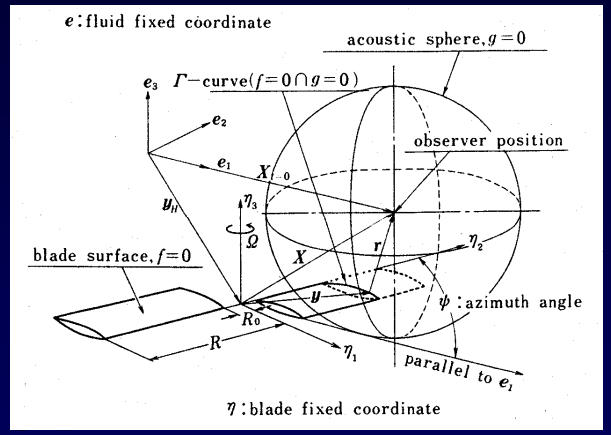
Acoustic analysis for noise prediction

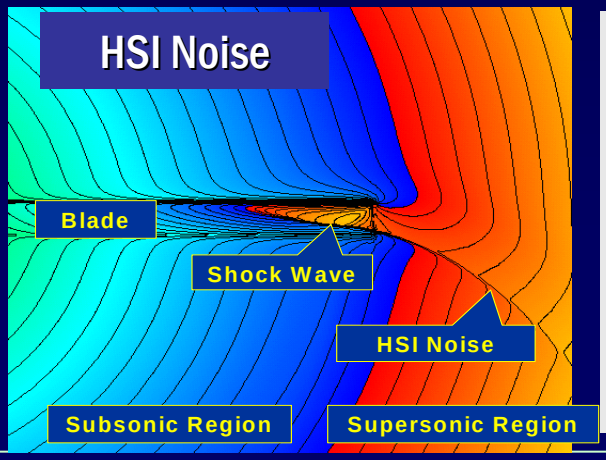
Using CFD Results

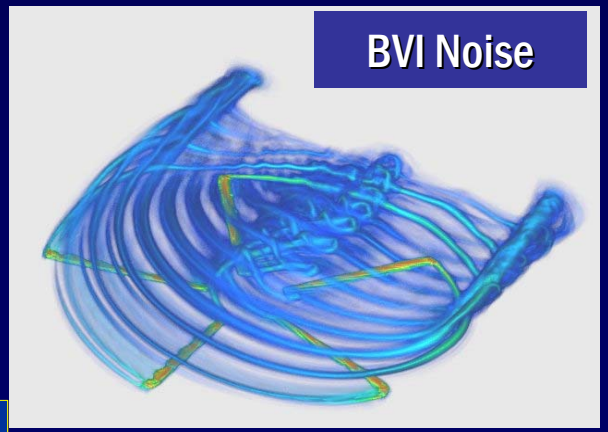
Kirchhoff Method



FW-H Method

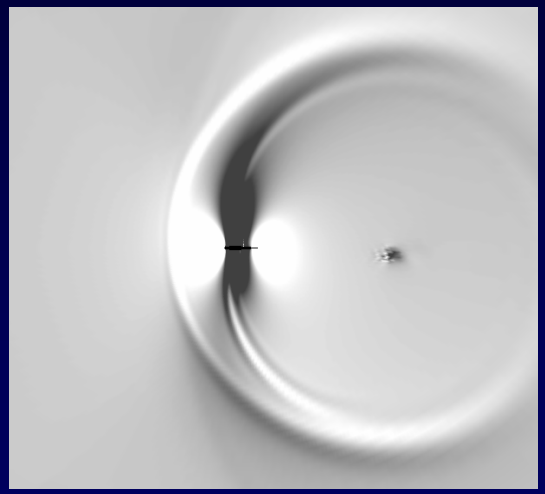






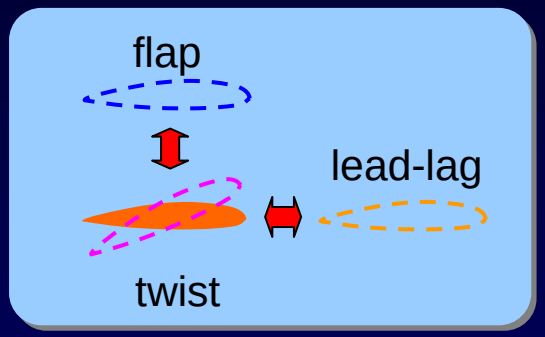
Direct Calculation

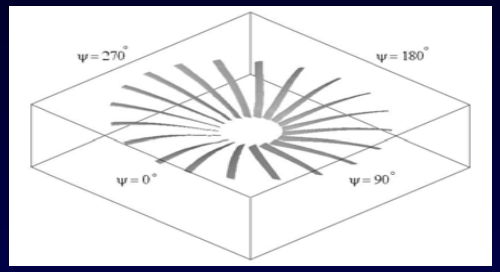
Computational Aeroacoustics (CAA)



Background

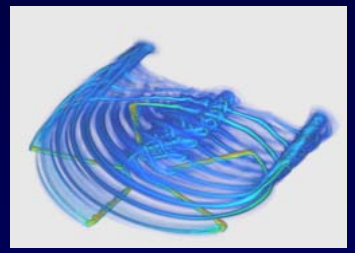
Questions to be solved for correct prediction of BVI noise

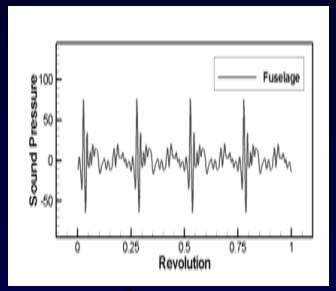




Q1

Q2





Q3

Aero-elastic analysis (CFD/CSD)

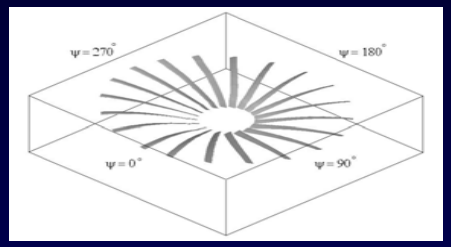
Q1. Can accurate blade motion be simulated by using CFD/CSD coupling method?

