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A FIRST PRINCIPLE BASED APPROACH FOR PREDICTION OF TONAL NOISE FROM ISOLATED AND INSTALLED PROPELLER

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ASSOCIAZIONE ITALIANA DI AERONAUTICA E ASTRONAUTICA

Council of European Aerospace Societies

PHD TOPIC: SEMI-EMPIRICAL MODELING OF SMALL AIRCRAFT NOISE EMISSION USING „FIRST PRINCIPLES“ BASED AEROACOUSTICS SIMULATIONS.

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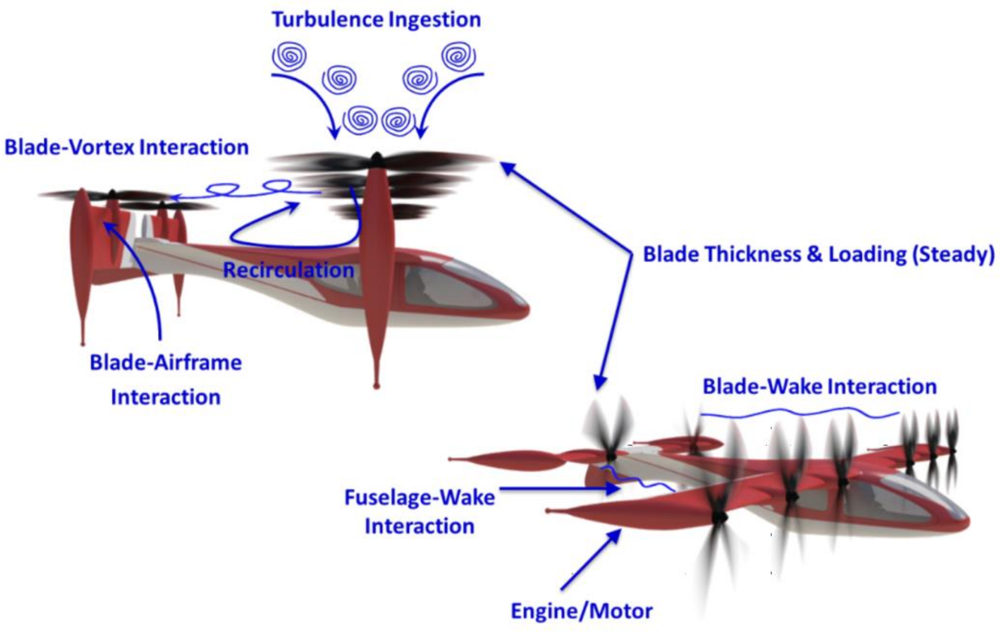
Overview of the PhD

Objective

- Development of very fast, reduced order, **AI semi-empirical model** combining physics based and empirical findings, for noise assessment in existing and low-noise design of general aviation (GA) and advanced air mobility (AAM) vehicles.

Research focus

- **Propeller installation noise** for different configuration of propeller arrangement in small Aircraft and AAM vehicles.



Potential noise sources on a AAM vehicle (NASA) **[1]**

Towards developing an AI based semi-empirical model

Propeller noise source model

- Selection of an appropriate propeller noise source model for CA and CAA simulations

Validation of the propeller noise source model

- Validating the simulation data from noise source model with flyover data

Reduced order model for AI database

- Considering a generic installation case
- Identifying parameters affecting the noise emissions

Simulation dataset for AI model

- Creating a huge database for AI model based on the reduced order model

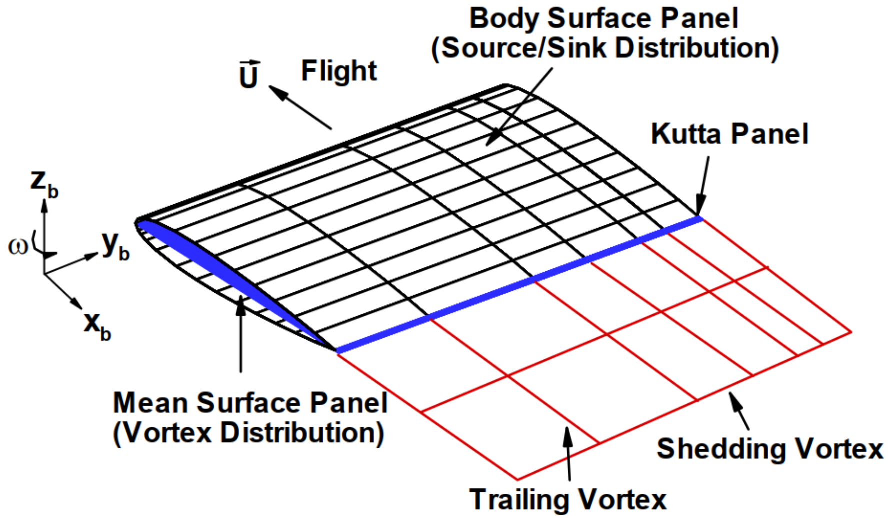
AI semi-empirical model

- Training the physics based AI model using the reduced order model dataset

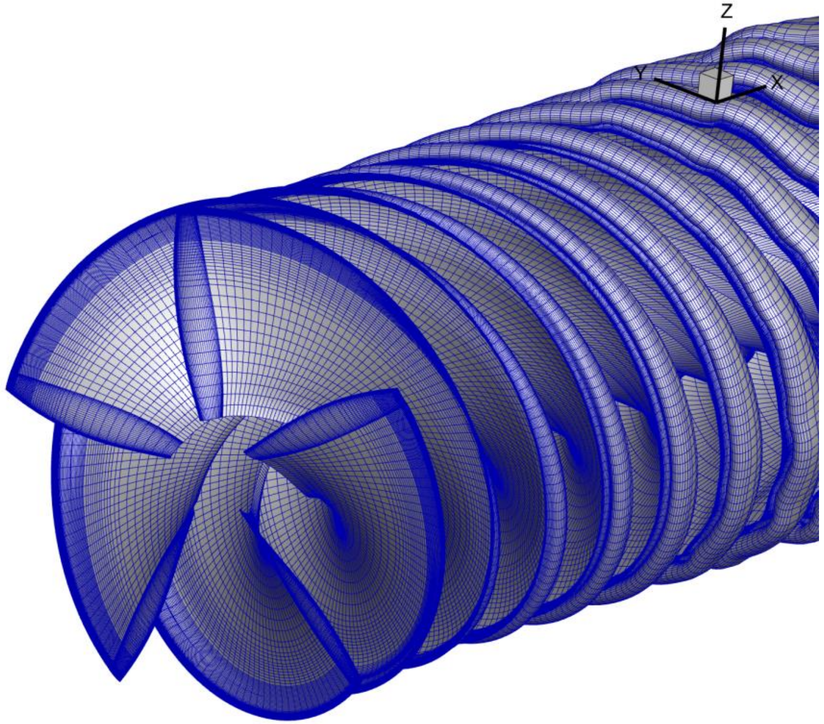
Implementing AI model into PANAM

- Infrastructure to implement the model into ground based noise assessment tool PANAM.

DLR's Unsteady free wake Panel Method (UPM)
Wake panel representation



Numerical model of blade and wake **[2]**

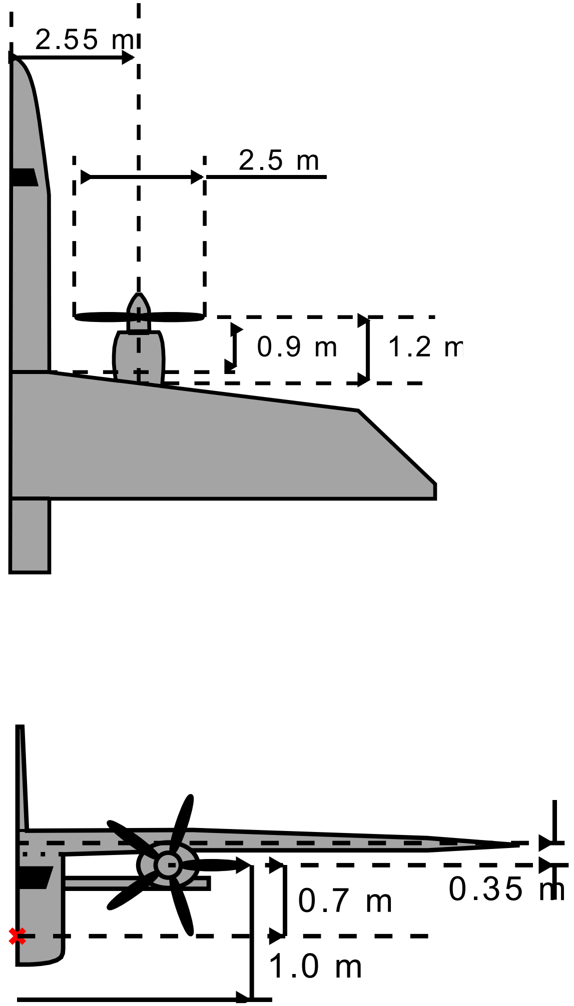


Wake development from DO-228 propeller blade.

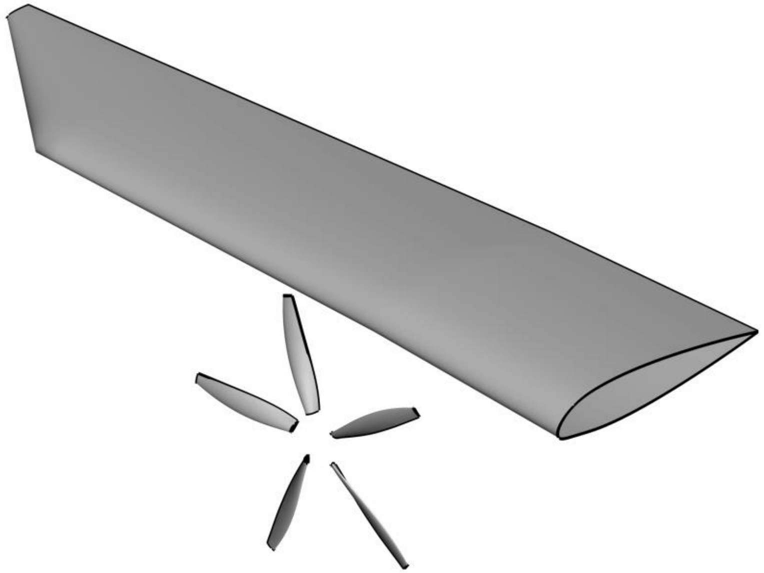
- Assumption of Incompressible, Inviscid, Irrotational flow for the UPM solver
- Mesh free solver with source/sink, double surface panels used for approximating the geometry
- Vortex core defined on each quad-wake filament

Detailed dimensions of simplified geometry
Propeller installed with half-wing

- For computational efficiency a simplified geometry of propeller installed with half wing is considered.
- For simplification fuselage and nacelle are omitted from the UPM simulations
- The effect of fuselage is defined using a wall boundary condition at the root of the wing.
- Airfoil used for creating the blade and wing geometry is approximated using sharp trailing edge (TE)

