Scattering of Aerodynamically Induced Noise and Nonlinear Sound Propagation

Seongkyu Lee, Ph.D.
Assistant Professor
Mechanical and Aerospace Engineering
University of California, Davis

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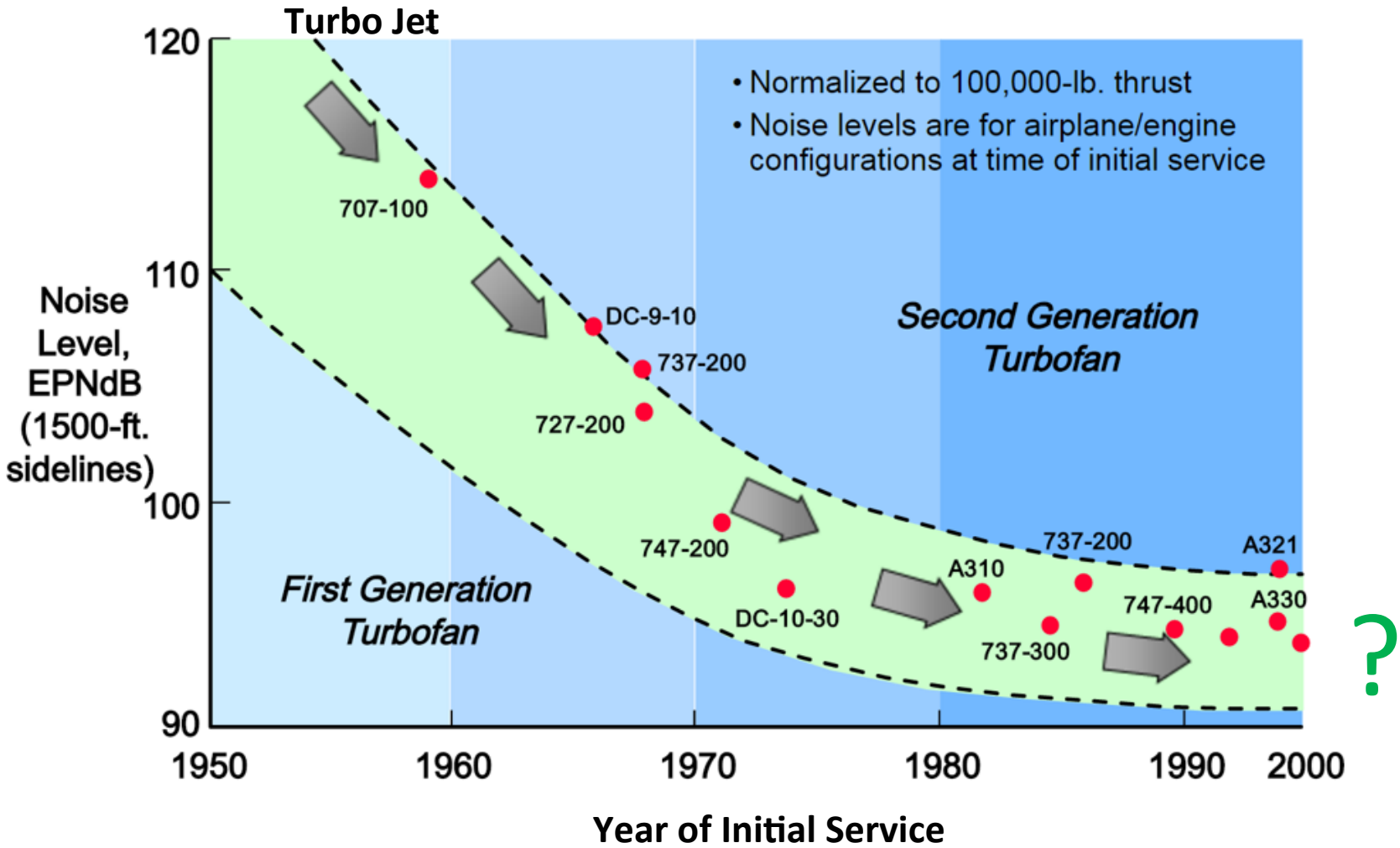
Outlines

- Aeroacoustics 101
- Acoustic Scattering
  - Pressure gradient formulations
  - Equivalent source method
  - Applications
- Nonlinear Sound Propagation
  - Numerical methods
  - Applications to sonic boom, jet noise, rotorcraft noise
- Conclusions

Aeroacoustics 101

Aircraft Noise Trend

- Aircraft noise trend



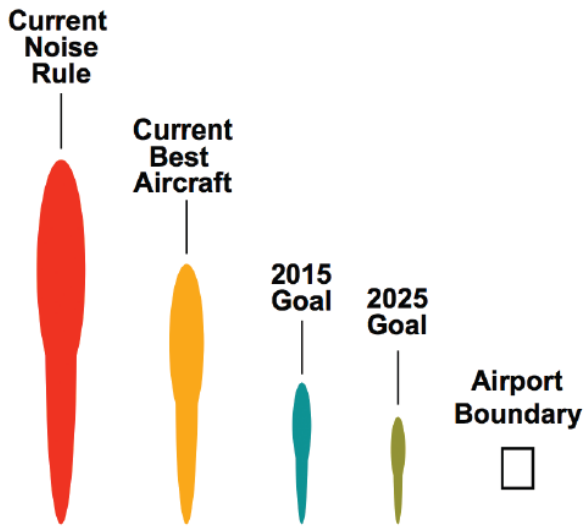
NASA's Vision

NASA's Goals for Green Aviation

- **Fuel Efficiency :** Burn 60% less fuel by 2025
- **Emissions :** Cut NOx emissions greater than 80% by 2025
- **Noise :** Shrink the nuisance noise footprint within airport property boundary (52dB EPNL reduction)
  - *Advanced and fundamental research in aeroacoustics needed*

v2013.1

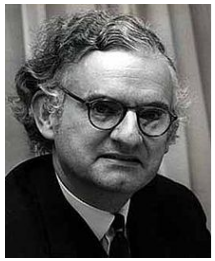
TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-52 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)	-33%	-50%	-60%



Courtesy: NASA, 2013

Milestones of Aeroacoustics

- James Lighthill…a father of aeroacoustics
  - 1952, Rearranged Navier-Stokes equation into acoustic equation with equivalent sources (acoustic analogy)
  - Found the role of turbulence in the noise generation



- Ffowcs Williams
  - 1969, Generalized Lighthill's acoustic analogy for moving surfaces (FW-H)

- Feri Farassat
  - 1982, Found integral solutions of FW-H equation Widely used in rotorcraft noise, jet noise

- Christopher Tam
  - 1990s, Computational aeroacoustics, jet noise

Lighthill's Acoustic Analogy

- **Aeroacoustics began with Lighthill's acoustic analogy, which is rearrangement of N-S equations**

$$\frac{\partial}{\partial t}\quad \frac{\partial \rho}{\partial t} + \cancel{\frac{\partial}{\partial x_i}(\rho u_i)} = 0$$

$$-\quad \frac{\partial}{\partial x_i}\quad \cancel{\frac{\partial}{\partial t}(\rho u_i)} + \frac{\partial}{\partial x_j}\left(\rho u_i u_j + p_{ij}\right) = 0$$

subtract $c_0^2 \nabla^2 \rho$

$$\boxed{\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \nabla^2 \rho = \frac{\partial^2}{\partial x_i \partial x_j} T_{ij}}$$

$$p_{ij} = -\sigma_{ij} + \delta_{ij} p$$

$$\sigma_{ij} = \mu\left\{\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial xi} - \frac{2}{3}\left(\frac{\partial u_i}{\partial x_i}\right)\delta_{ij}\right\}$$

$$T_{ij} = \rho u_i u_j + p_{ij} - c_0^2 \rho \delta_{ij}$$

$$\rho = \rho' + \rho_0$$

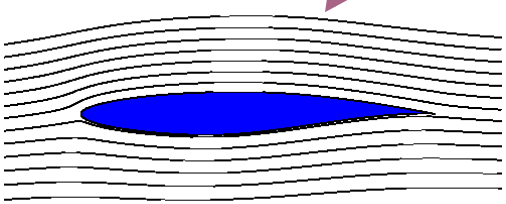
- **Aerodynamic noise is generated by Lighthill stress tensor (T_{ij}) and propagted with the speed of sound (c_0)**

FW-H Equation

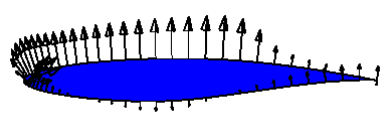
- Ffowcs Williams–Hawkings Equation : Generalized acoustic analogy for moving sources like rotor baldes

$$\Box^2 p'(\vec{x},t) = \frac{\partial}{\partial t}\left[Q\delta(f)\right] - \frac{\partial}{\partial x_i}\left[F_i\delta(f)\right] + \frac{\bar{\partial}^2}{\partial x_i \partial x_j}\left[T_{ij}H(f)\right]$$

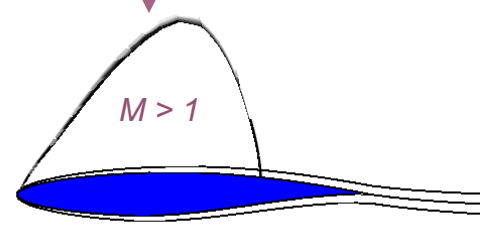
$f = 0$ describes the integration surface



Thickness
displacement of fluid generates sound



Loading
accelerating force distribution generates sound (unsteady flows)



Quadrupole
All volume sources, non-linear effects nonuniform sound speed

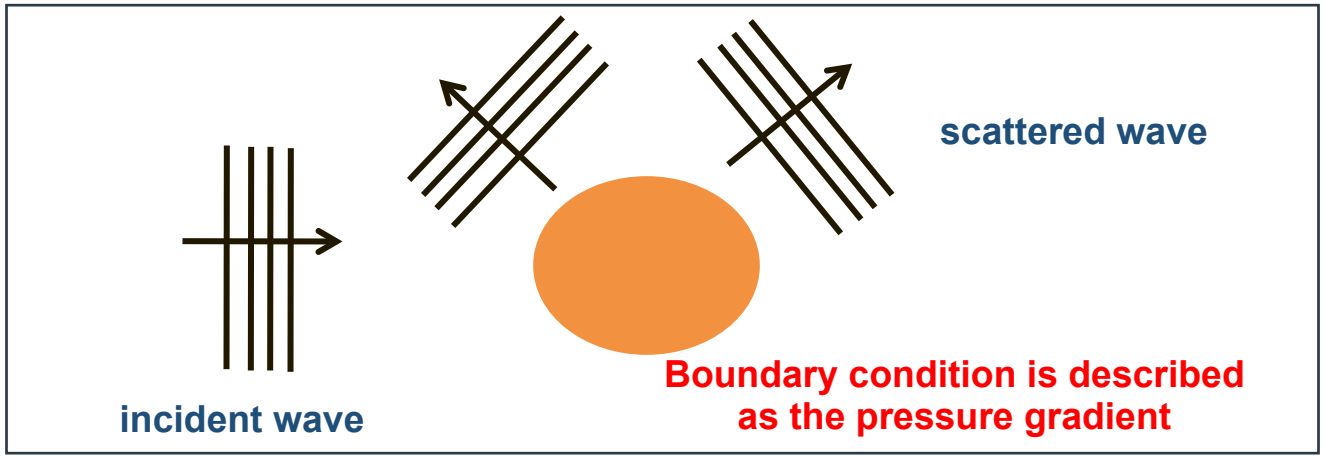
Challenges of Aeroacoustic Predictions

- Small magnitude and a wide range of pressure amplitudes
  - Aerodynamic: $p / p_{amb} \sim O(1)$
  - Acoustic: $p / p_{amb} \sim O(10^{-6})$
- CAA requires robust and efficient algorithms, good turbulence models, and parallel code capability, etc.
  - Numerical dissipation and dispersion errors require high order numerical schemes in space and time
  - Require non-reflective boundary conditions