Q2. If the blade motion is correctly simulated, can CFD capture the tip vortex trace and simulate the blade vortex interaction (BVI) accurately?

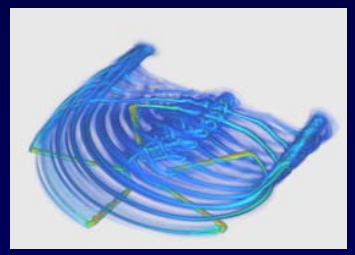
Q3. Can acoustic code predict BVI noise correctly from obtained pressure data?

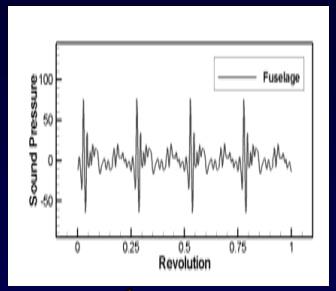
Objectives

BVI noise prediction using blade motion data from experiment



Q2





Q3

As the middle step for full coupling aero-elastic analysis, primary focus on the second and third questions using elastic blade motion data captured from the experiment (HART II experiment).

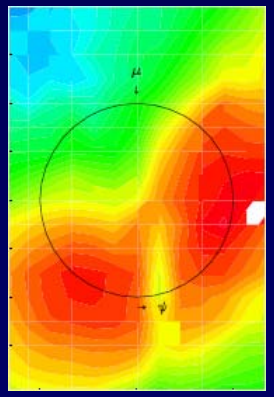
HART II Experiment

International co-operative project on <u>higher harmonic blade motion control</u>

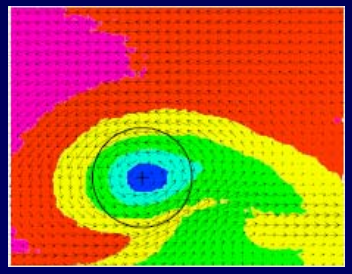
- BL : Baseline
- MN: Minimum Noise
- MV: Minimum Vibration

- Blade air-loading
- Blade elastic deformation
- Pressure distribution on blades
- Noise
- Wake
- etc.