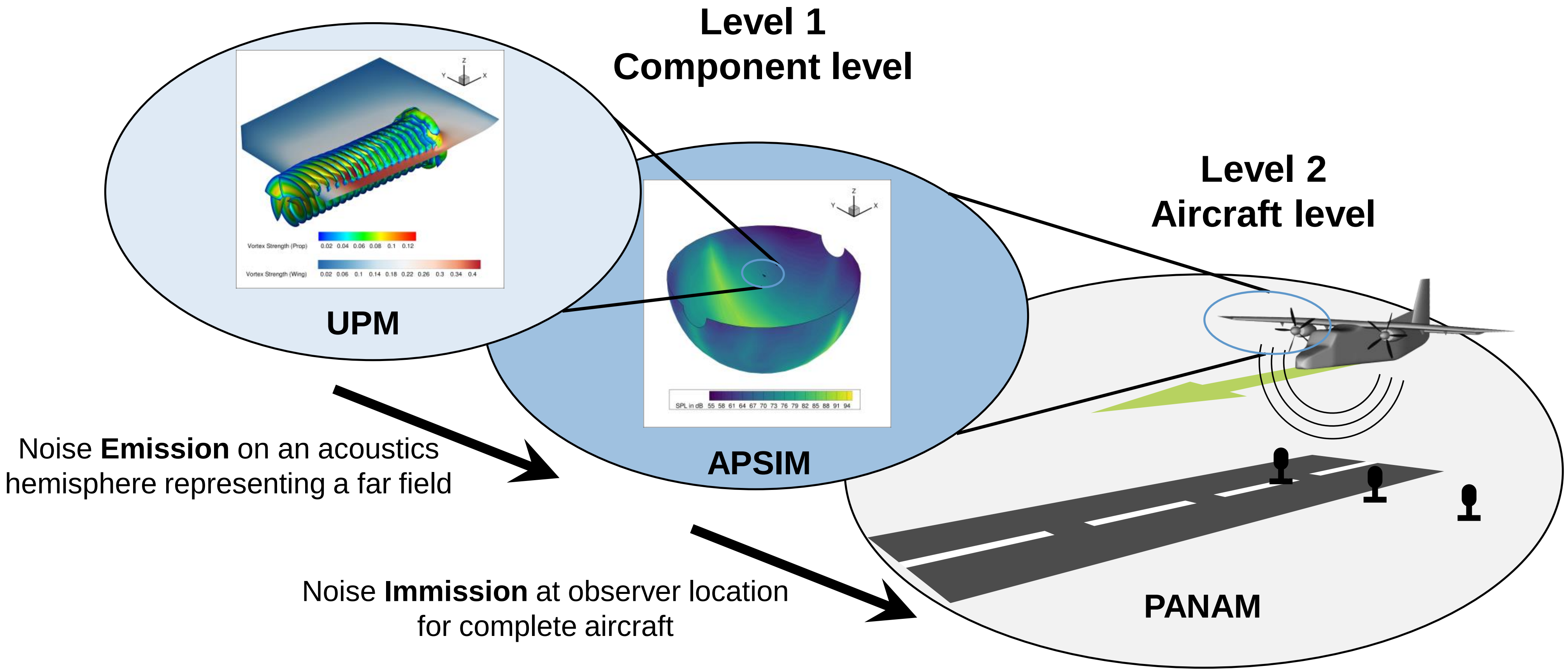


Front view and Top view



Simplified approximated geometry of propeller installed with wing

Computational methodology

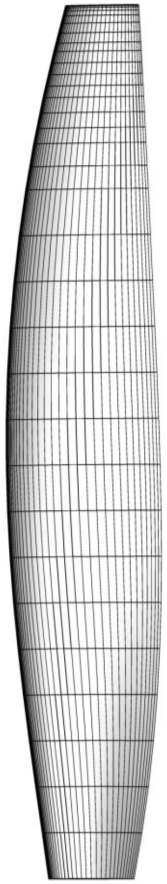
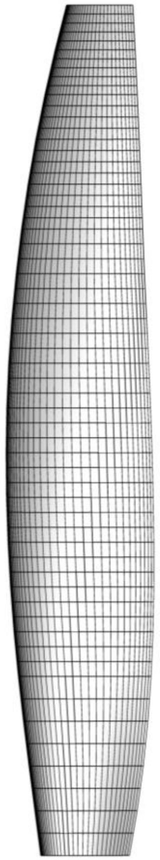
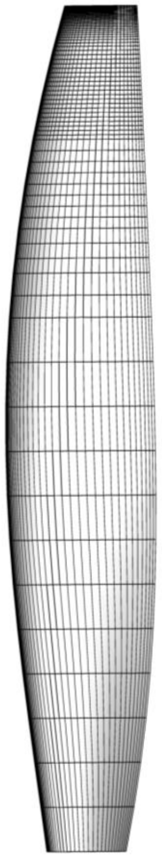


- Coupling of UPM-APSIM (first principle based tools) to calculate the noise **Emission** at the component level
- Coupling PANAM to UPM-APSIM to calculate noise **Immission** for complete aircraft at observer location, considering Doppler effect and ground reflections

Goals of presentation

Grid sensitivity study	Effect of changing the number of surface panel grid on aerodynamic and aeroacoustics of isolated and installed propeller
Vortex core radius sensitivity study	Effect of varying the vortex core diameter on aerodynamic and aeroacoustic simulations
Vortex core model sensitivity study	Effect of varying the vortex core model on aerodynamic and aeroacoustic simulations
Verification	Verification of simulations of UPM-APSIM coupling with BEMT-HANSON coupling
Validation	Validation of the UPM-APSIM-PANAM simulation with the flyover measurement data

Grid refinement study: Isolated propeller
Blade surface panel grid

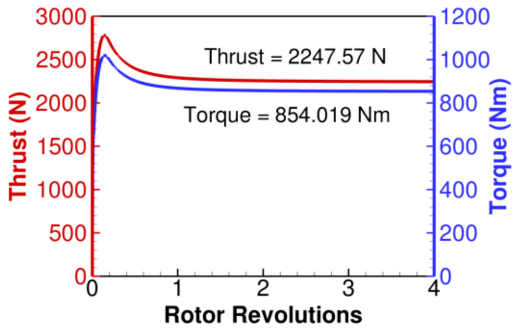
Grid 1	Grid 2	Grid 3
		
Number of panels = 80 x 32	Number of panels = 80 x 60	Number of panels = 80 x 75

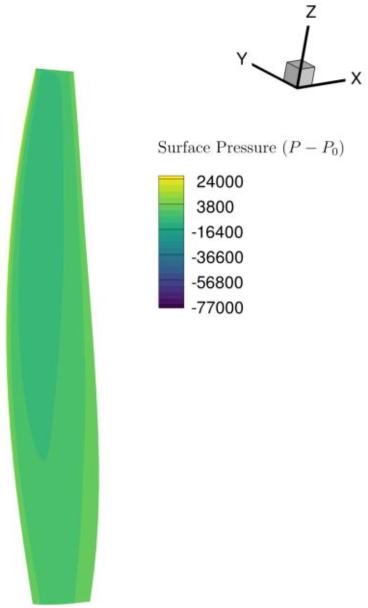
Aerodynamic loading on the propeller blade

Thrust, Torque, and Surface pressure

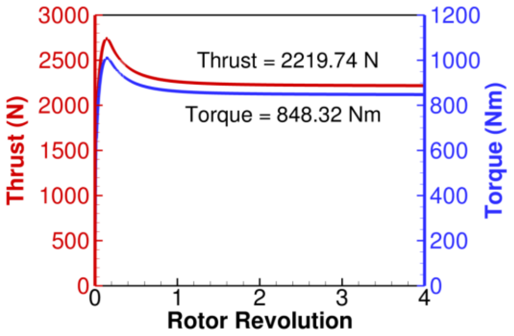
Grid 1	Grid 2	Grid 3

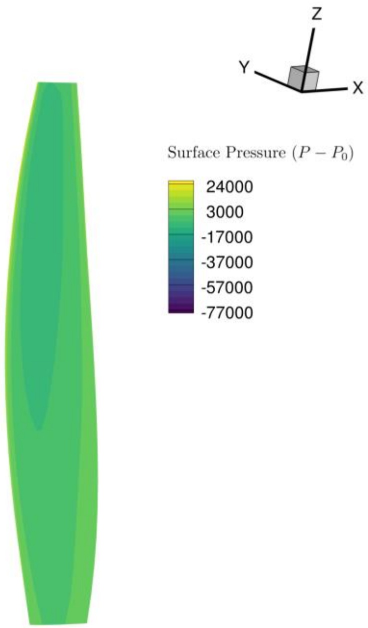
Grid 1



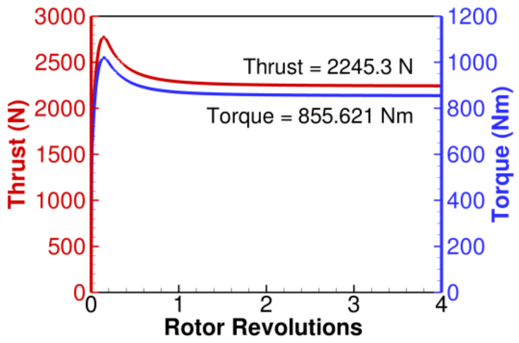


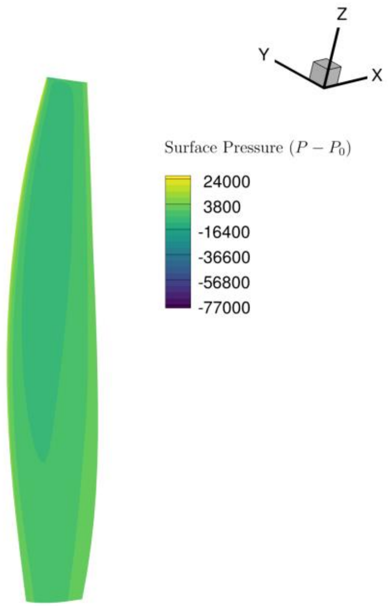
Grid 2



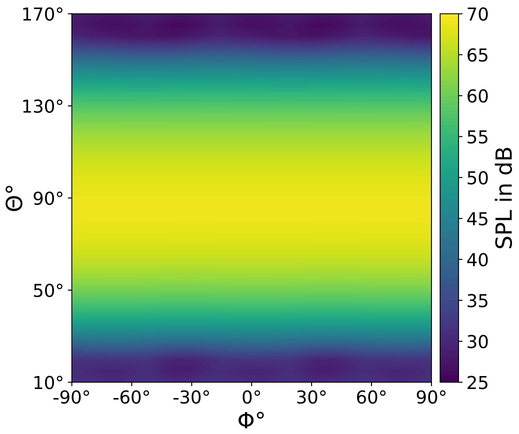


Grid 3

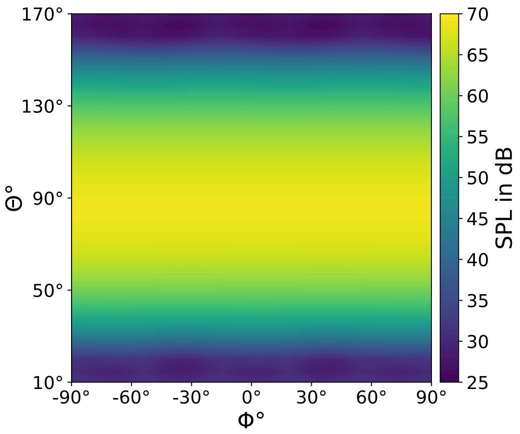




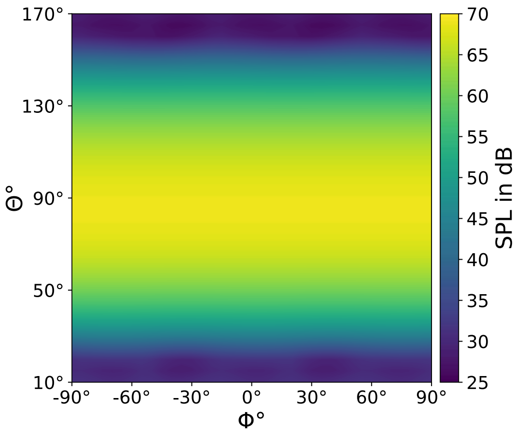
Effect of changing surface panel density on acoustics