Acoustic Scattering

Acoustic Scattering

- **Acoustic scattering : sound propagation is modified by surrounding bodies. The application is very diverse**



Civil Aircraft

- **propulsion-airframe interaction**

Rotorcraft

- **rotor/fuselage interaction**

Lauch Vehicle

- **jet noise scattering**

Acoustic Pressure Gradient

- Ffowcs Williams–Hawkings Equation : Generalized acoustic analogy for rotating blades as noise source

$$\Box^2 p'(\vec{x},t) = \frac{\partial}{\partial t}\left[Q\delta(f)\right] - \frac{\partial}{\partial x_i}\left[F_i\delta(f)\right] + \frac{\bar{\partial}^2}{\partial x_i \partial x_j}\left[T_{ij}H(f)\right]$$

$f = 0$ describes the integration surface

Farassat Formulation 1A : Analytic solution of the FWH equation using the free-space Green function

$$p'(x,t) = \int_{f=0} [\cdots]_{ret}\, dS$$

Can we obtain the pressure gradient by

$$\nabla p'(x,t) = \nabla \int_{f=0} [\cdots]_{ret}\, dS \quad ?$$

Analytic solution of the acoustic pressure gradient is needed for acoustic scattering problems

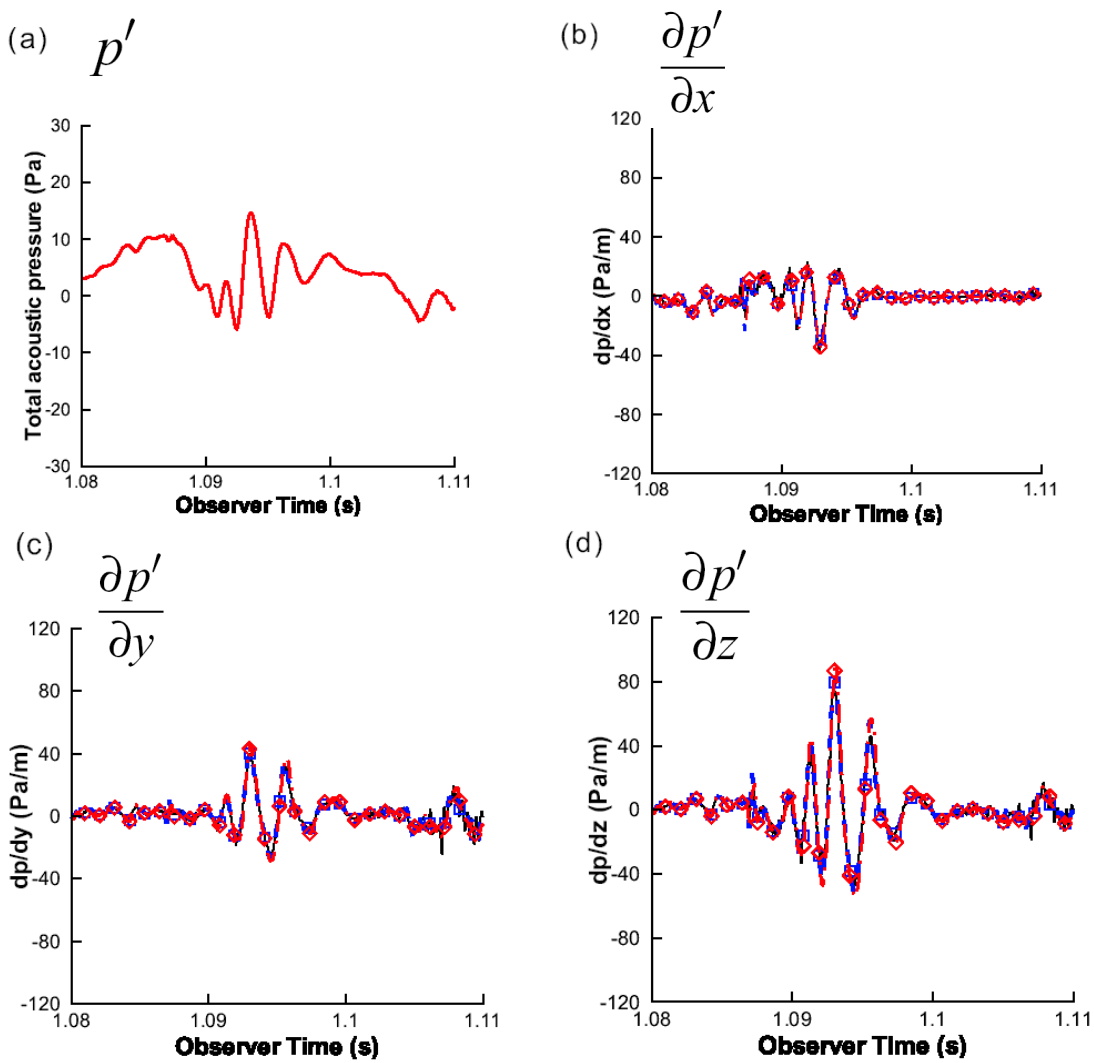
Analytic Formulations of the Pressure Gradient

- A basic idea to derive formulations

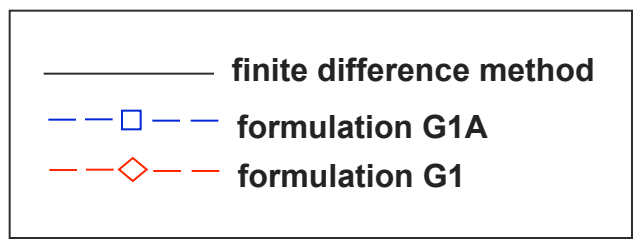
	Formulation 1A	Formulation G1	Formulation G1A
Value	**Acoustic pressure**	**Acoustic pressure gradient**	**Acoustic pressure gradient**
Key operation	$\nabla_x\left(\frac{\delta(g)}{r}\right) = -\frac{1}{c}\frac{\partial}{\partial t}\left(\frac{\hat{\mathbf{r}}\delta(g)}{r}\right) - \frac{\hat{\mathbf{r}}\delta(g)}{r^2}$	$\frac{\partial}{\partial t}[\cdots]\Big\|_{\mathbf{x}} = \left[\frac{1}{1-M_r}\frac{\partial}{\partial \tau}[\cdots]\Big\|_{\mathbf{x}}\right]_{\text{ret}}$	
Form	$p'(\mathbf{x},t) = \int_{f=0}[\cdots]_{\text{ret}}dS$	$\nabla p'(\mathbf{x},t) = \frac{\partial}{\partial t}\int_{f=0}[\cdots]_{\text{ret}}dS$	$\nabla p'(\mathbf{x},t) = \int_{f=0}\frac{1}{1-M_r}\frac{\partial}{\partial \tau}[\cdots]_{\text{ret}}dS$
Characteristics		**Semi-analytical form**	**Analytical form**

Developed new analytical formulations for the pressure gradient

Numerical Validation – HART I Helicopter

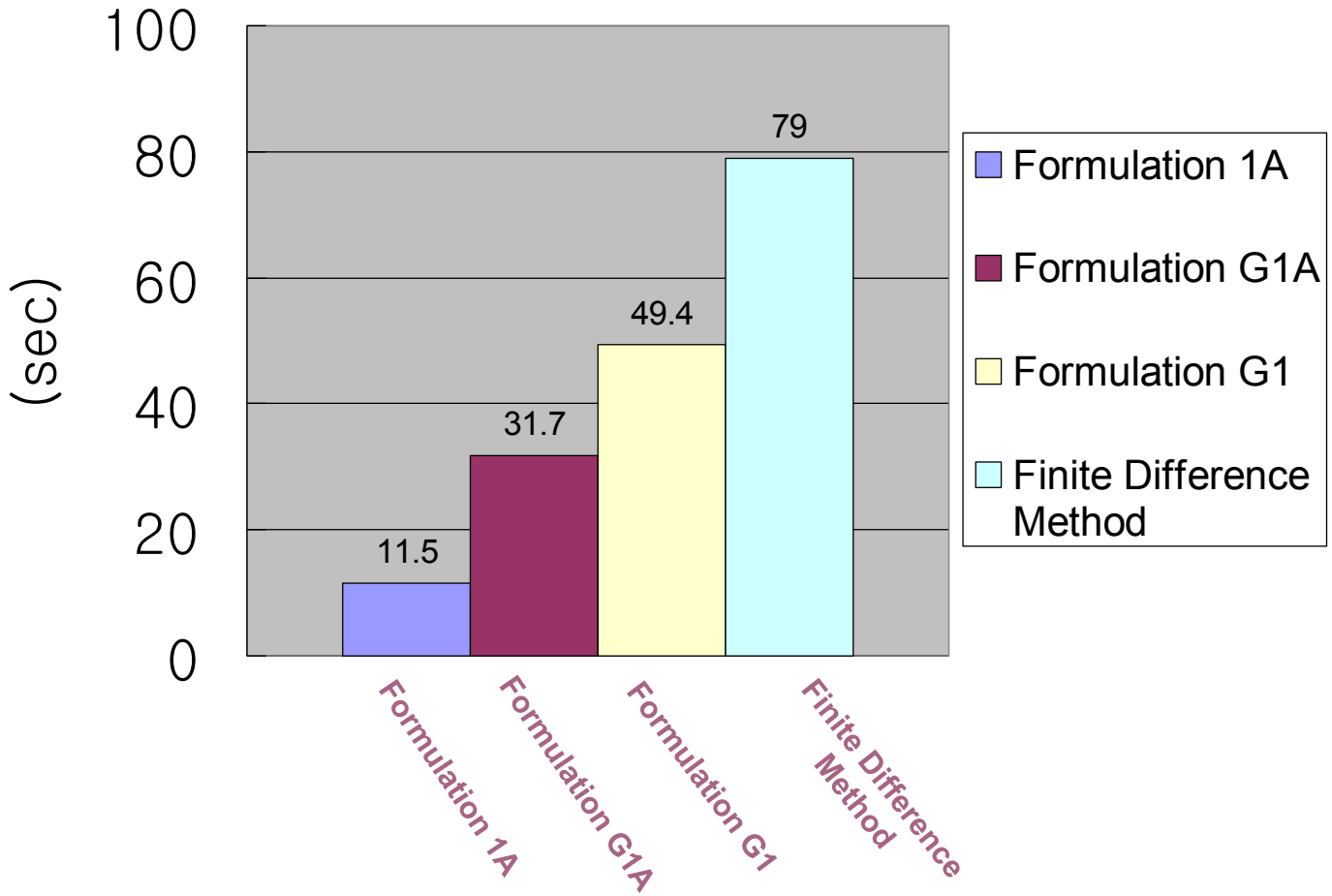


- Simulation
  - CFD (OVERFLOW) / CSD (RCAS) coupling used to provide unsteady aerodynamics and trim solutions of the blade motion
  - Advancing Tip Mach number, M=0.73
  - Blade radius, R=2 m
  - Observer location (0.0,-2.70,-2.29)m