Available for research use



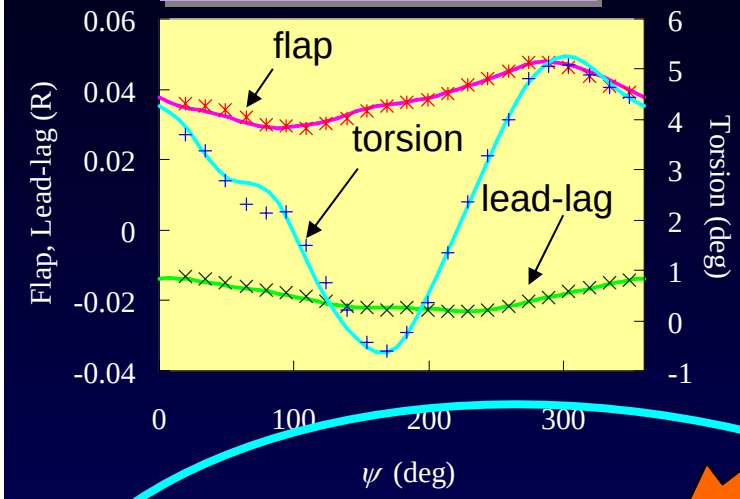
Noise contour

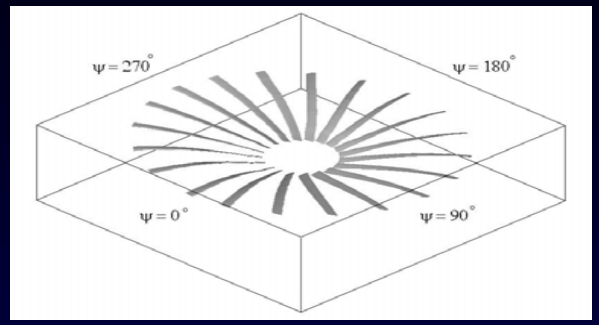


PIV

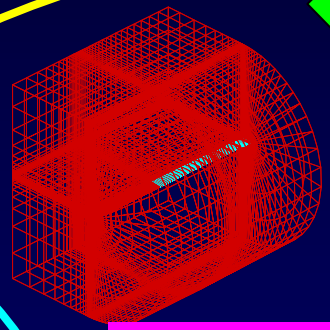
HART II Calculation

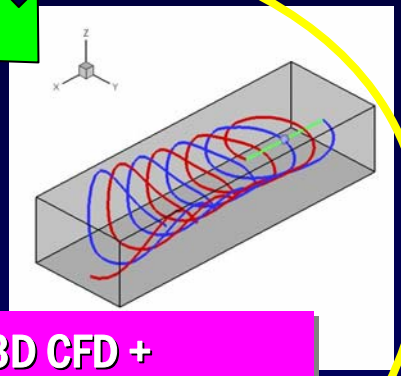
HARTII Exp. Data





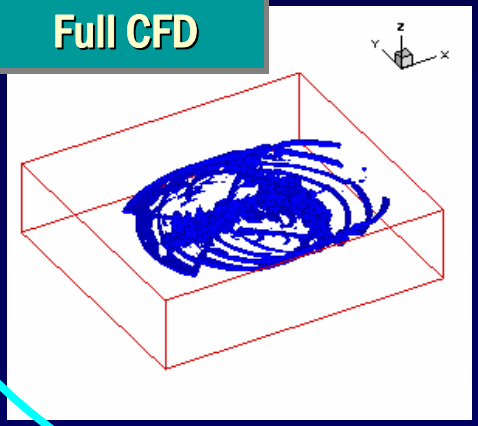
Blade motion with elastic deformation



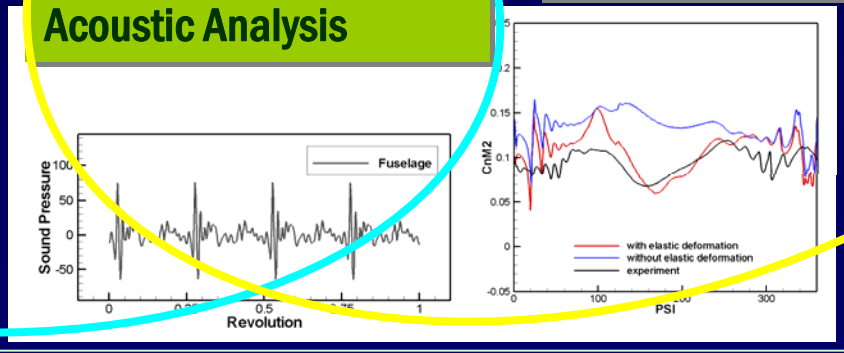


Single blade 3D CFD + Beddoes model

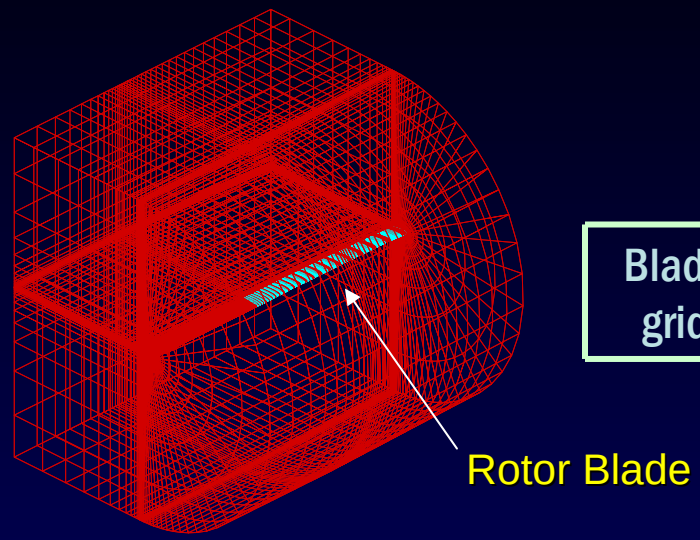
Full CFD



Aerodynamic/ Acoustic Analysis



Single Grid Model



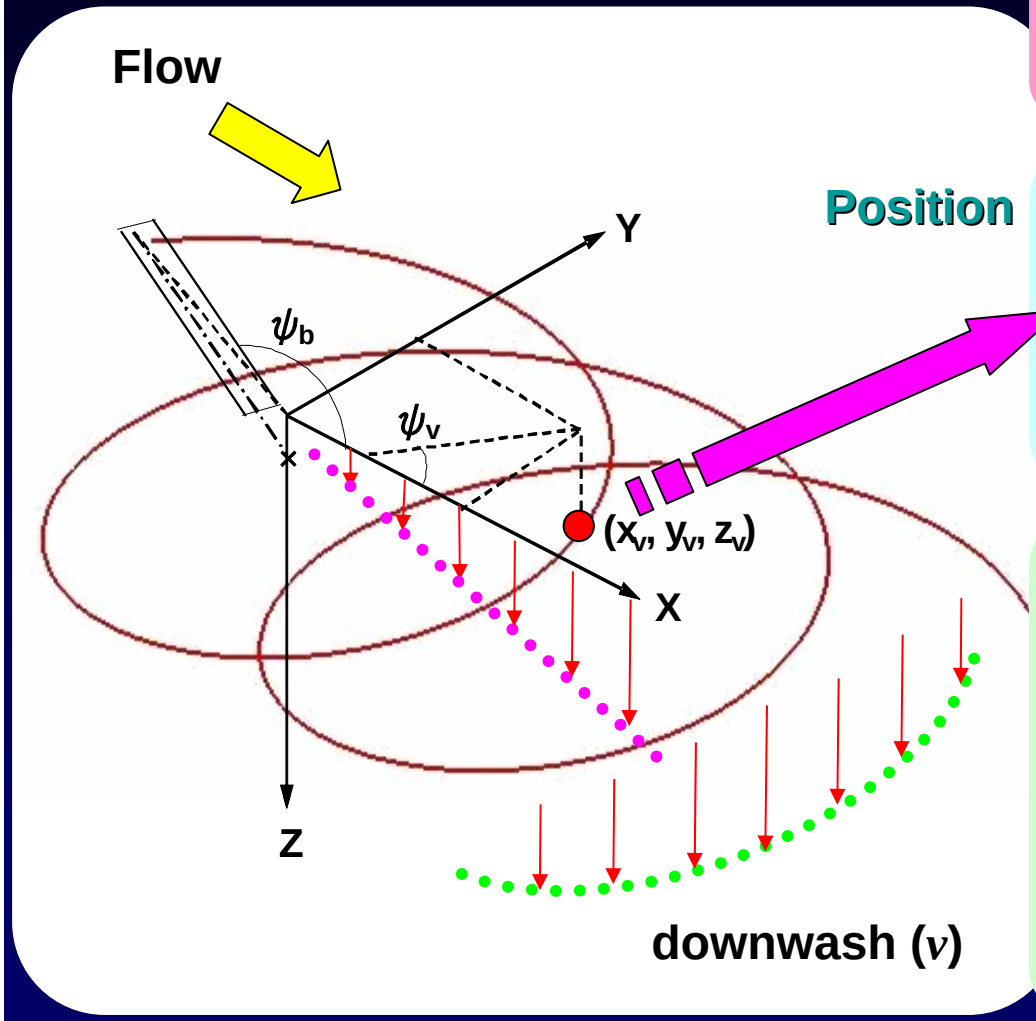
Blade grid	(chord × normal × span) × blade (219 × 42 × 100) × 1 = 919,800

Numerical Scheme for rotor (Curvilinear Grid):

- Governing Equation: 3D unsteady Euler equation
- Space: Beam-Warming scheme + TVD scheme
  - 2nd Order Accuracy
  - MUSCL approach using minmod limiter
- Time: Euler Backward Implicit Time Integration
  Newton iterative method in unsteady calculation
- Solution algorithm: Upwind Line Gauss-Seidal Relaxation Method