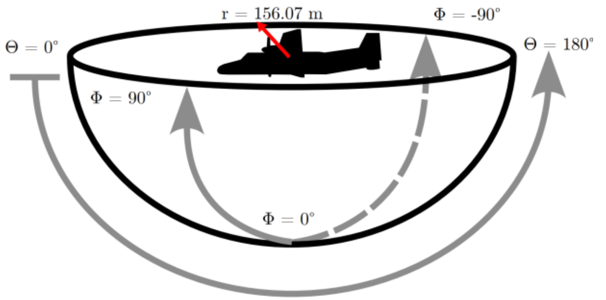
Panel grid 1



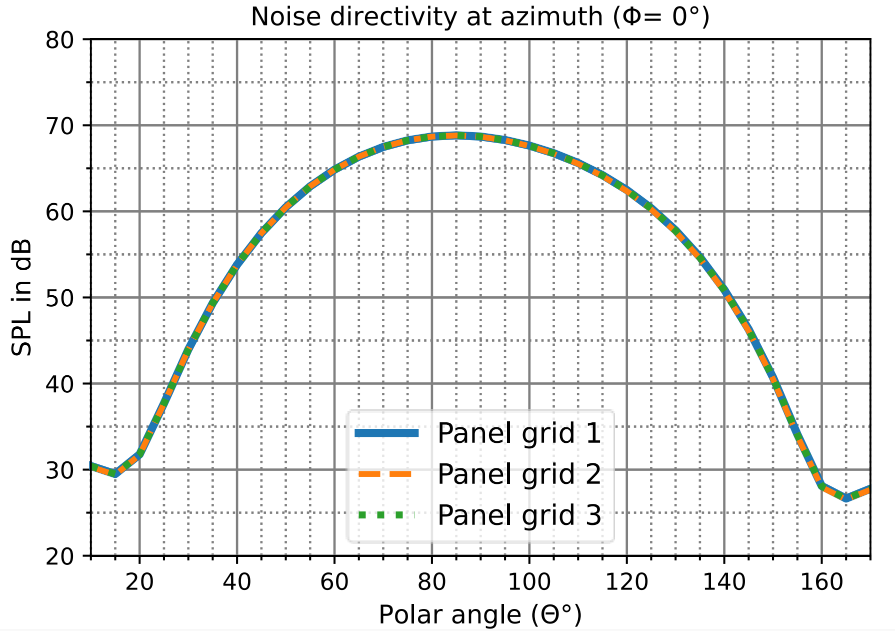
Panel grid 2



Panel grid 3



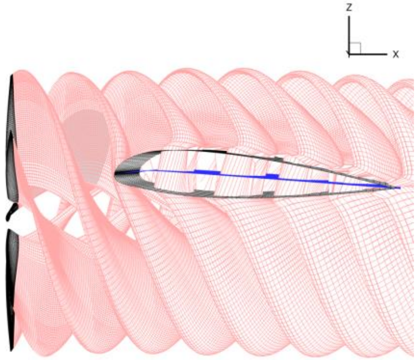
Acoustics hemisphere representing the far field

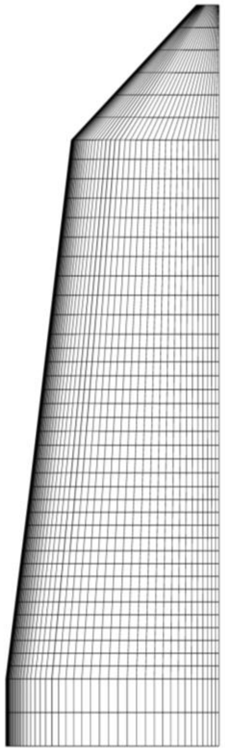
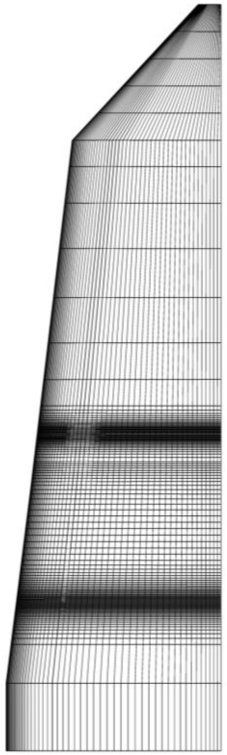
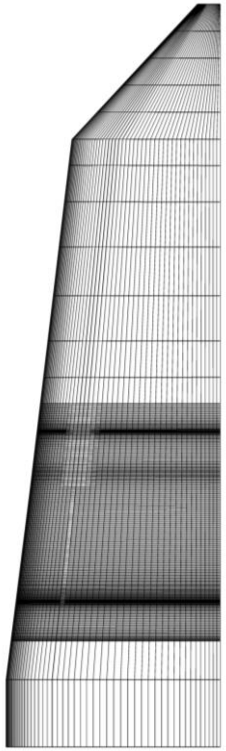


Overview

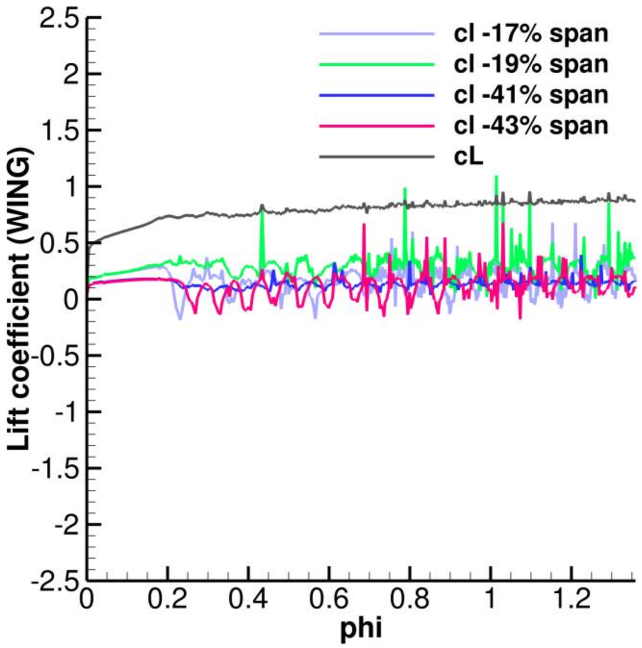
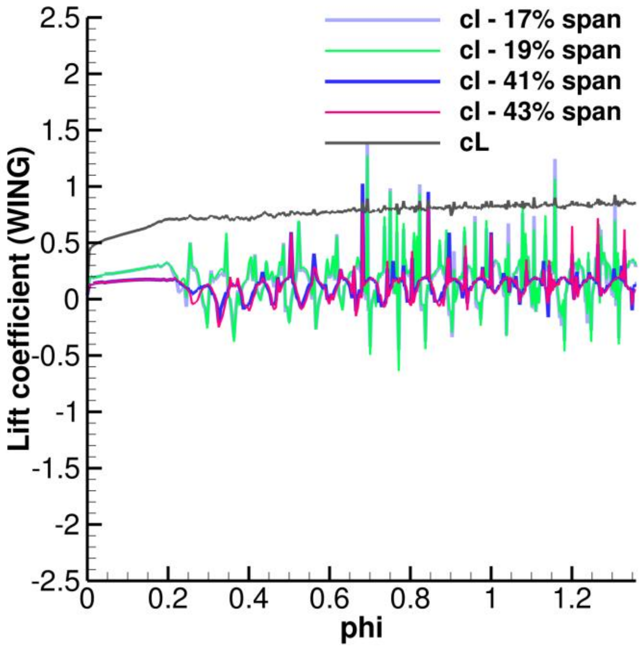
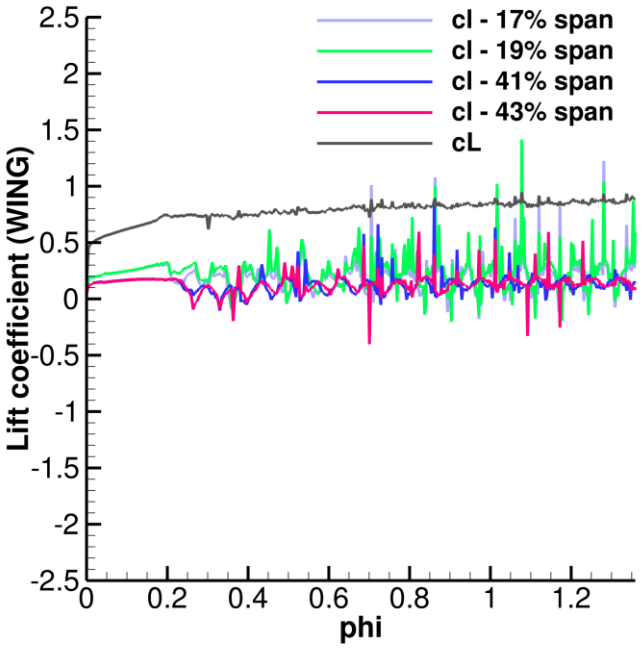
- Surface pressure used for loading noise calculation and spatial co-ordinates for thickness noise in FW-H equation
- Acoustics hemisphere is a simulation grid of virtual microphones arranged at varying polar and azimuth angles.
- No effect observed on the noise emitted to the far-field with varying the number of surface panels used for describing the geometry.
- Directivity remains unchanged over varying polar and azimuth angles on the acoustics hemisphere.
- Panel grid 1 is selected as an optimal grid.