Computational Efficiency

- **Comparison of computational time**

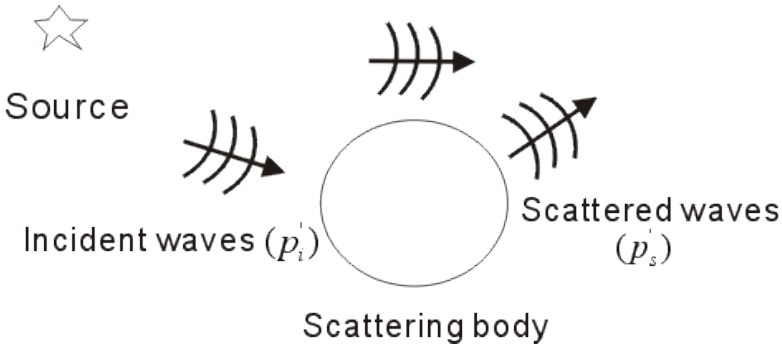


Acoustic Scattering : Frequency domain .vs. Time domain

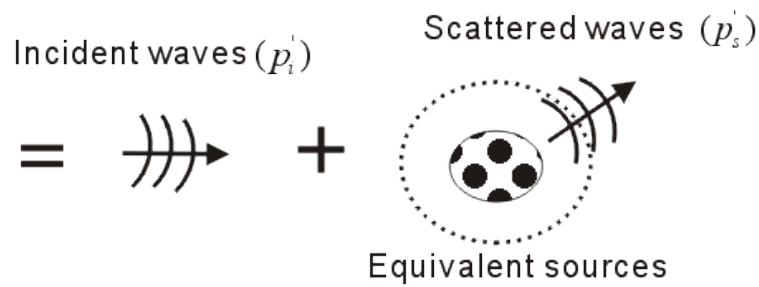
	Frequency domain method	Time domain method
Frequency	Single frequency (tone noise)	Multiple frequency (broadband noise)
Periodicity	Only periodic signal	Periodic / Non-periodic signal
Source motion	N/A	Transient source
Coding effort	simple	complicated
Numerical instability	stable	Subject to instability

Developed a new efficient time-domain acoustic scattering method

Equivalent Source Method for Scattering



(Ref. S. Lee et al., AIAA Journal, Vol.48 (12), Dec. 2010)



- Scattered field separated from incident field♪
- Strength of equivalent sources determined based on the boundary condition on the scattering surfaces♪
- No dissipation and dispersion errors involved♪

- **Boundary condition on the scattering body is given by**

$$\frac{1}{4\pi}\sum_{n=1}^{N}\left[\frac{1}{cr}\frac{\partial q_n}{\partial \tau}+\frac{q_n}{r^2}\right]_{\text{ret}}[\hat{\mathbf{r}}]_{\text{ret}}\cdot\mathbf{n}=\frac{\partial p_i'}{\partial n}$$

$\nabla p' \cdot \mathbf{n}$ **(q : source strength)**

- **Source strength is discretized at each time step**

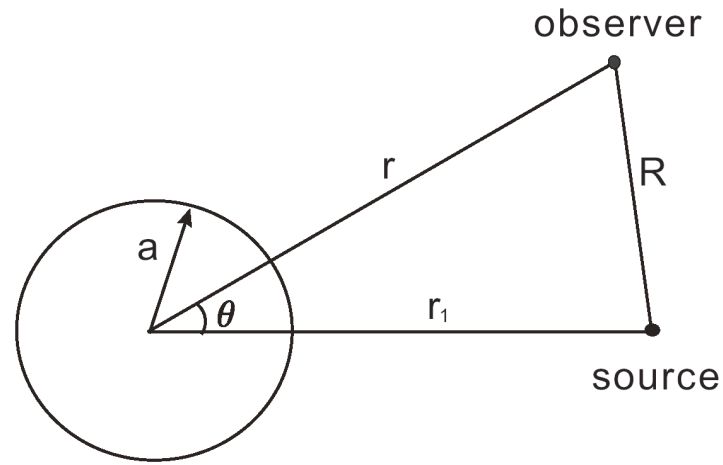
$$q_n(\tau)=\sum_{p=1}^{NP}\phi^p(\tau)\tilde{q}_n^p$$

(Linear shape functions used)

Validation Problem : Point Source and Sphere

- Validation of the prediction system for the scattering problem

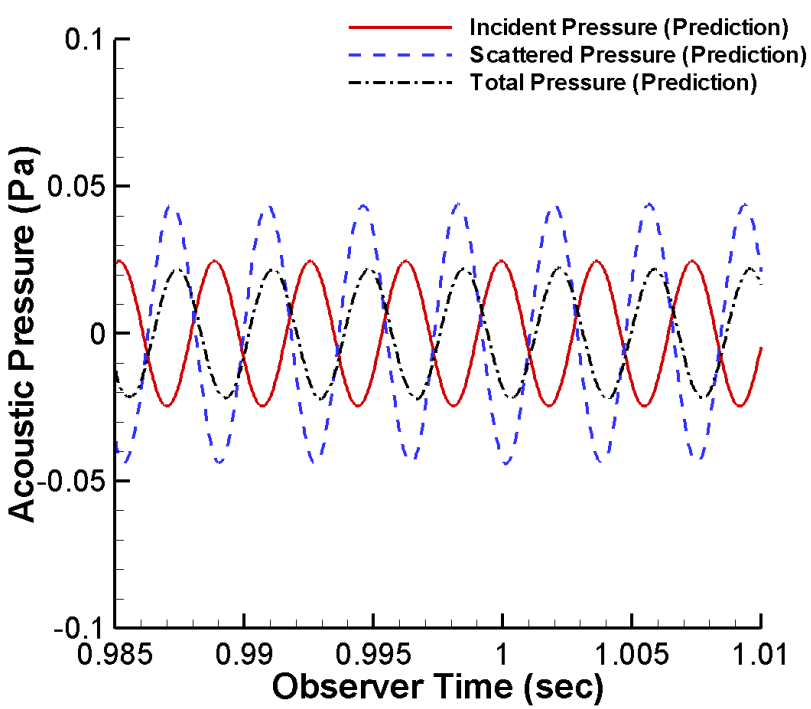
- Conditions of the problem
  - wavenumber of a source : k=5
  - center of a scattering sphere : (0,0,0) m
  - radius of a scattering sphere : a=1 m
  - position of a point source : (2,0,0) m
  - radius of observer : r=1.2 m