Wake Model

Beddoes Generalized Wake Model



Swirl velocity

$$v_\theta(r) = \frac{\Gamma}{2\pi r}\frac{r^2}{\left(r_a^2 + r^2\right)}$$

Translation by blade elastic deformation

Position

$$\begin{cases} x_v = r_v \cos\psi_v + \mu_x \Delta\psi_v \\ y_v = r_v \sin\psi_v \\ z_v = -\mu_z \Delta\psi_v + \int_{\psi_b}^{\psi_v} (v / R\Omega)\, d\psi \end{cases}$$

$+ X_e$

$+ Y_e$

$+ Z_e$

downwash

inside the disk

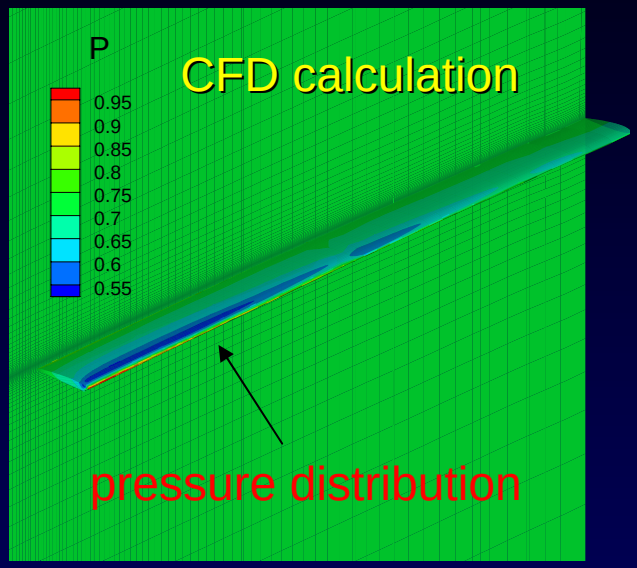
$$v = v_0\left(1 + \frac{8E}{15\pi} - 2\mu_x y' + Ex' - E\left|y'^3\right|\right)$$

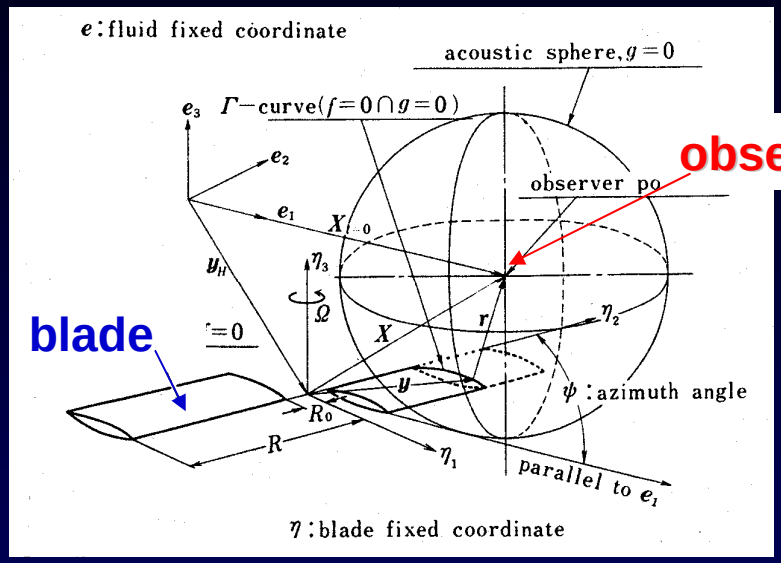
outside the disk

$$v = 2v_0\left(1 + \frac{8E}{15\pi} - 2\mu_x y' - E\left|y'^3\right|\right)$$

(van der Wall, 2000)

Acoustic Analysis





Ffowcs Williams & Hawkings (FW-H) equation

$$p(x,t) = \frac{1}{4\pi}\left(\frac{\partial}{\partial t}\int \frac{\rho_0 v_n}{r\Lambda} d\Sigma + \frac{1}{c_0}\frac{\partial}{\partial t}\int \frac{p_b \cos\theta}{r\Lambda} d\Sigma + \int \frac{p_b \cos\theta}{r^2\Lambda} d\Sigma\right)$$

Sound pressure

Thickness noise | Load noise (far) | Load noise (near)

$$\Lambda = (1 + M_n^2 - 2M_n \cos\theta)^{1/2}$$

Σ : Influential surface

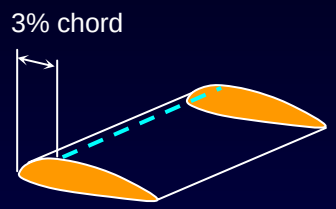
Condition

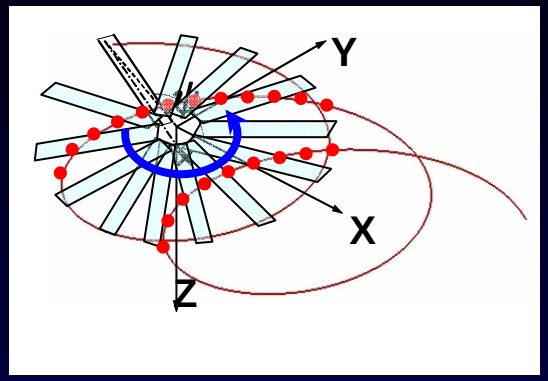
Blade motion parameter

Rotor radius, R(m)	2.0
Blade chord length, c(m)	0.121
Twist angle ($/R$)	-8.0°
Precone angle, b_0	2.5°
Thrust Coefficient, C_T	0.0044
Tip Mach number, M_{tip}	0.6387
Inflow ratio, μ	0.15
Angle of tip path plane, a_{TPP}	4.5° or 5.3°
Blade motion data	**BL**
Collective pitch angle, θ_0	3.2°
Lateral cyclic pitch angle, θ_{1C}	2.0°
Longitudinal cyclic pitch angle, θ_{1S}	-1.1°
HHC lateral cyclic pitch angle, θ_{3C}	0°
HHC long. cyclic pitch angle, θ_{3S}	0°