Grid refinement study
Propeller installed with wing



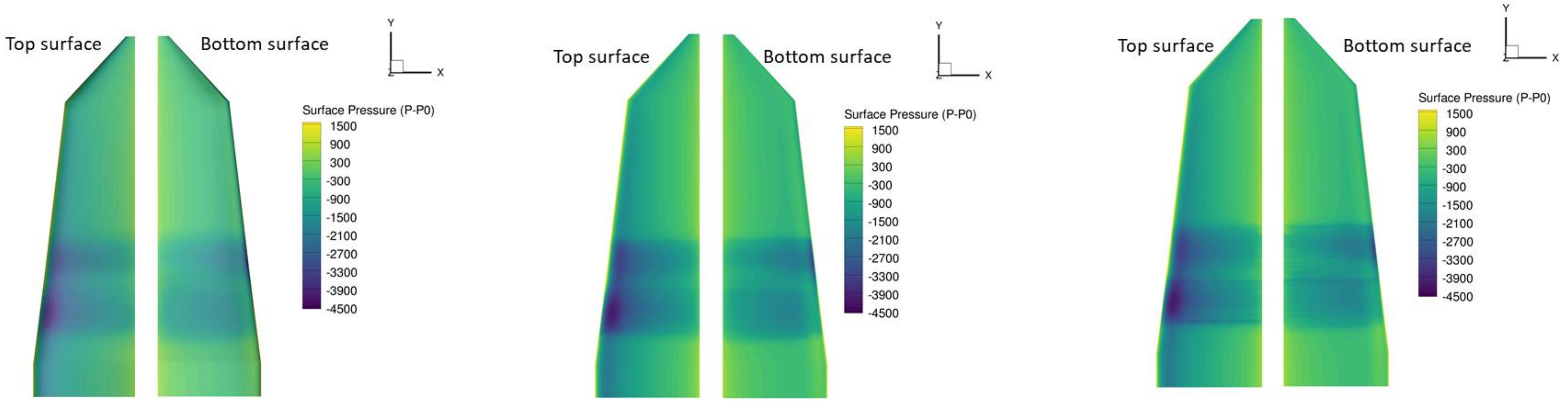
Grid 1	Grid 2	Grid 3
		
Number of panels = 100 x 44	Number of panels = 100 x 125	Number of panels = 100 x 180

Aerodynamic loading on wing
Time history of lift-coefficient

Grid 1	Grid 2	Grid 3
		

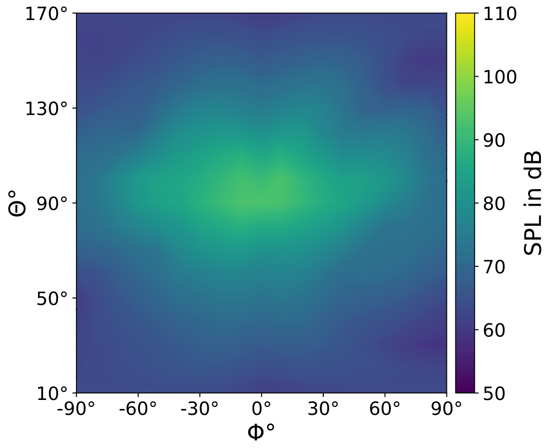
Aerodynamic loading on wing
Surface pressure

Grid 1	Grid 2	Grid 3

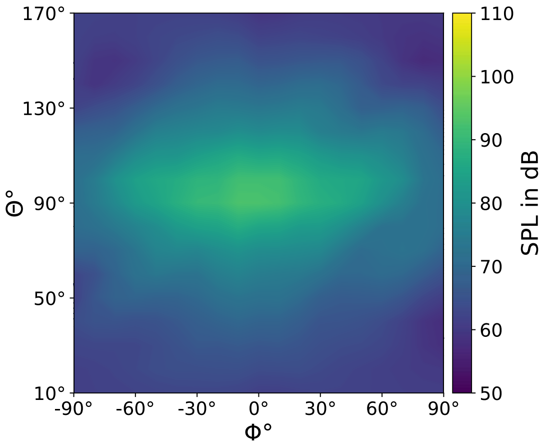


- Increasing the panel density on the wing-span under direct influence of propeller wake shows low pressure region near LE of wing with fluctuations in spanwise direction
- Surface pressure on wing for grid 3 (most refined grid) shows fluctuation in the pressure in the spanwise direction due to interference between neighboring vortex defined on each quad wake panel
- Increased panel density in the spanwise direction specifically for those sections which are under direct influence of tip vortex shed from the propeller captures the effect of wing-vortex interaction in a better way compared to less dense panel grid

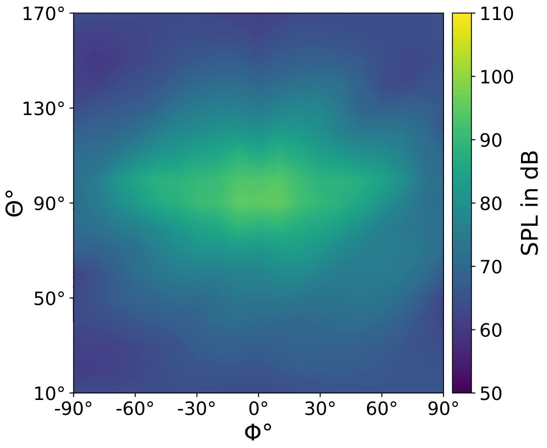
Effect of changing surface panel density on acoustics



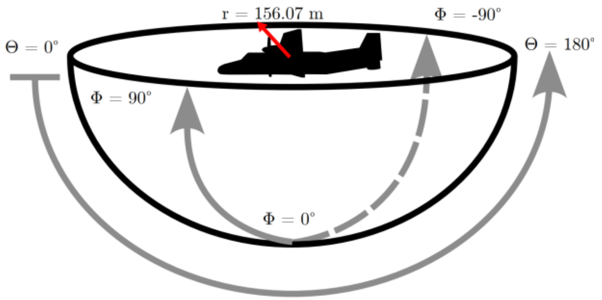
Panel grid 1



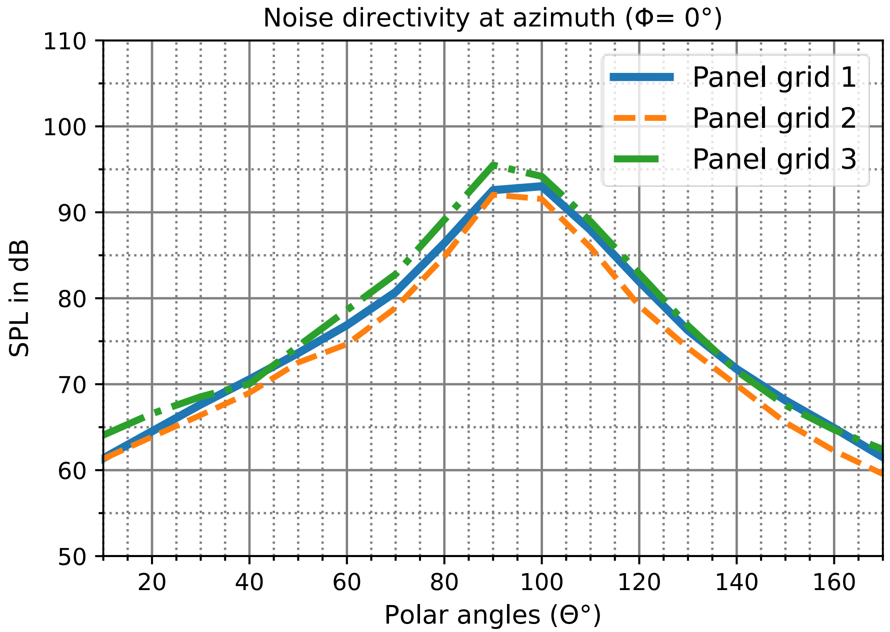
Panel grid 2



Panel grid 3



Acoustics hemisphere representing the far field



Overview

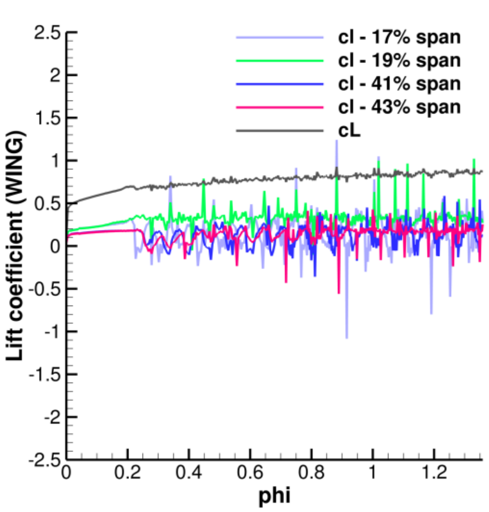
- Changing the surface panel density of the span under direct influence of wake from propeller results in increased levels by 1dB to 3 dB.
- Noise directivity at $\boldsymbol{\Phi} = 0°$ changes as the panel density is increased in region influencing wing-wake interaction.
- Surface panel grid 2 selected as an optimal condition for further analysis.

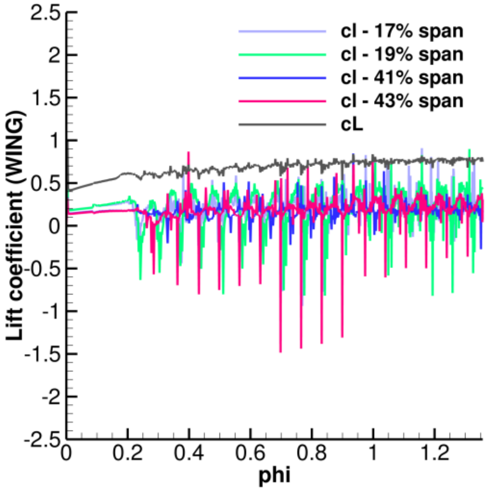
Goals of presentation

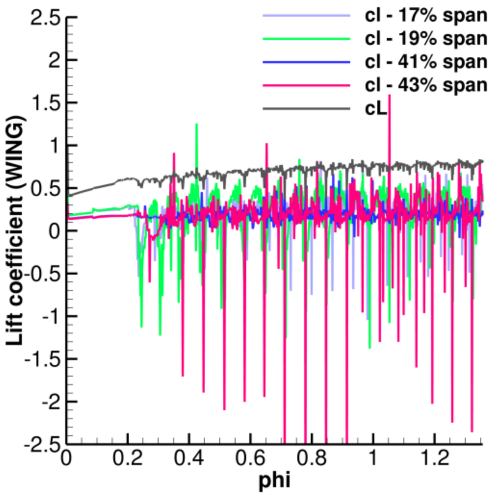
Grid sensitivity study	Effect of changing the number of surface panel grid on aerodynamic and aeroacoustics of isolated and installed propeller
Vortex core radius sensitivity study	**Effect of varying the vortex core diameter on aerodynamic and aeroacoustic simulations**
Vortex core model sensitivity study	**Effect of varying the vortex core model on aerodynamic and aeroacoustic simulations**
Verification	Verification of simulations of UPM-APSIM coupling with BEMT-HANSON coupling
Validation	Validation of the UPM-APSIM-PANAM simulation with the flyover measurement data

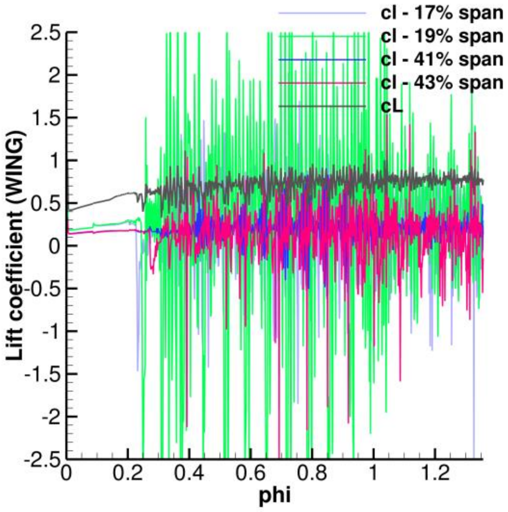
Aerodynamic simulations
Vortex core model: Rankine