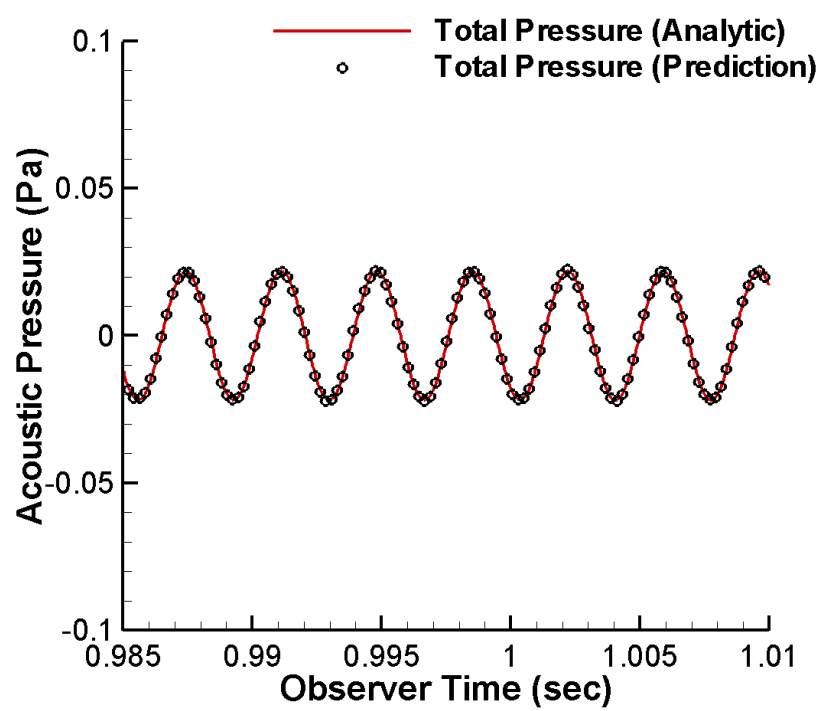


A source (r_1,0) near a sphere of radius a

Validation Problem : Point Source and Sphere

- Acoustic pressure (ka=5) at θ =180 deg and r/a=1.2

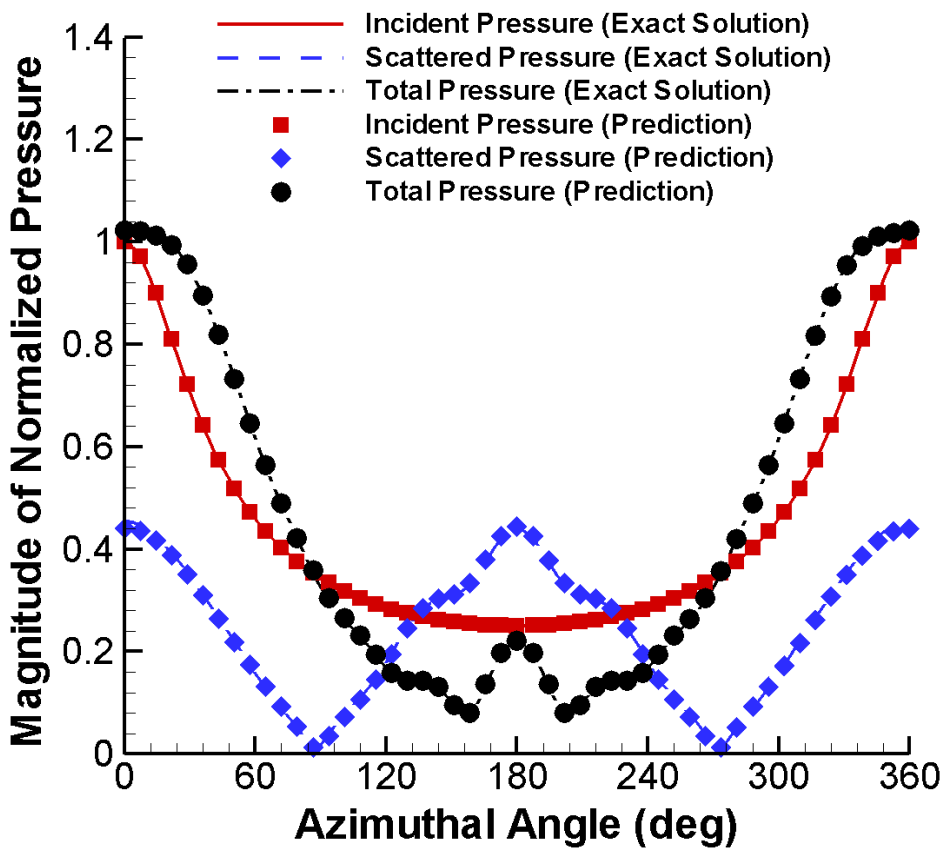




Excellent agreement between numerical prediction and analytic solution

Validation Problem : Point Source and Sphere

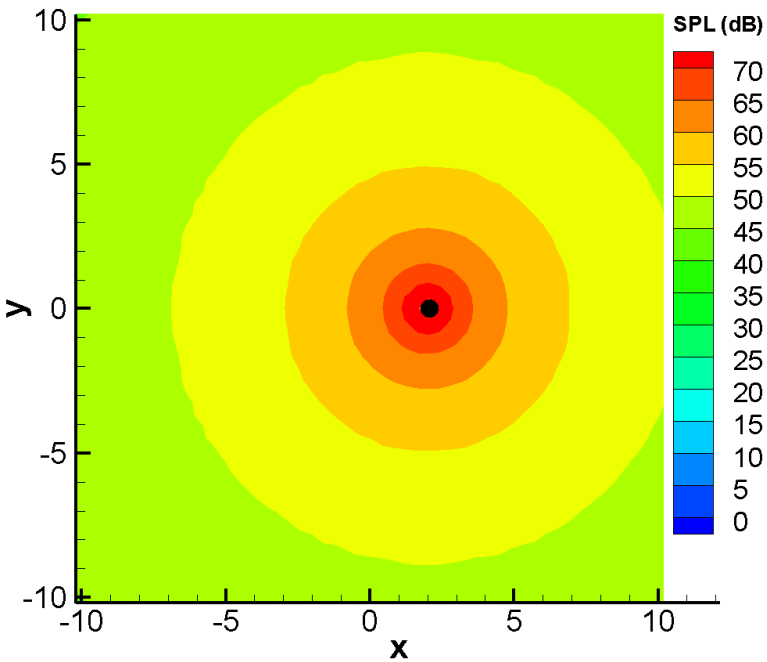
- Comparison of pressure magnitude (*r/a=1.2*)



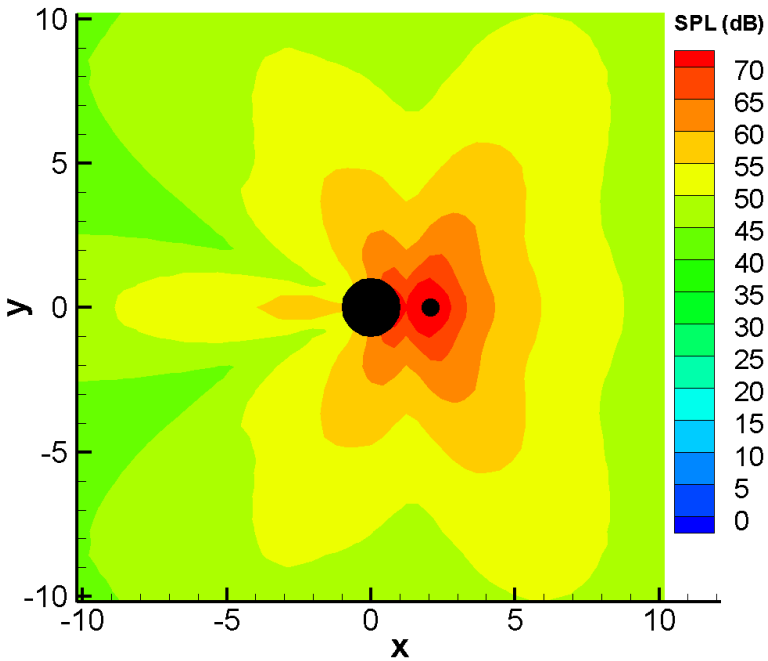
Numerical results agree very well with the analytical solutions