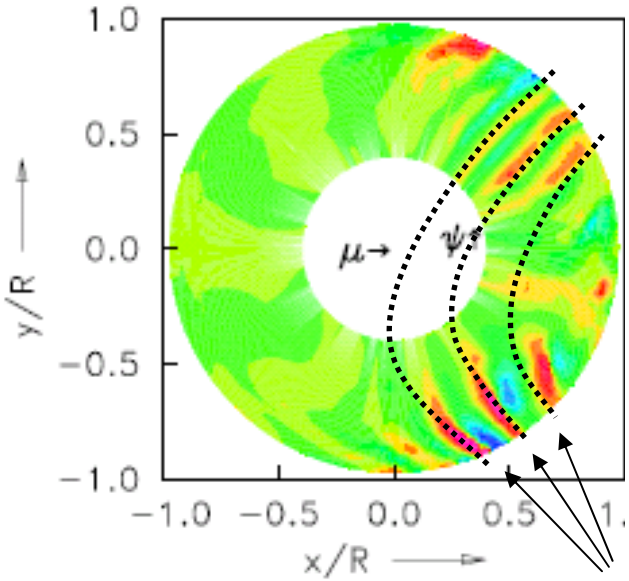
Results (Single Grid Cal.)

Leading edge differential pressure distribution

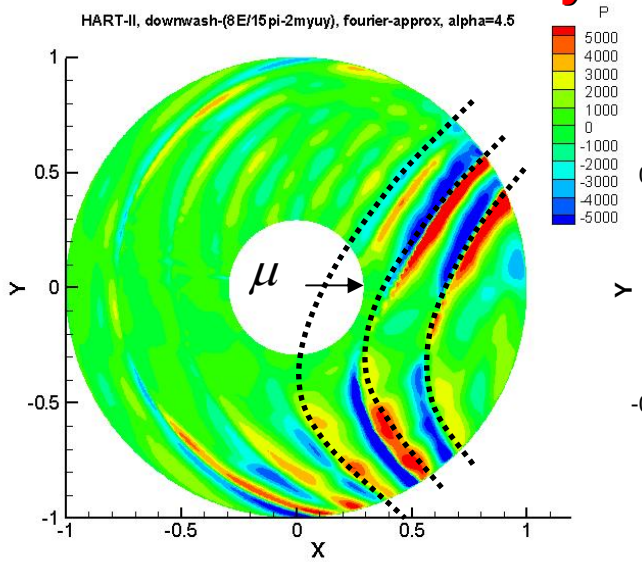




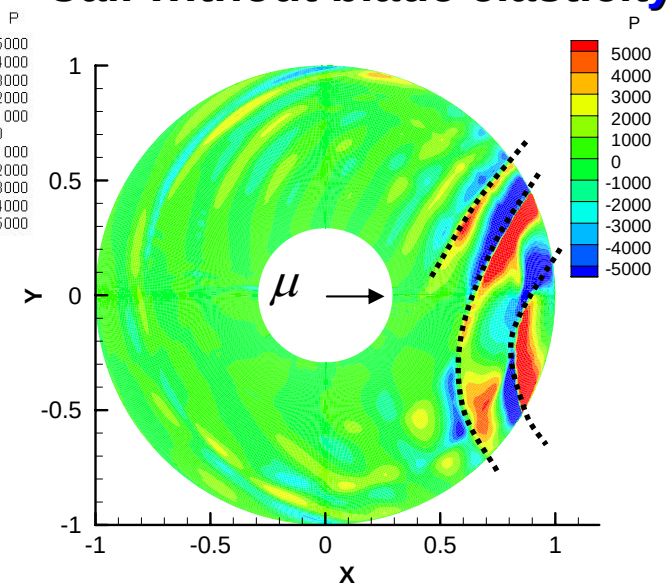
HART II Experiment



Cal. with blade elasticity



Cal. without blade elasticity



Blade vortex interactions (BVI) are occurring.

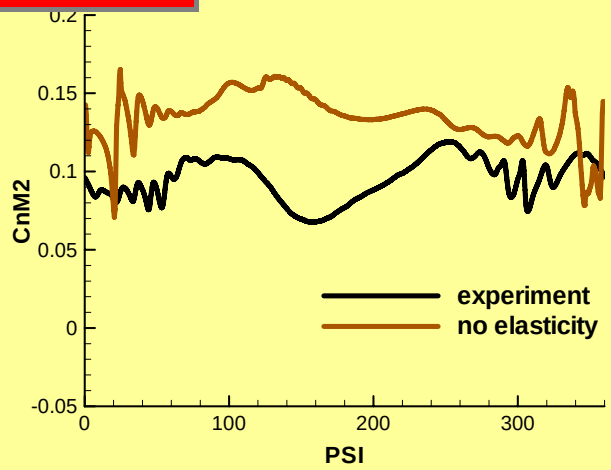
Results (Single Grid Cal.)