R_0 = 10% MAC	R_0 = 30% MAC	R_0 = 50% MAC	R_0 = 80% MAC







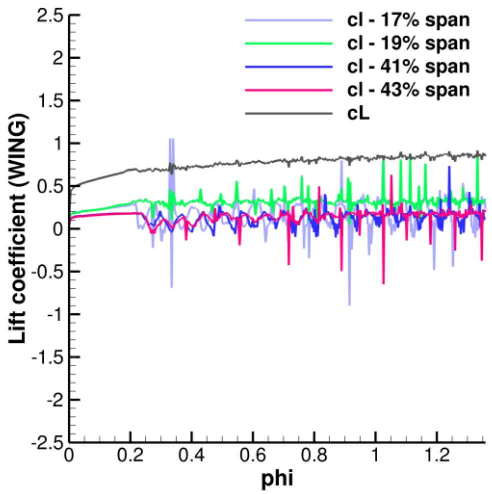


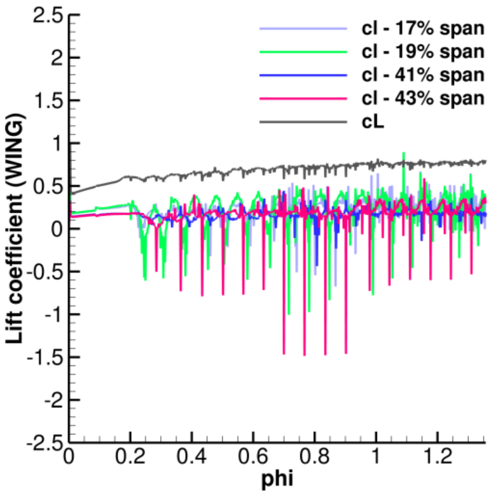
- A larger vortex core defined on each filament of the wake panels results in higher oscillations of the lift-coefficient over time
- A smaller vortex core results in oscillations of lift-coefficient over time but in a more periodic manner
- Time history of lift-coefficient (c_L) over the whole span of the wing is plotted by integrating c_l for each section to check convergence

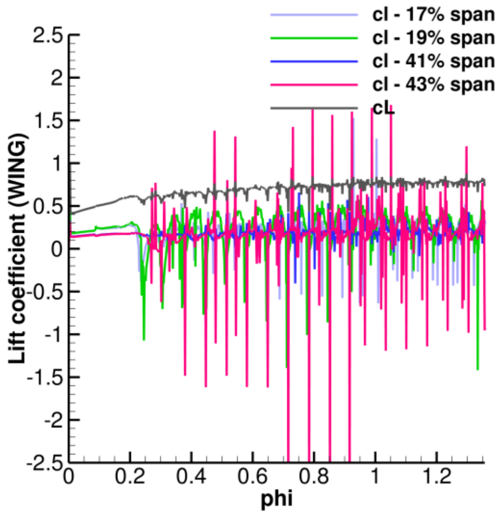
Aerodynamic simulations

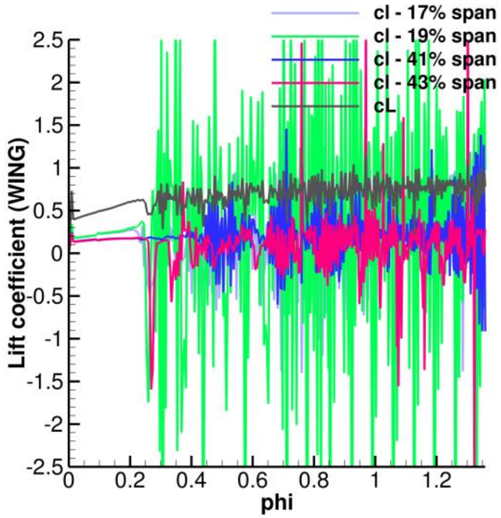
Vortex core model: Lamb-Oseen

R_0 = 10% MAC	R_0 = 30% MAC	R_0 = 50% MAC	R_0 = 80% MAC





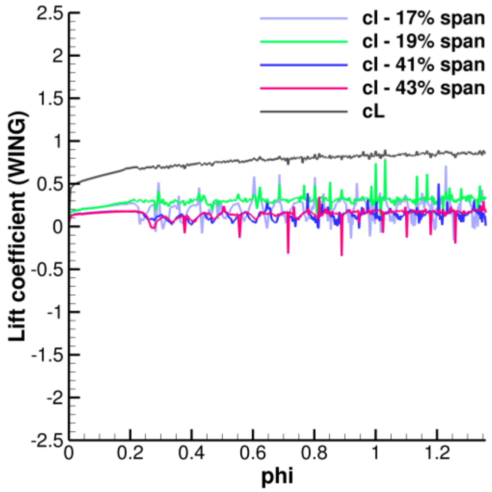




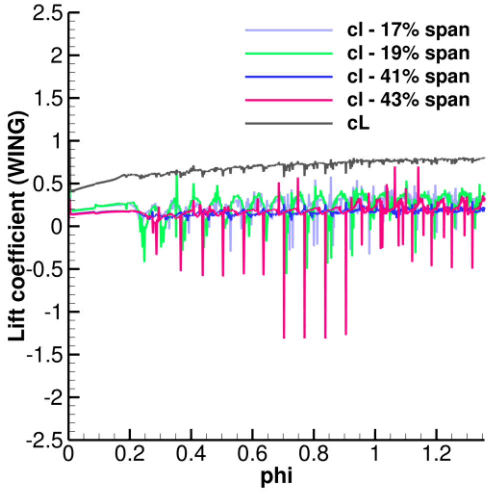
- Oscillations in the lift-coefficient over time are reduced for smaller vortex core compared to the case of Rankine vortex core model
- With increasing the size of the vortex core the oscillation in c_l increases and periodicity is lost

Aerodynamic simulations
Vortex core model: Kaufmann-Scully

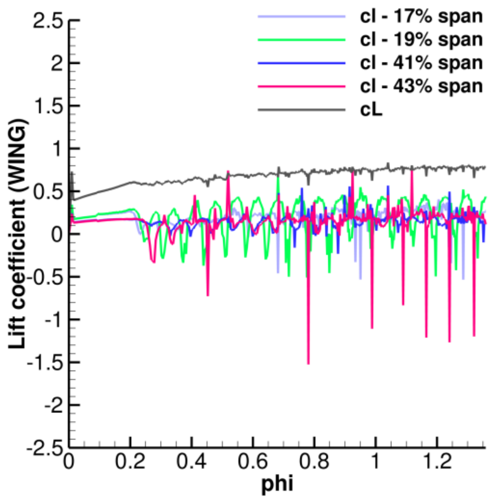
R_0 = 10% MAC



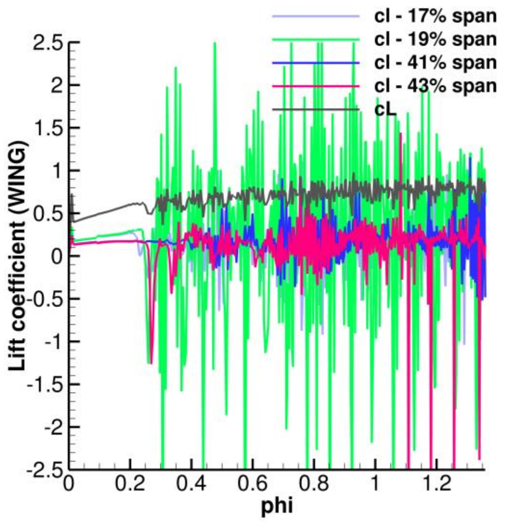
R_0 = 30% MAC



R_0 = 50% MAC



R_0 = 80% MAC



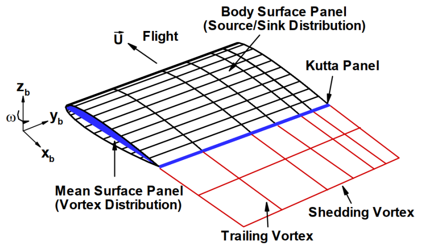
- Oscillation in the lift-coefficient over time for Scully model are reduced until R_0 = 50% MAC, compared to the vortex core model of Rankine and Lamb-Oseen
- For R_0 = 10% MAC & 30% MAC, oscillation are occurring in periodic manner
- For R_0 = 50% MAC the periodicity is lost

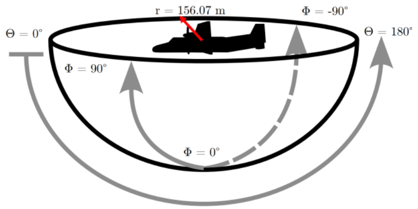
Aeroacoustics simulations

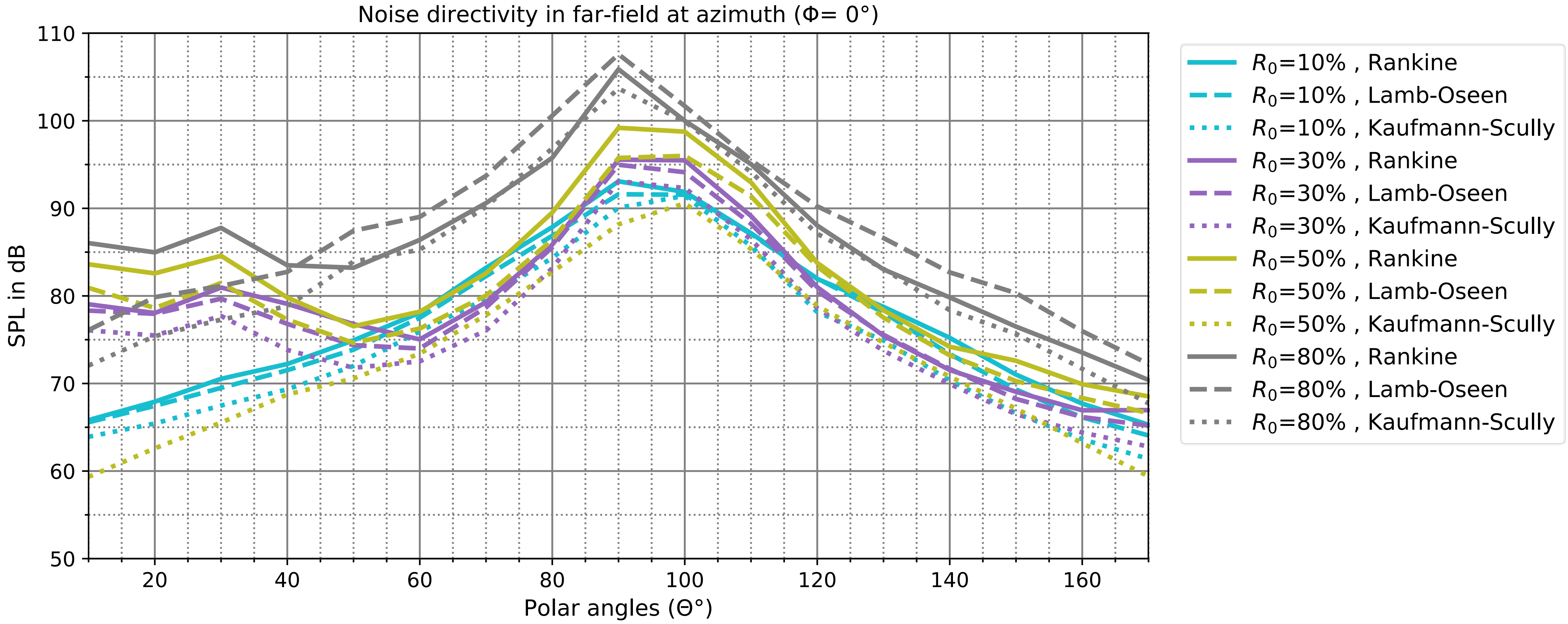
Effect of vortex core radius and core model on noise directivity