Validation Problem : Point Source and Sphere

- SPL map



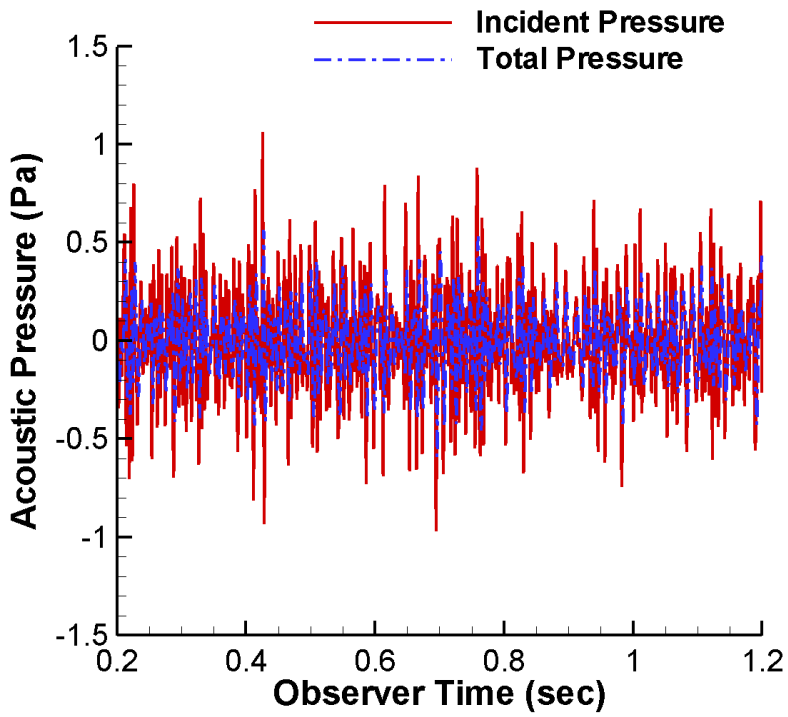
Incident Field



Exact Solution
Total Field

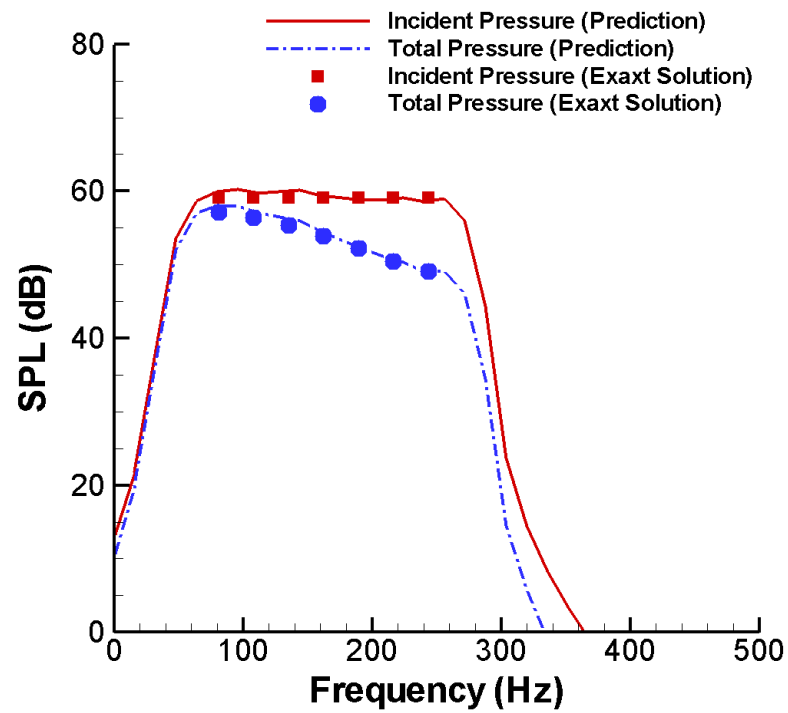
Validation Problem : Broadband noise

- **Acoustic pressure (*ka*=5) and SPL at *θ*=155 deg and *r/a*=1.2**



Acoustic Pressure

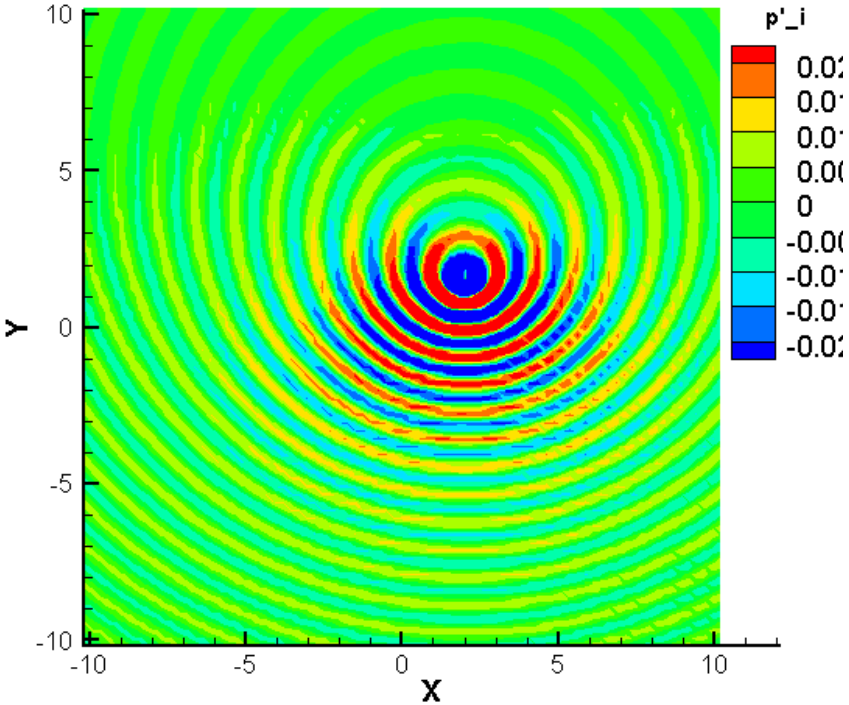
FFT

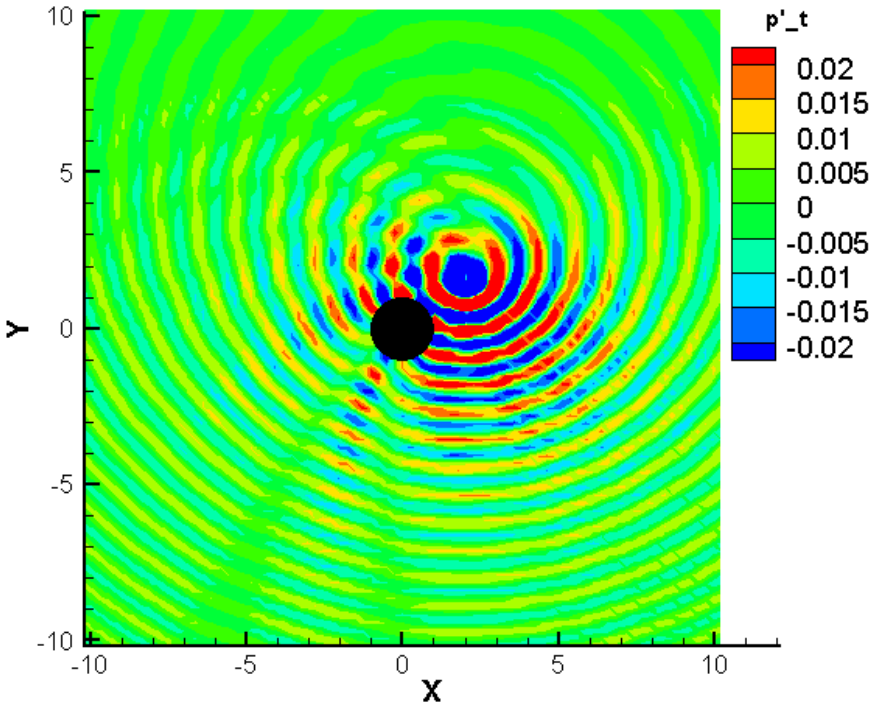


SPL (RMS Averaging)

Scattering of a Moving Source

- Moving source : M=0.3, ka=5





Scattering of a Moving Source

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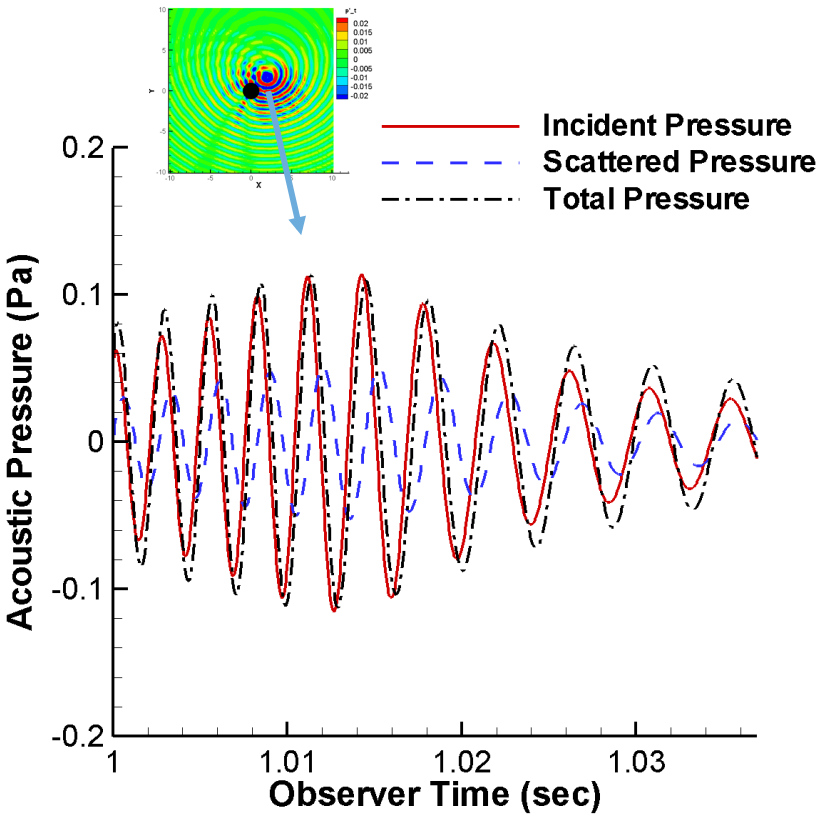
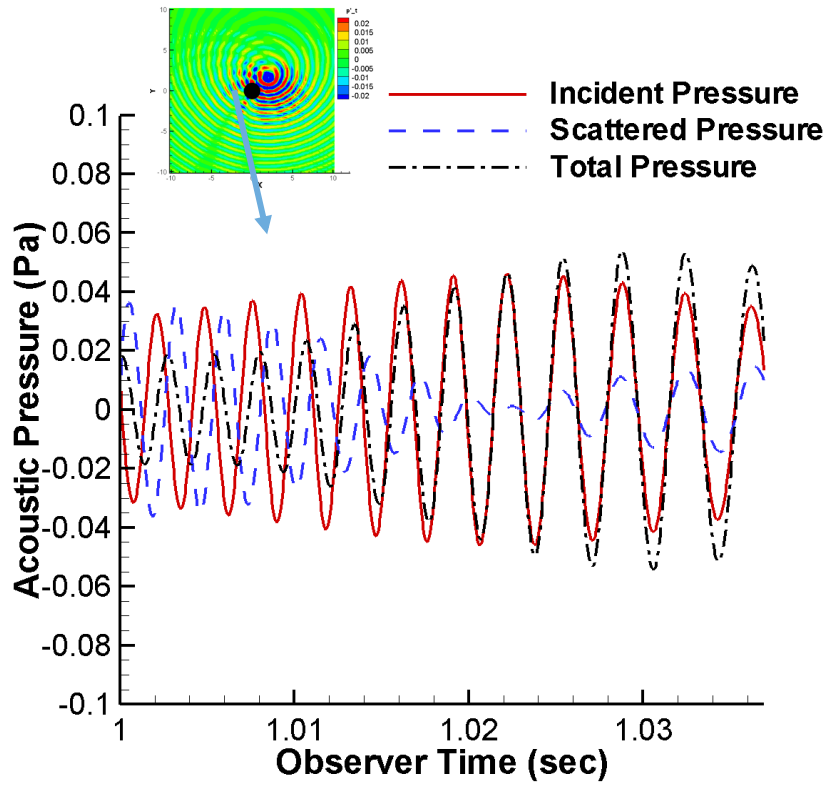


θ=0 deg

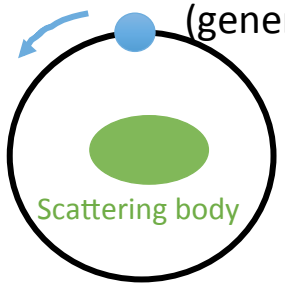


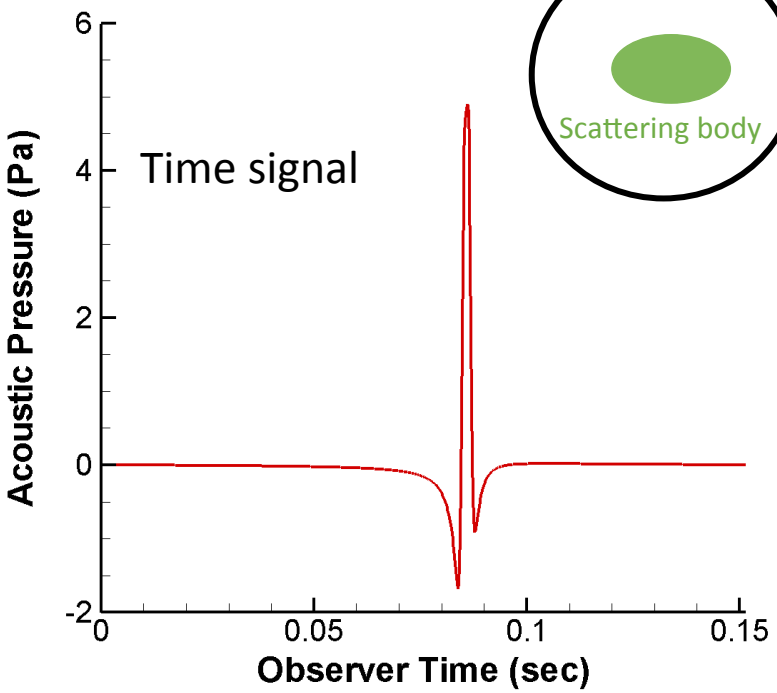
θ=180 deg

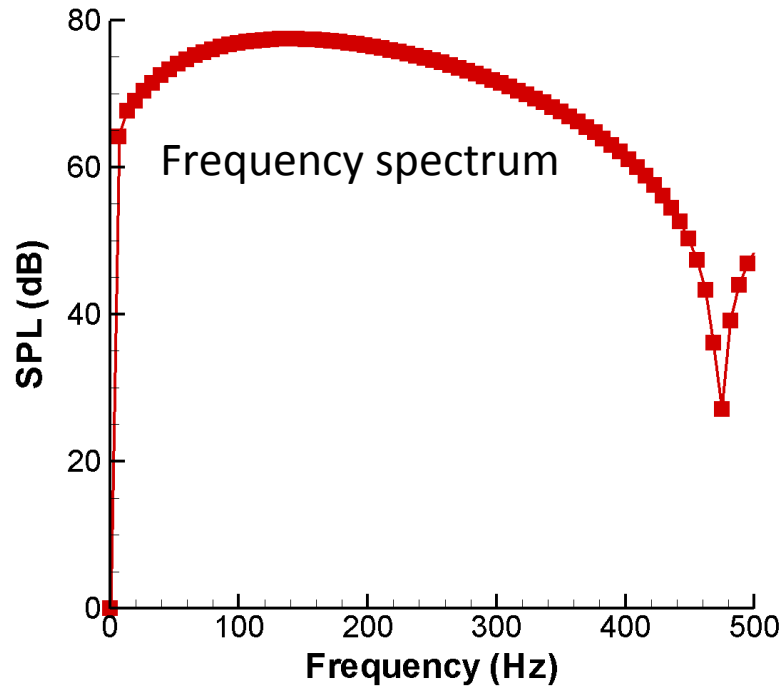
Application : Impulsive Moving Source

- **Rotating point impulsive noise generated to simulate BVI noise**

Rotating point source
(generating impulsive noise at 0 o'clock position)