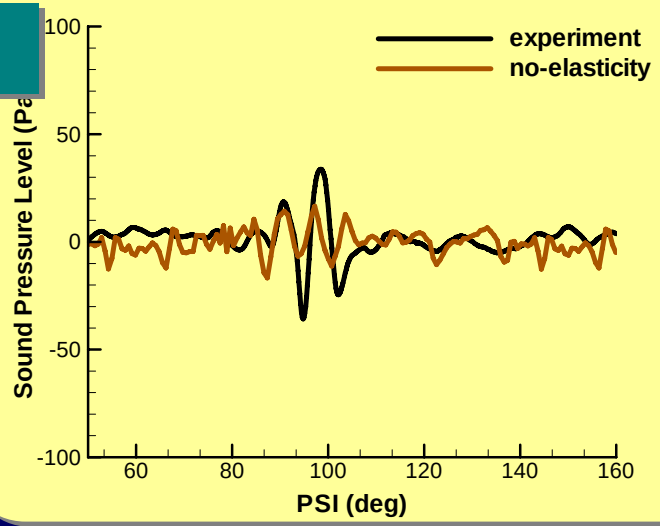
Blade air-loading and acoustic results

Blade air-loading

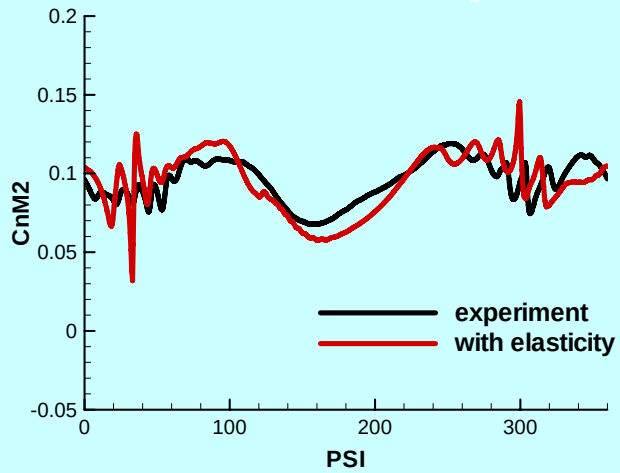
Acoustics

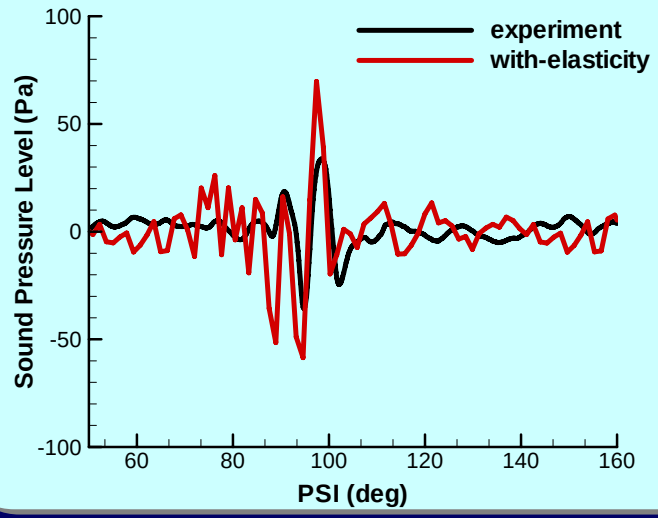
without elasticity





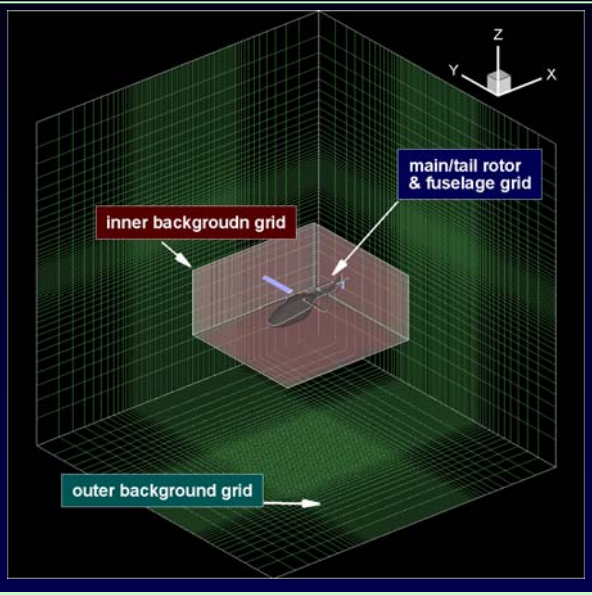
with elasticity





Full CFD Model

Full CFD Model
(Overlapped grid system)



Specifications of grid system

Grid type	(X×Y×Z) = number of grid points			
	rotor only			with fuselage
	coarse	medium	fine	medium
Inner background grid	290×230×50 = 3,335,000	450×400×80 = 14,400,000	750×580×140 = 60,900,000	480×400×200 = 38,400,000
Outer background grid	83×79×49 = 321,293			100×80×70 = 560,000
Blade grid	(chord×normal×span) × blade (141×25×131) × 4 = 1,899,500			
Fuselage grid	-	-	-	71×21×83 = 123,753
Total	~5,560,000 points	~16,600,000 points	~61,400,000 points	~41,000,000 points
Inner background spacing	0.17c (=0.0105R)	0.099c (=0.006R)	0.066c (=0.004R)	0.099c (=0.006R)

Full CFD Model

Numerical Scheme for rotor and fuselage (Curvilinear Grid):

- Governing Equation: 3D unsteady Euler equation
- Space: Beam-Warming scheme + TVD scheme
  - 2nd Order Accuracy
  - MUSCL approach using minmod limiter
- Time: Euler Backward Implicit Time Integration
  Newton iterative method in unsteady calculation
- Solution algorithm: Upwind Line Gauss-Seidal Relaxation Method

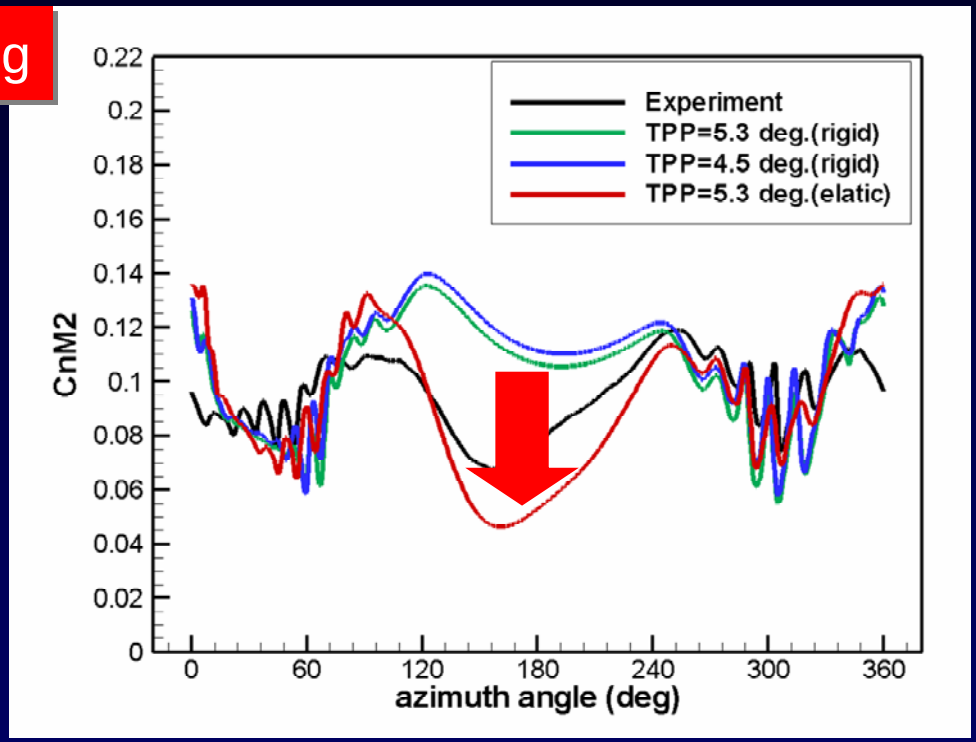
Numerical Scheme for background grid (Cartesian Grid):