DLR

Noise directivity at azimuth (Φ = 0°)



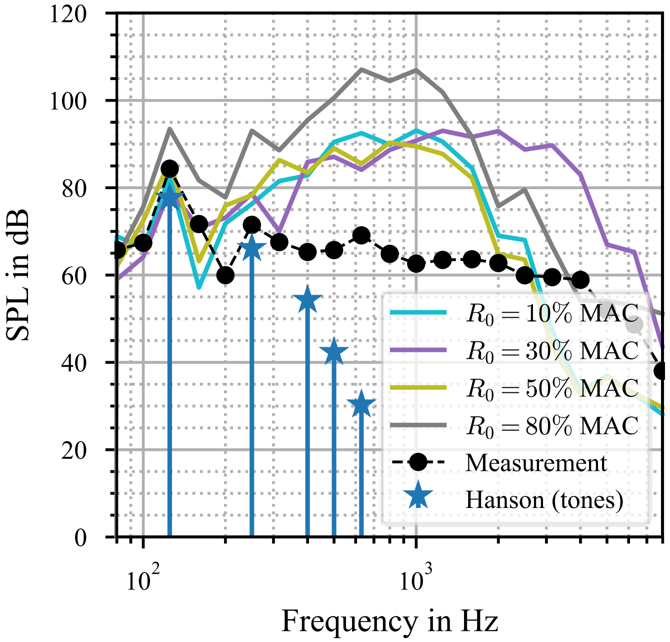




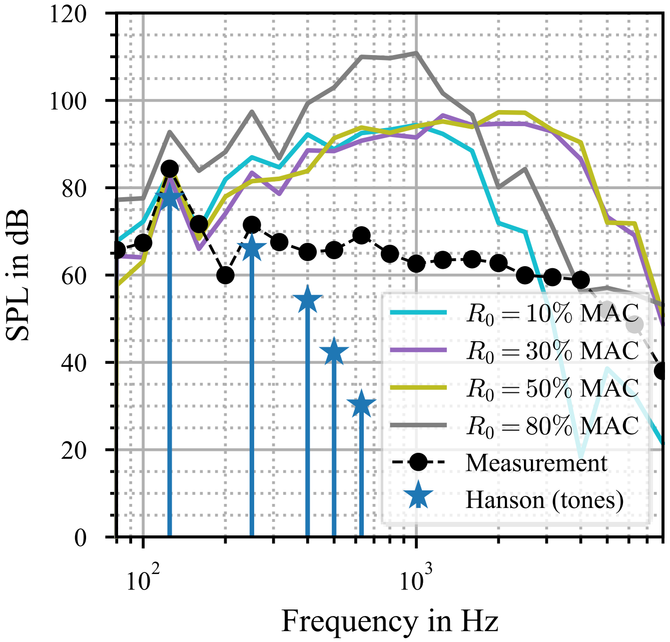
Validation of sensitivity study using flyover data

Spectrum plot at same immission angle

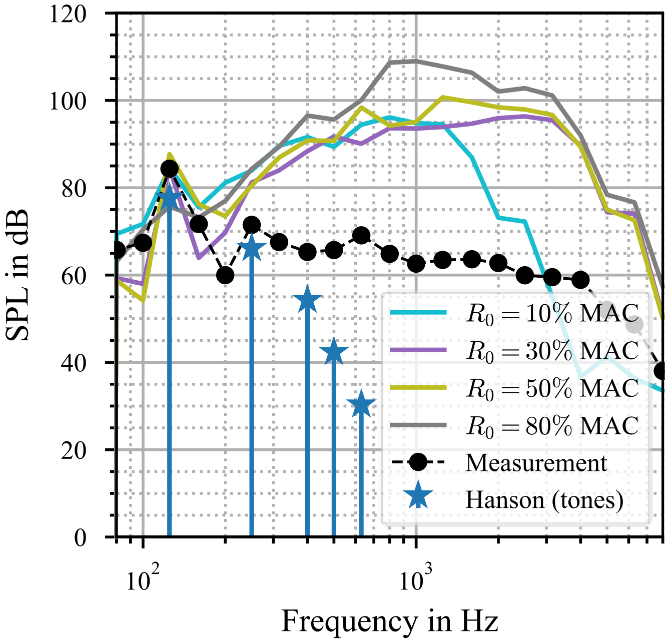
Kaufmann Scully vortex core model



Lamb-Oseen vortex core model



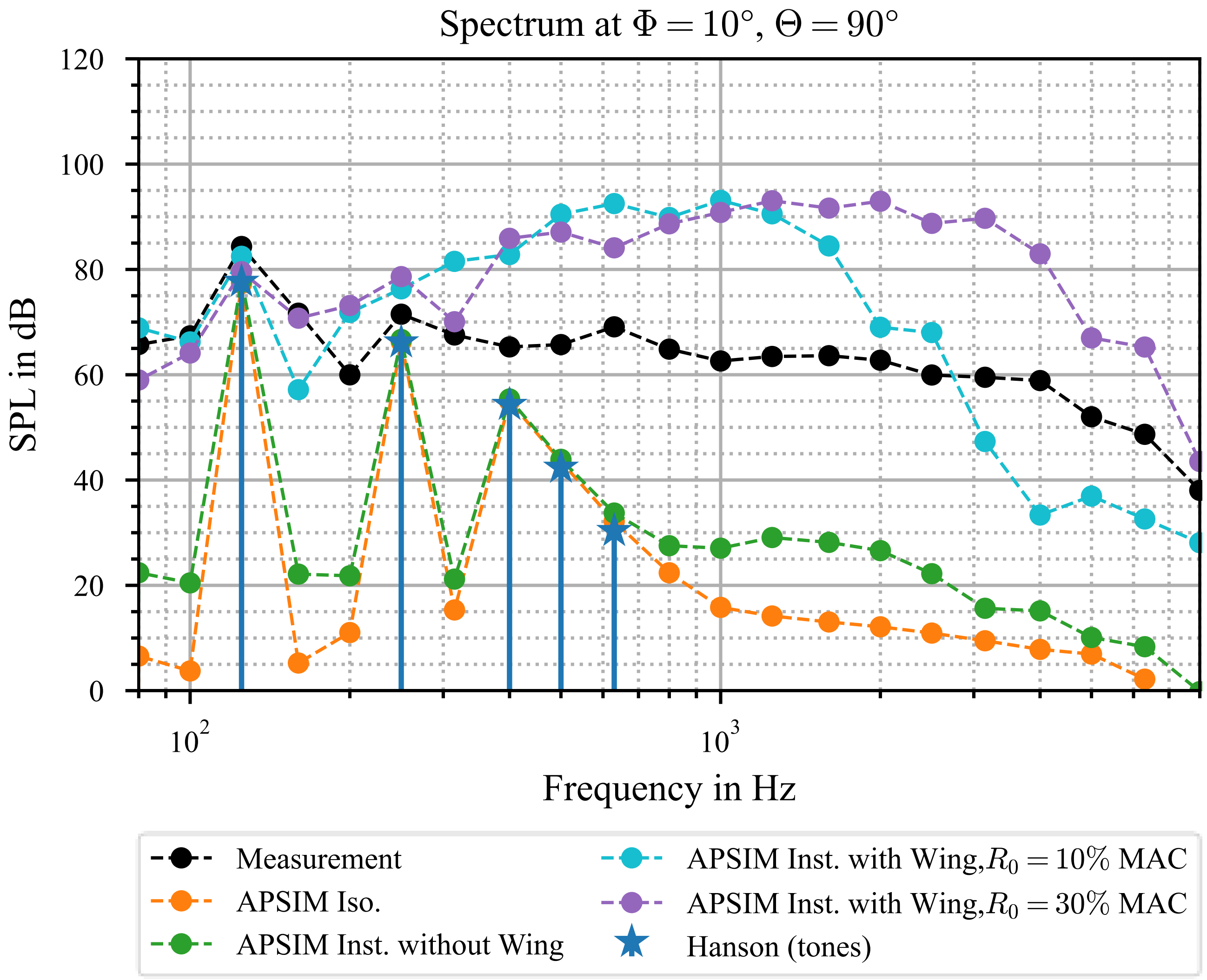
Rankine vortex core model



- Increasing the vortex core radius from $R_0 = 10\%$ to $R_0 = 80\%$ increase the noise levels
- All three vortex core model predicts the tone at 1st harmonics close to the tone from measured data until $R_0 = 50\%$ MAC
- Sudden increase in noise levels after 1st harmonics indicates the presence of interference between propeller wake panels and wing doublet panels in UPM-APSIM simulation

Validation of sensitivity study using flyover data
Spectrum plot for Kaufmann-Scully vortex core model

- Tones from UPM-APSIM closely resembled the tones from HANSON model
- Large propeller installed distance from wing results in tones from UPM-APSIM to closely resembles tones from HANSON model for installed case without wing
- Negligible backloading from wing onto the propeller due to large installed distance between propeller and wing
- Inclusion of wing in CAA simulation leads to increased levels after 2nd BPF



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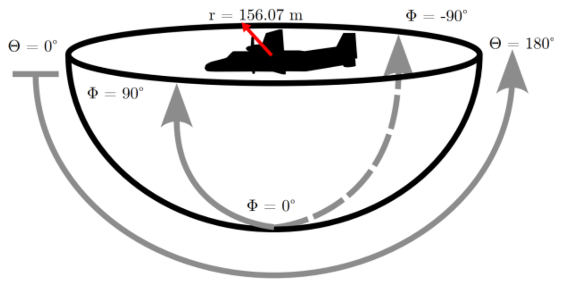
Verification using HANSON model