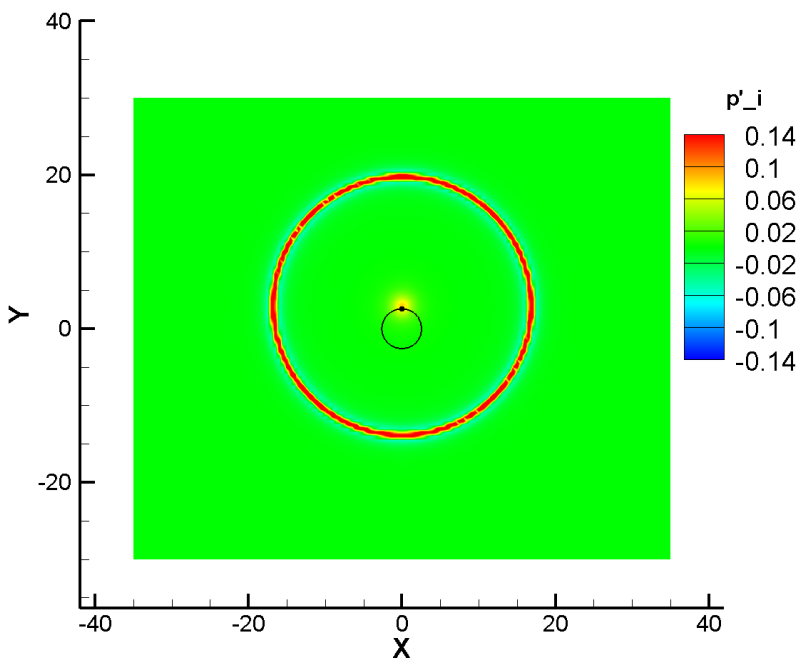




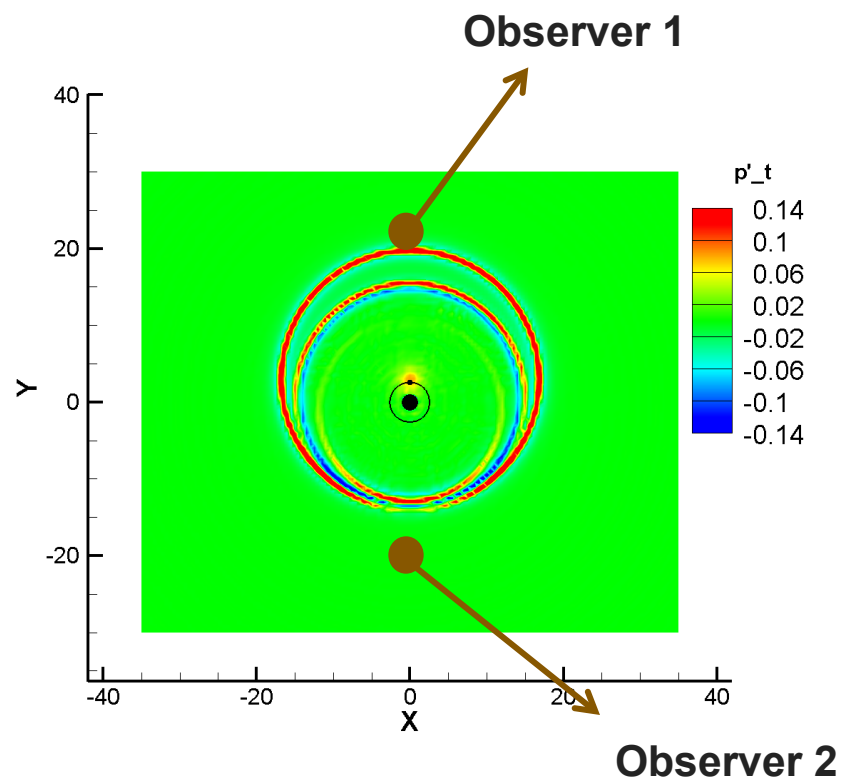


Application : Impulsive Moving Source

- **Pressure contour**



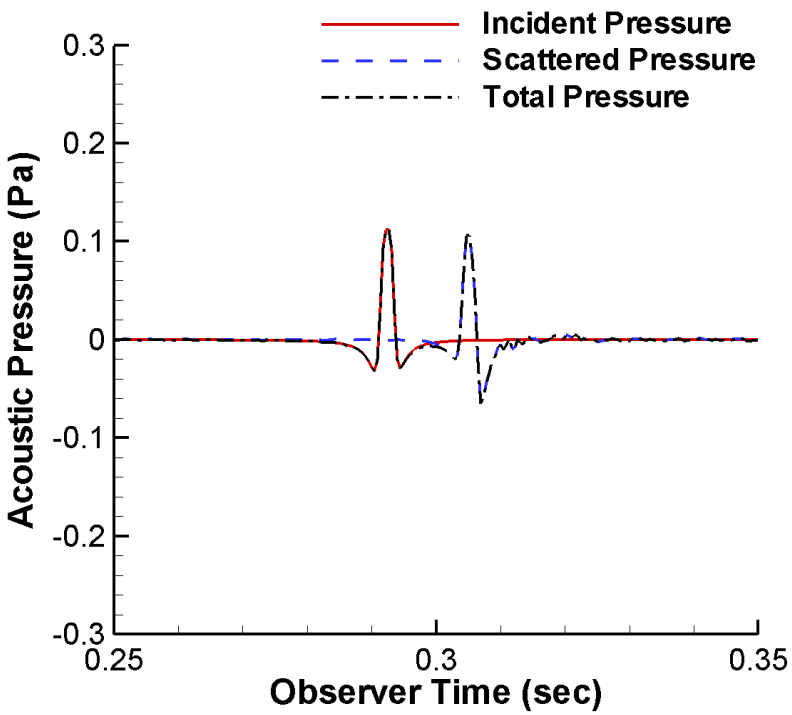
Incident Field



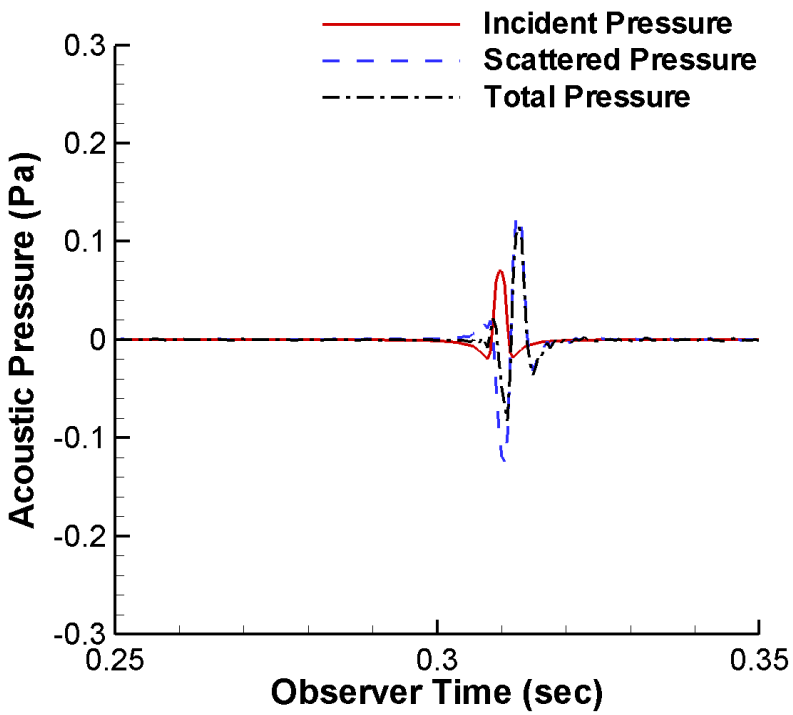
Scattering by a Sphere

Application : Impulsive Moving Source

- **Acoustic pressure time history at *r*=25m**



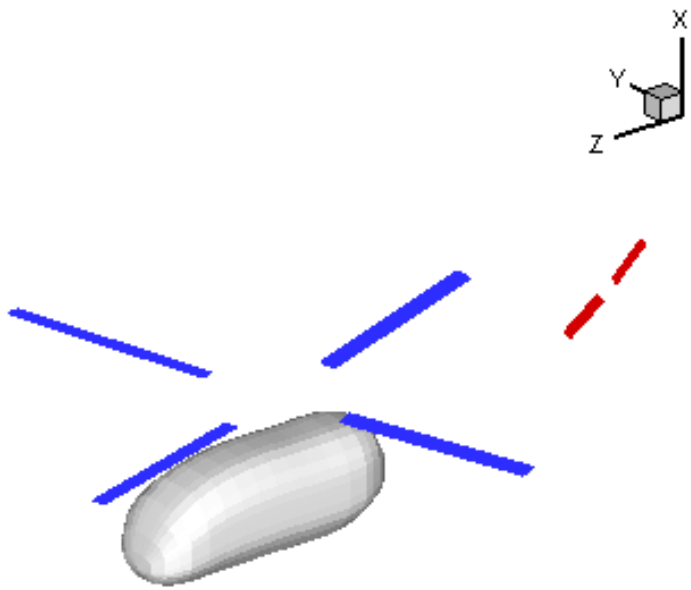
Observer 1



Observer 2

Application : Helicopter Noise

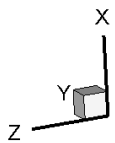
- Example : BO105 helicopter



Configuration of BO105 helicopter

- Operating conditions of main rotor
- Radius : 4.92 m
- Hovering Tip Mach number : 0.64
- Blade Passage Frequency : 28.21 Hz

- Operating conditions of tail rotor
- Radius : 0.95 m
- Hovering Tip Mach number : 0.65
- Blade Passage Frequency : 74.05 Hz



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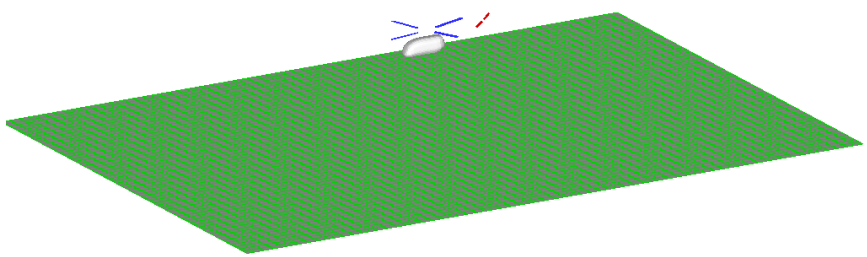
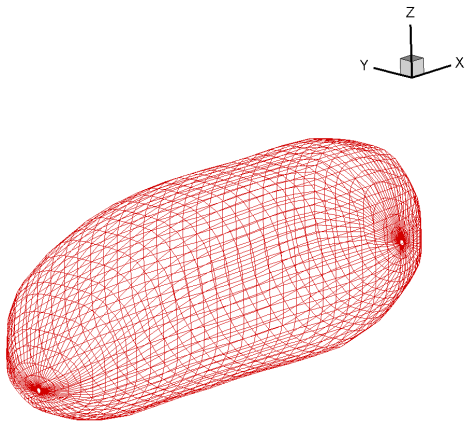
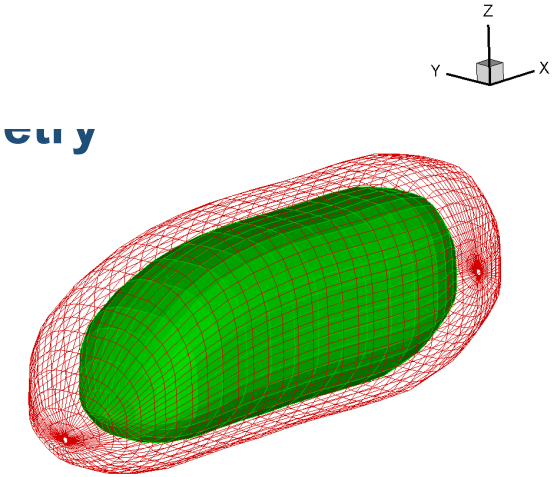