- Governing Equation: 3D unsteady Euler equation
- Space: Compact TVD scheme (4th Order Accuracy)
  Simple High-resolution Upwind Scheme (SHUS)
  - Advection Upstream Splitting Method (AUSM)
- Time: Explicit Time integration
  Four stage Runge-Kutta method (4th Order)

Results (Full CFD Cal.)

Effect of blade elasticity consideration

Blade air-loading

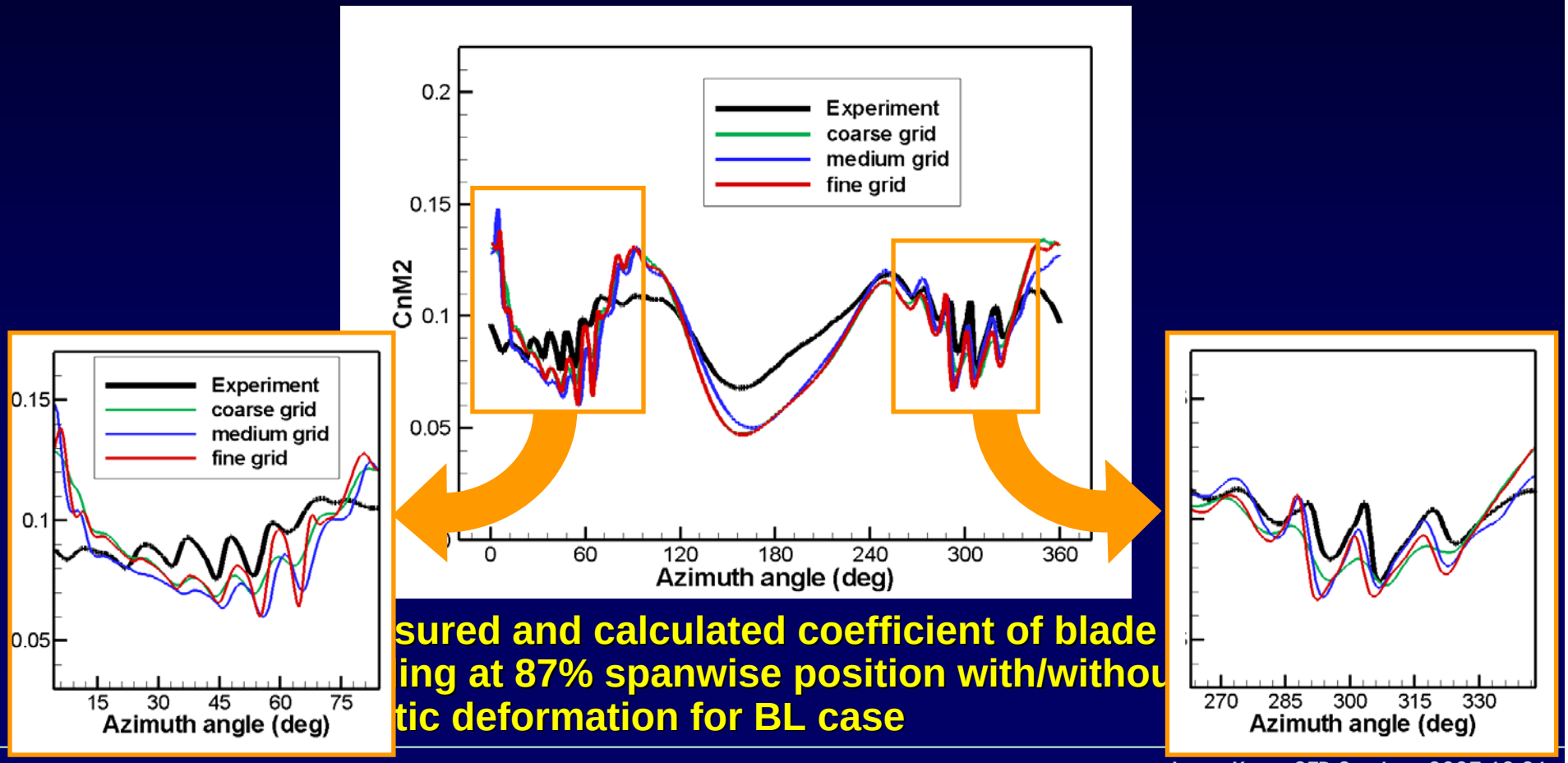


Measured and calculated coefficient of blade loading at 87% spanwise position with/without elastic deformation for BL case

Results (Full CFD Cal.)

Effect of grid size

coarse	medium	fine
290×230×50 = 3,335,000	450×400×80 = 14,400,000	750×580×140 = 60,900,000
0.17c (=0.0105R)	0.099c (=0.006R)	0.066c (=0.004R)