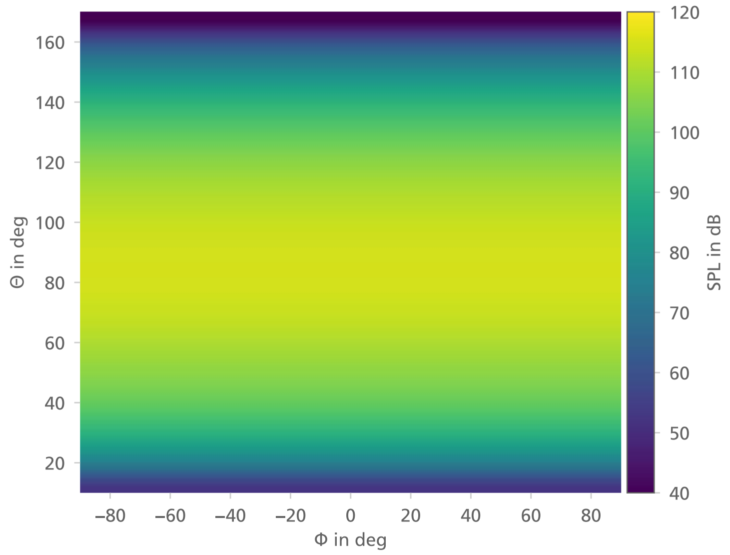
Directivity on acoustic hemisphere

- Noise source model of propeller in UPM-APSIM and HANSON for isolated propeller configuration gives smooth contour over the acoustics hemisphere

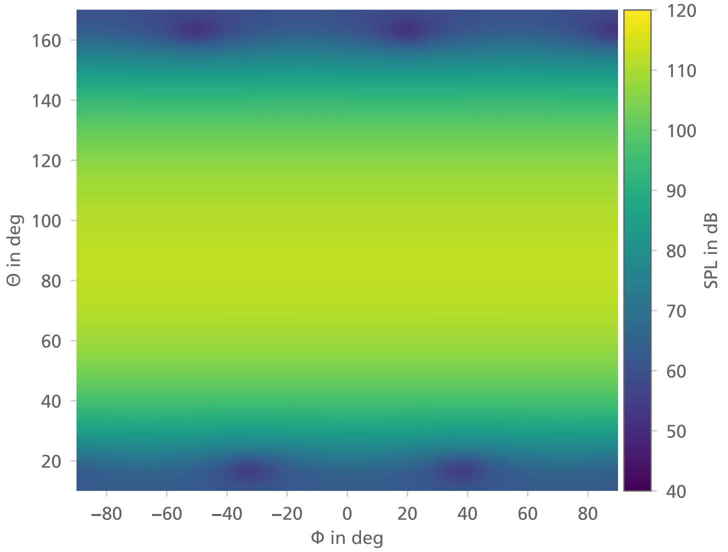
- Interference observed in the case of installed propeller without wing towards the two extremes of polar angle of acoustic hemisphere



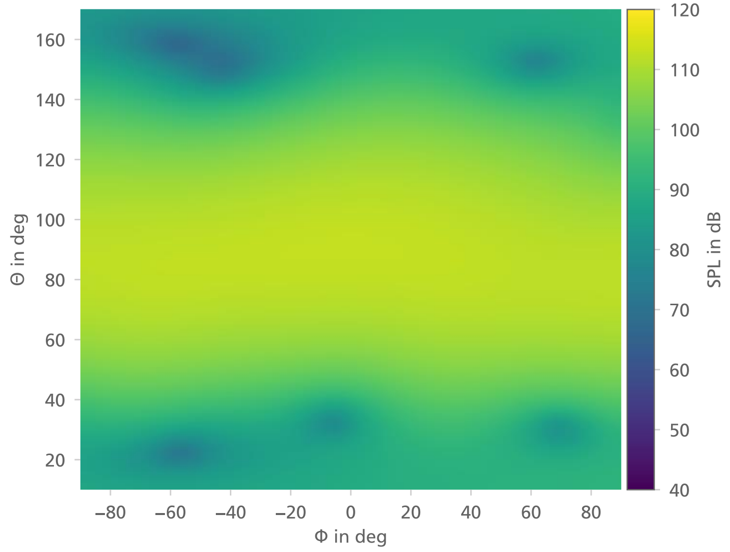
1st BPF HANSON model



1st BPF APSIM isolated



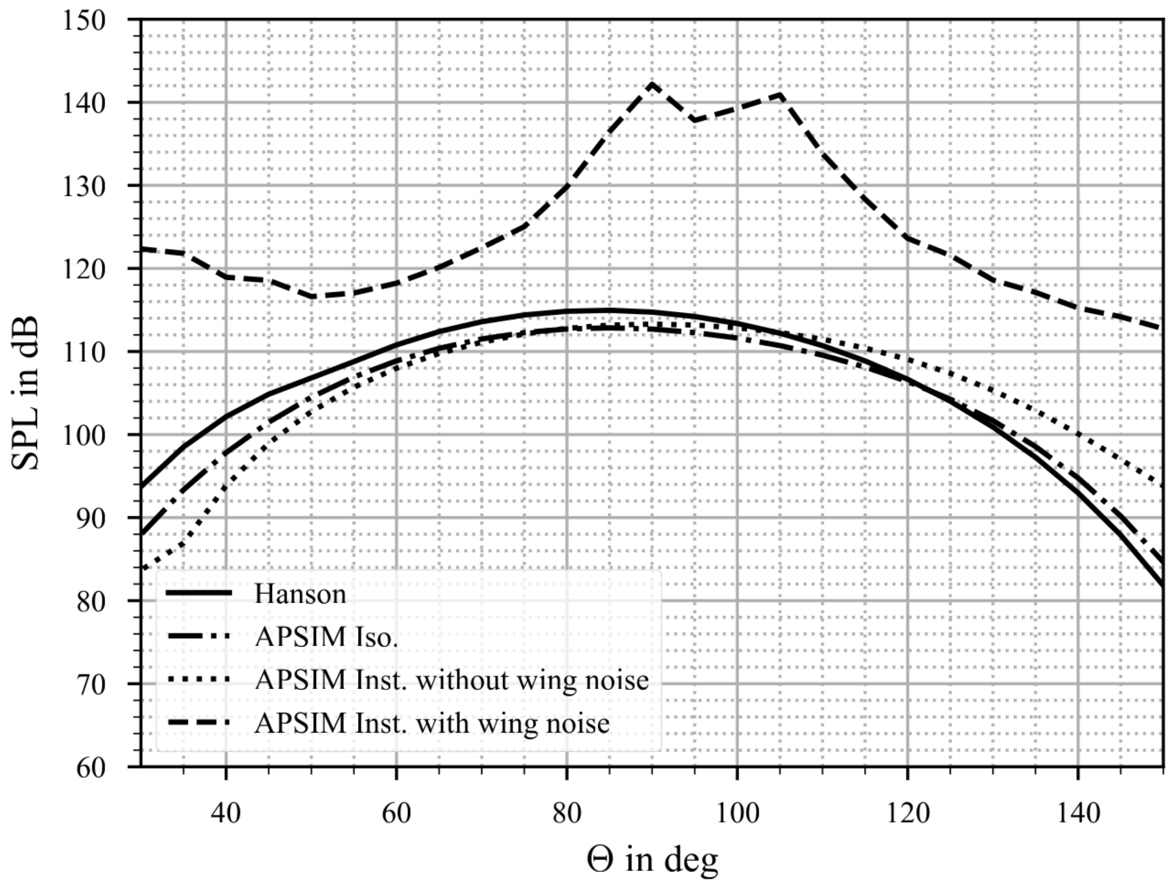
1st BPF APSIM installed propeller without wing



Verification using HANSON model

Noise directivity for fixed azimuth ($\Phi = 0°$)

- Isolated propeller configuration simulated using propeller source model of UPM-APSIM shows a close agreement with the noise levels from HANSON model
- Installed propeller configuration without wing underpredicts the maximum noise level by 1 dB - 2 dB at $\Theta = 90°$ compared to the HANSON model with noise directed in downstream of the propeller
- unreasonably high noise obtained in the directivity plot of installed propeller with wing due to higher harmonics in 1 KHz – 4 KHz range for mic-1 in the spectrum plot for same immission angle



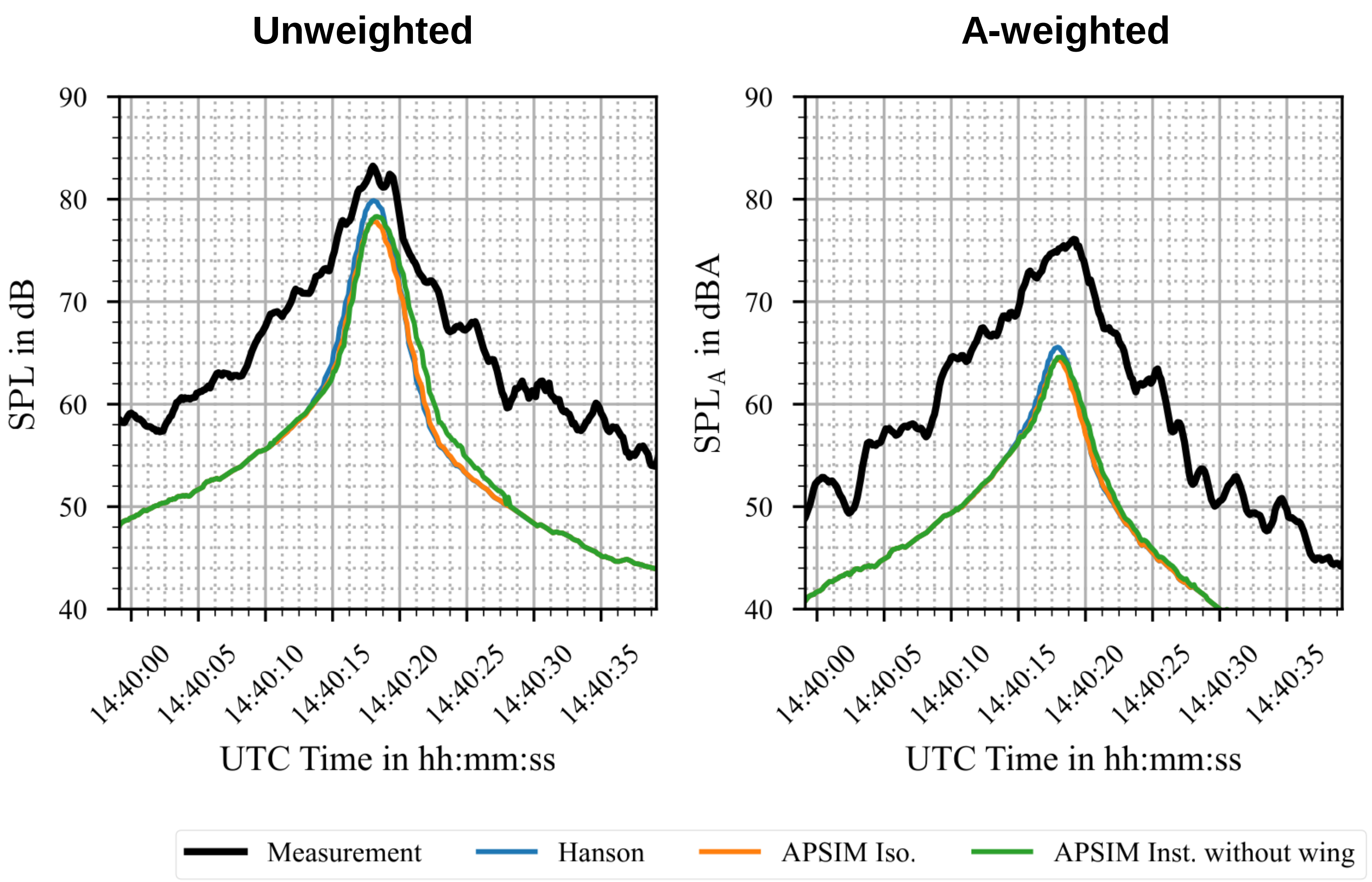
Goals of presentation

Grid sensitivity study	Effect of changing the number of surface panel grid on aerodynamic and aeroacoustics of isolated and installed propeller
Vortex core radius sensitivity study	Effect of varying the vortex core diameter on aerodynamic and aeroacoustic simulations
Vortex core model sensitivity study	Effect of varying the vortex core model on aerodynamic and aeroacoustic simulations
Verification	Verification of simulations of UPM-APSIM coupling with BEMT-HANSON coupling
Validation	**Validation of the UPM-APSIM-PANAM simulation with the flyover measurement data**