Observer Plane

Application : Helicopter Noise



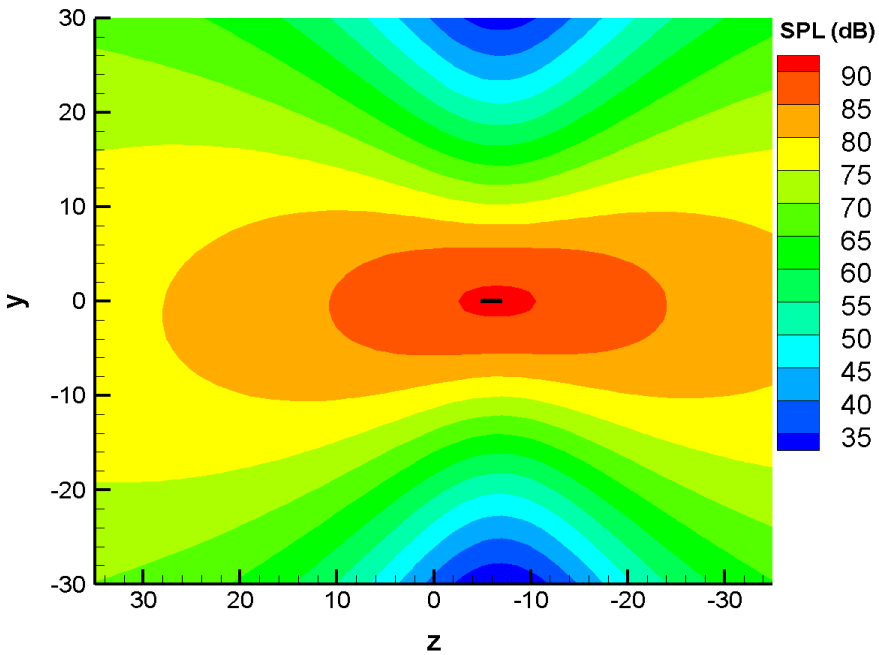
Equivalent source geometry



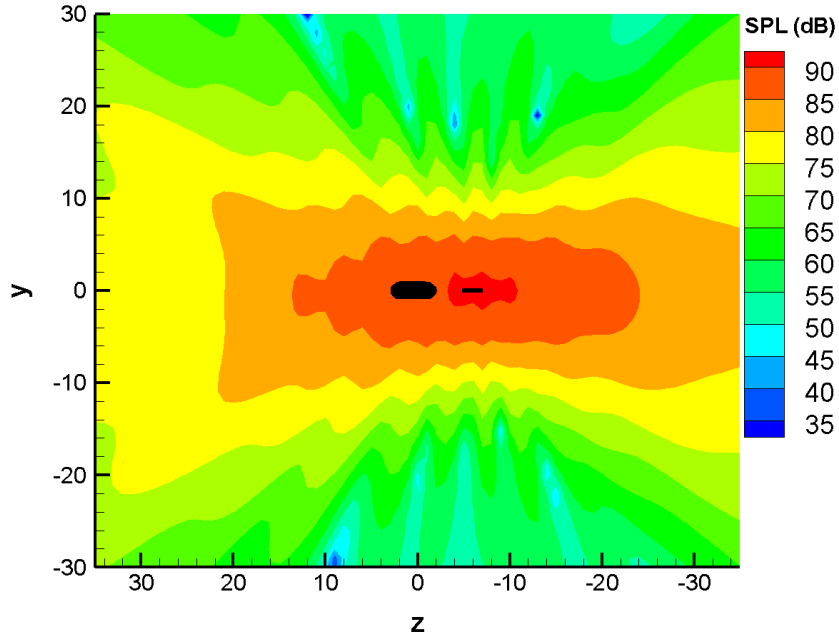
Equivalent source geometry embedded in the fuselage

Application : Helicopter Noise

- SPL at 222 Hz (3 x Tail Rotor BPF)



Incident Field

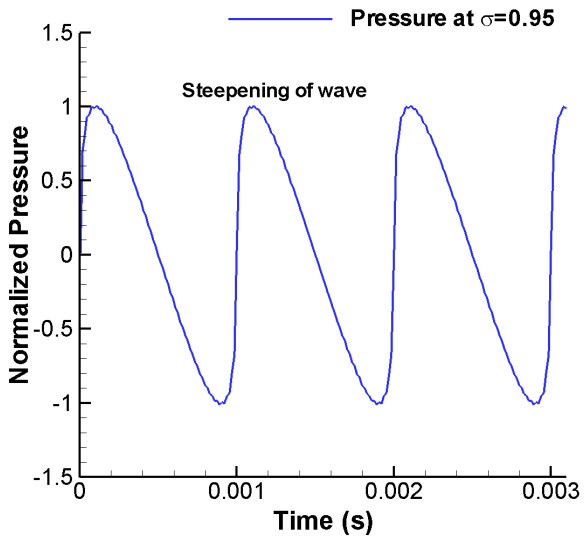


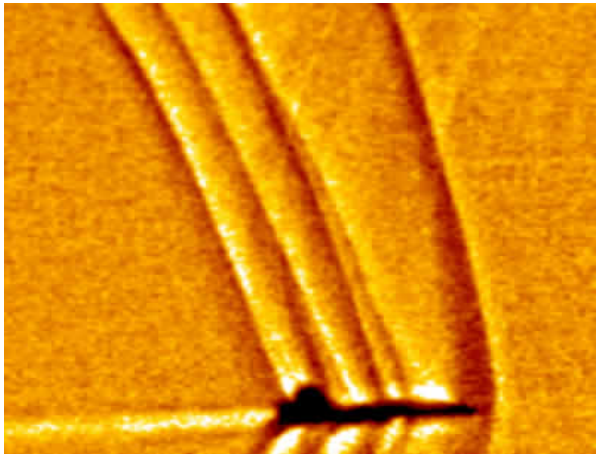
Scattering by a fuselage

Nonlinear Sound Propagation

Nonlinear Sound Propagation

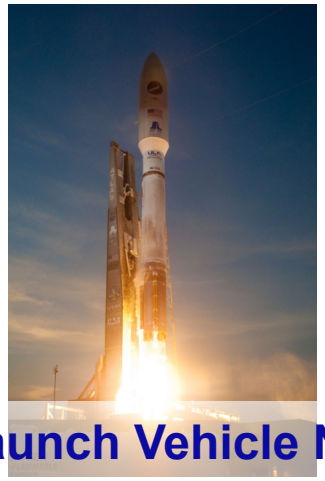
- Sound waves with large amplitude propagate nonlinearly





Sonic Boom

Broadband Jet Engine Noise



Launch Vehicle Noise

Numerical Methods

- Mixed Time domain/Frequency domain Method
  - Anderson (1974), Gee (2005)
  - Slowly convergent
- Nonlinear Frequency-Domain Algorithm (NLFDA)
  - Saxena, et al. (2009)
  - High frequency errors
- **New Split Method**
  - **Lee, et al. (2010)**
  - **Fast convergent and free of high frequency errors**

Developed a new numerical algorithm to accurately predict nonlinear sound propagation

Burgers Equation

- **Generalized Burgers equation**

$$\frac{\partial p}{\partial r} + \boxed{m\frac{p}{r}} - \boxed{\frac{\varepsilon}{2}\frac{\partial p^2}{\partial \tau}} = \boxed{\frac{\delta}{2c_0^3}\frac{\partial^2 p}{\partial \tau^2}}$$

Geometrical Spreading **Nonlinear Steepening** **Atmospheric Absorption**

- **Frequency-domain Burgers equation**

$$\frac{d\tilde{p}}{dr} + m\frac{\tilde{p}}{r} + \alpha'\tilde{p} = \frac{i\omega\varepsilon}{2}\tilde{q}$$

- **Real part of the pressure**

$$\frac{dX}{dr} = -m\frac{X}{r} - (\alpha X - \beta_d Y) - \frac{\omega\varepsilon}{2}V$$

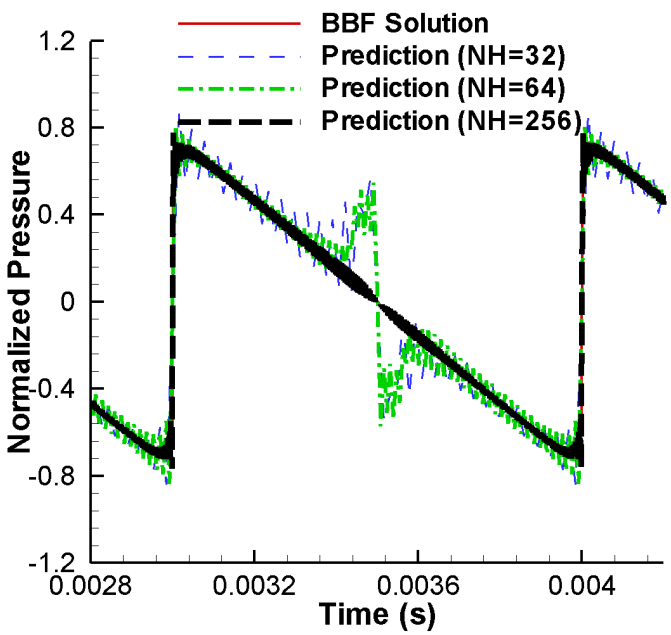
$$\boxed{\begin{aligned}\tilde{p}(r,\omega) &= X + iY \\ \tilde{q}(r,\omega) &= U + iV\end{aligned}}$$

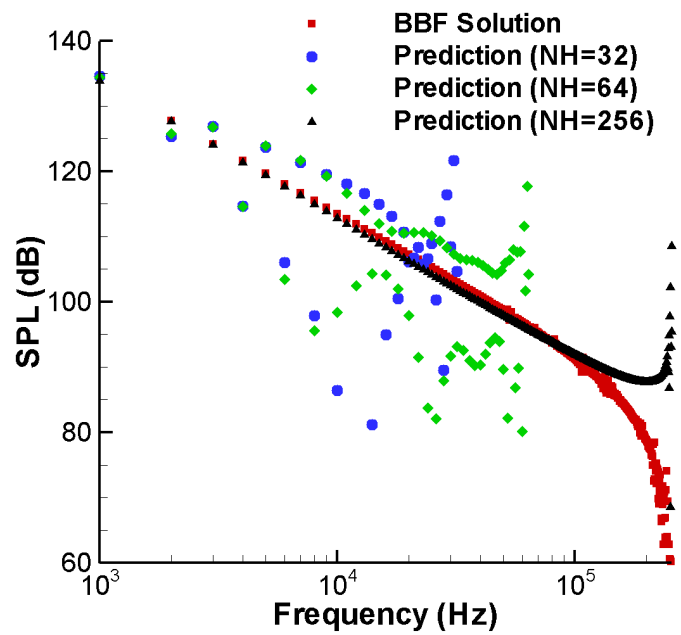
- **Imaginary part of the pressure**

$$\frac{dY}{dr} = -m\frac{Y}{r} - (\beta_d X + \alpha Y) + \frac{\omega\varepsilon}{2}U$$