sured and calculated coefficient of blade
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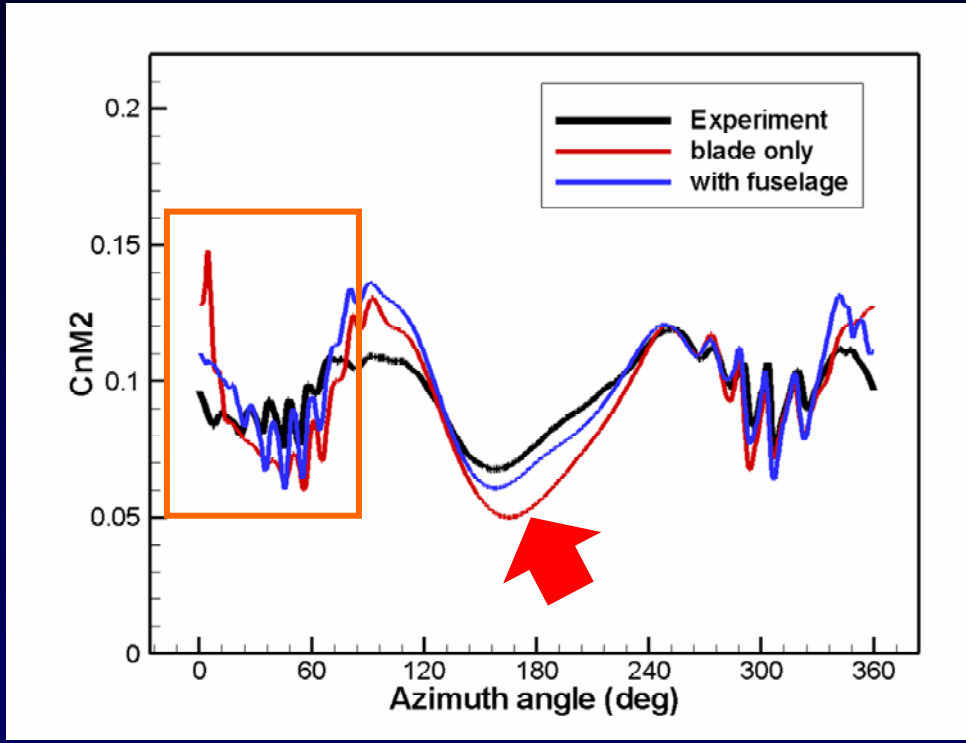
tic deformation for BL case

Results (Full CFD Cal.)

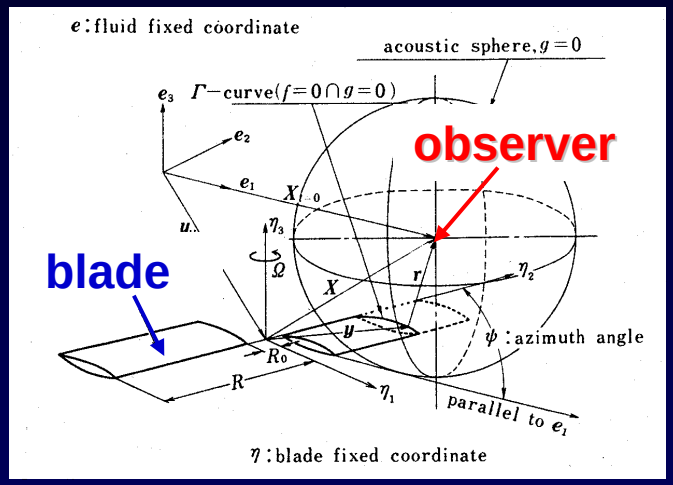
Effect of fuselage



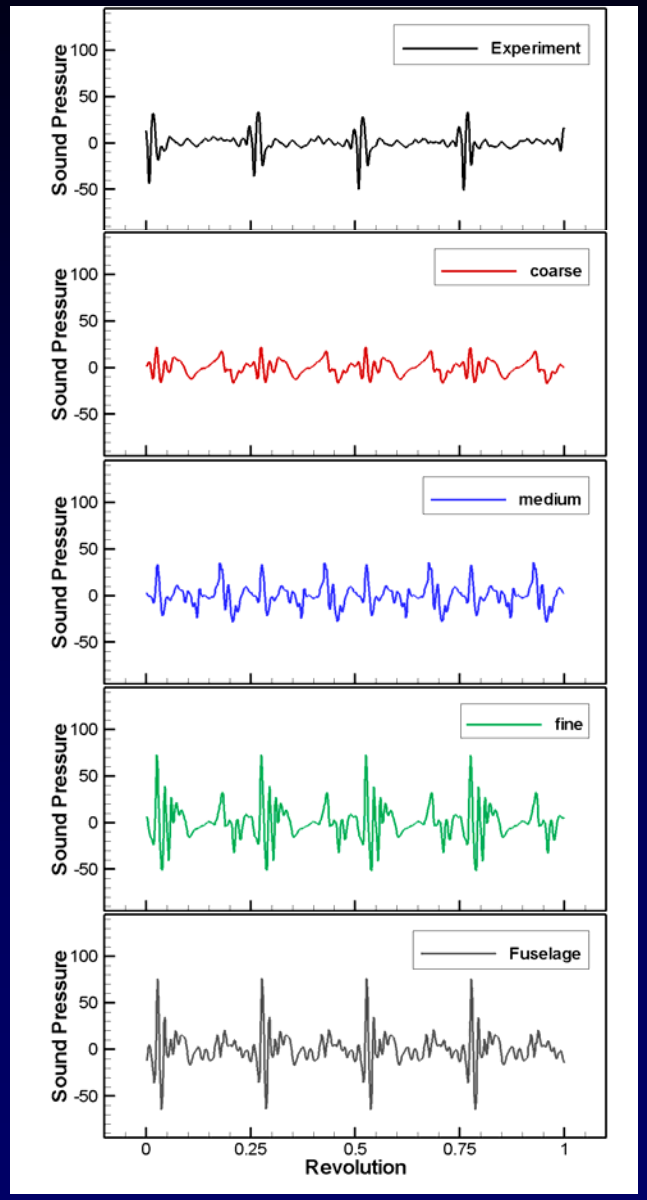
Measured and calculated coefficient of blade loading at 87% spanwise position with/without elastic deformation for BL case

Results (Full CFD Cal.)

Acoustic results



Measure and calculated sound pressure for BL case using high pass filter at 4/rev.



Conclusions

For both single grid and full CFD calculation

Consideration of blade elastic deformation remarkably enhanced the calculation quality, thus indicating the necessity of CFD/CSD coupling in a future prediction system.

For single grid calculation

Beddoes generalized wake model successfully simulated the tip vortex trace in the wake, realizing the reasonable quality of calculation, but overestimation of air-loading and the BVI noise still remain.

For full CFD calculation

- The calculation quality is dependent on the inner-background grid size, proper grid size should be used to enhance the precision.
- Fairing effect also should be considered for high quality of calculation.

Thank you for attention