Validation with flyover measurement data

Level time history plot

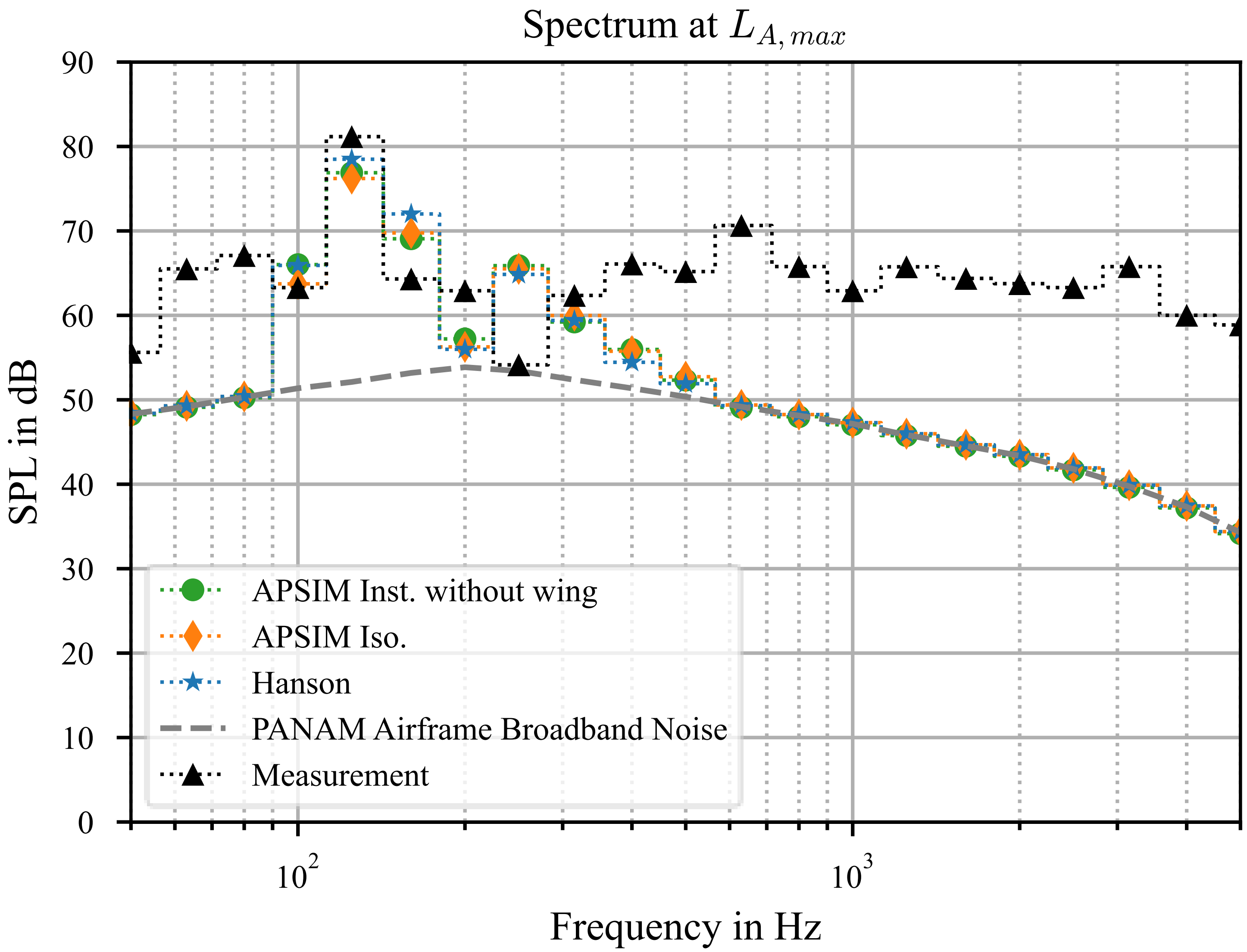
- Installed propeller with wing configuration not considered for validation
- Absence of Installation leads to underprediction by 3 dB - 5 dB for HANSON and UPM-APSIM noise source model in unweighted plot
- Reduced influence of tonal noise at lower frequency by A-weighting leads to 10 dB underprediction by simulated data compared to measured data



Validation with flyover measurement data

Frequency spectrum at $L_{A,\,max}$

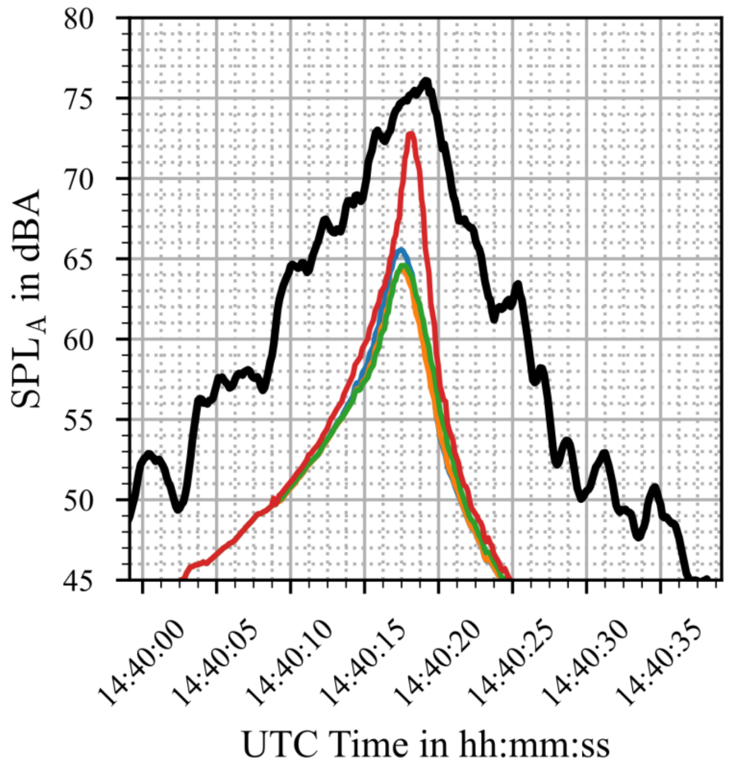
- Close agreement observed between HANSON tones and UPM-APSIM tones for isolated and installed case without wing
- Both HANSON model and UPM-APSIM underpredicts the first harmonics by 2 dB to 4 dB
- Underprediction of PANAM airframe broadband noise compared to the broadband noise from measured data



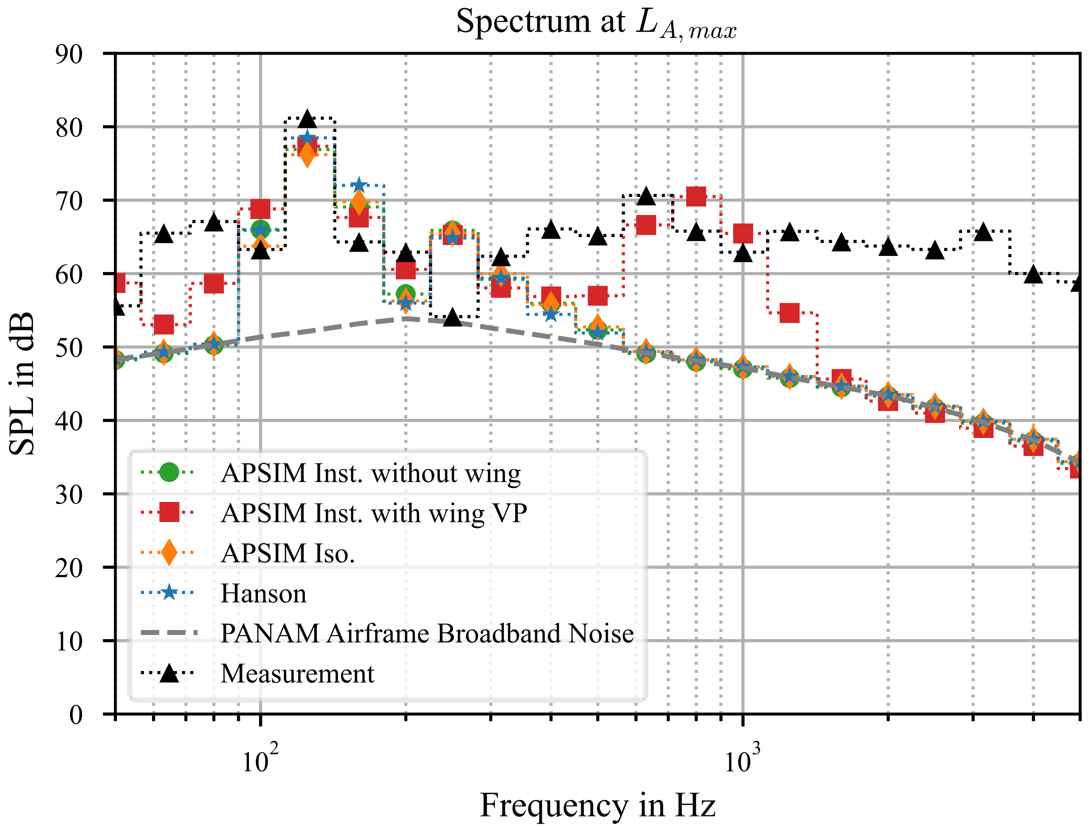
Validation with flyover measurement data

Using vortex particle method in UPM for Aerodynamic simulations

Level time history plot



Frequency spectrum at $L_{A,\,max}$



Summary and Conclusion

1 Grid Sensitivity study

- Increased panel density requires a smaller vortex core and with a coarser grid a larger vortex core could be used

2 Sensitivity study
Vortex core radius

- Vortex core radius defined in range of 5% to 30% of MAC of propeller
  - Larger installation distance between propeller & wing requires larger core radius

3 Sensitivity study
Vortex core model

- Kaufmann-Scully vortex core model shows a plausible agreement to the first two harmonics compared to other vortex core model

4 Verification using HANSON model

- A good agreement is observed between the noise levels obtained from coupling of UPM-APSIM compared to the HANSON model for isolated propeller configuration

5 Validation using flyover data

- Vortex filament method in UPM is unable to handle the installation effects and gives numerical error after 2nd harmonics.
  - Vortex particle method solves the problem encountered in installed propeller configuration

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Impressum

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