Numerical Issue

- **Sinusoidal signal** $p(r,\tau) = p_a \sin(2\pi f_0 \tau)$ **, Pa=140 dB, f_0=1kHz**
- **Prediction of the NLFDA method for a sine wave at** $\sigma = x/\bar{x}$ **=3**





*NH : number of harmonics used in the prediction

Acoustic Pressure Time History **Sound Pressure Level**

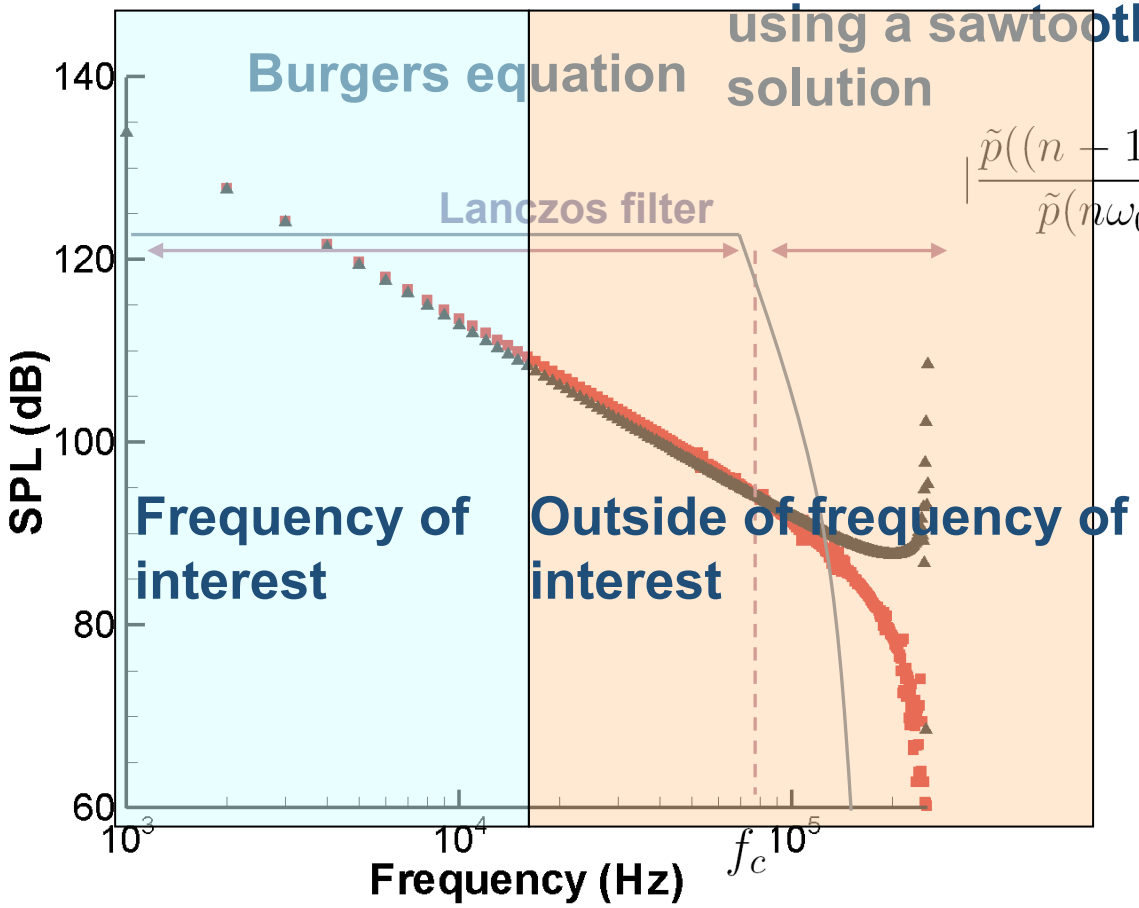
Split Method

(Ref. S. Lee et al., AIAA Journal, Vol 48 (11), Nov. 2010)

- Split Method

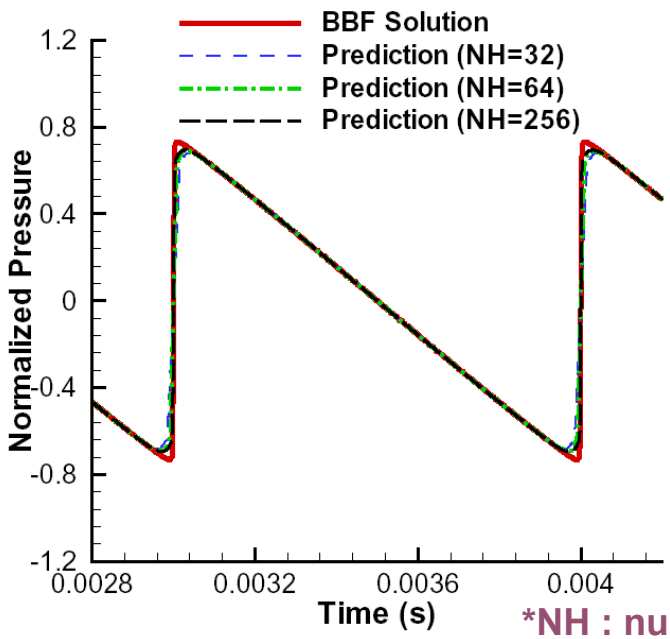
Recursive amplitude ratio using a sawtooth analytic solution

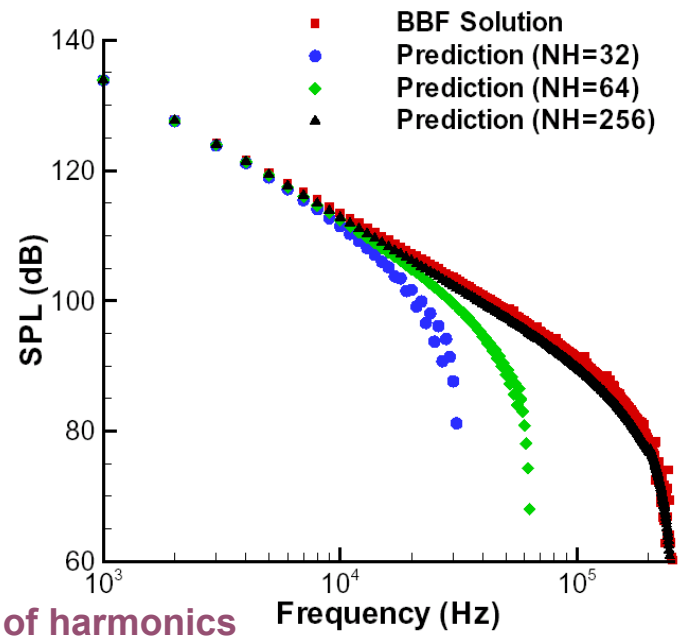
$$\left|\frac{\tilde{p}((n-1)\omega_0)}{\tilde{p}(n\omega_0)}\right| = \frac{n-1}{n}$$



Validation Problem

- **Sinusoidal signal** $p(r,\tau) = p_a \sin(2\pi f_0 \tau)$ **, Pa=140 dB, f_0=1kHz**
- **Prediction of the Split method for a sine wave at** $\sigma = x/\bar{x}$ **=3**



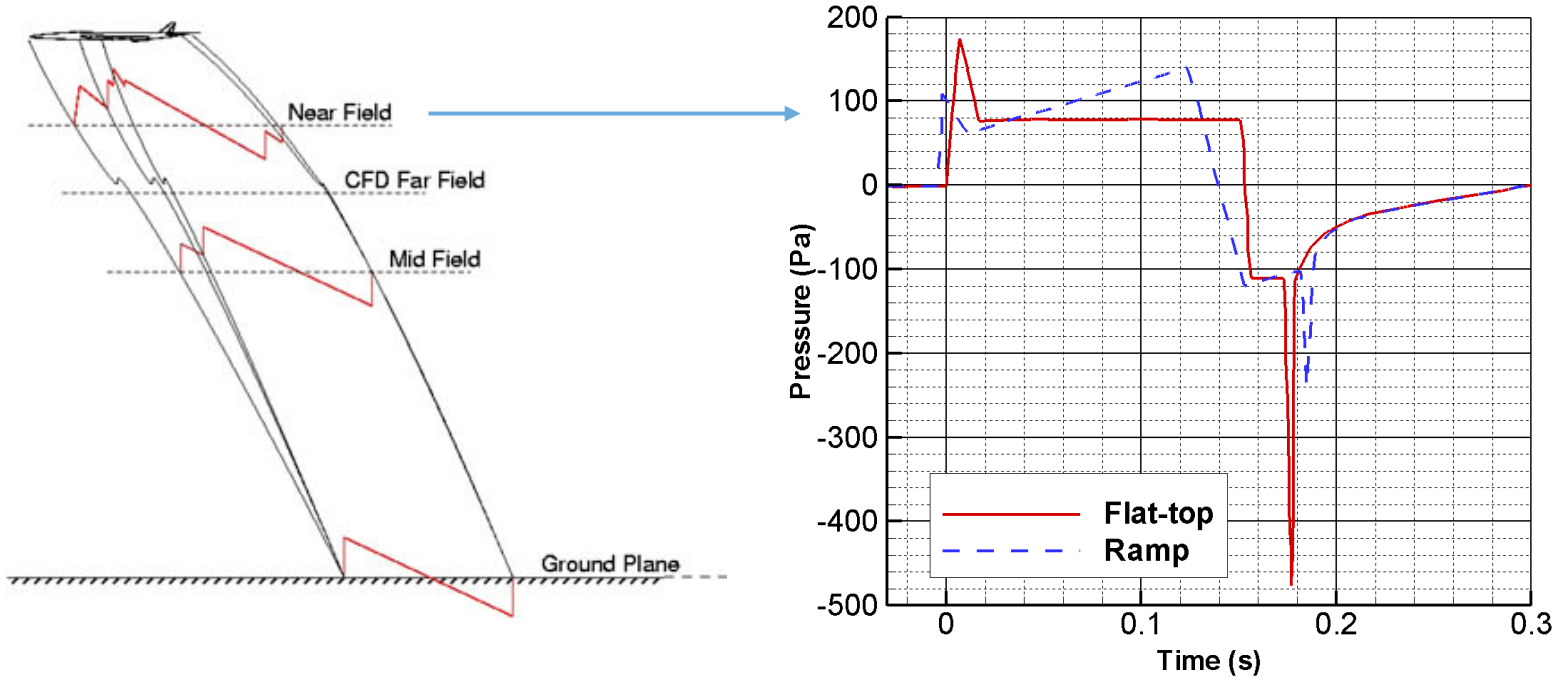


*NH : number of harmonics used in the prediction

Acoustic Pressure Time History **Sound Pressure Level**

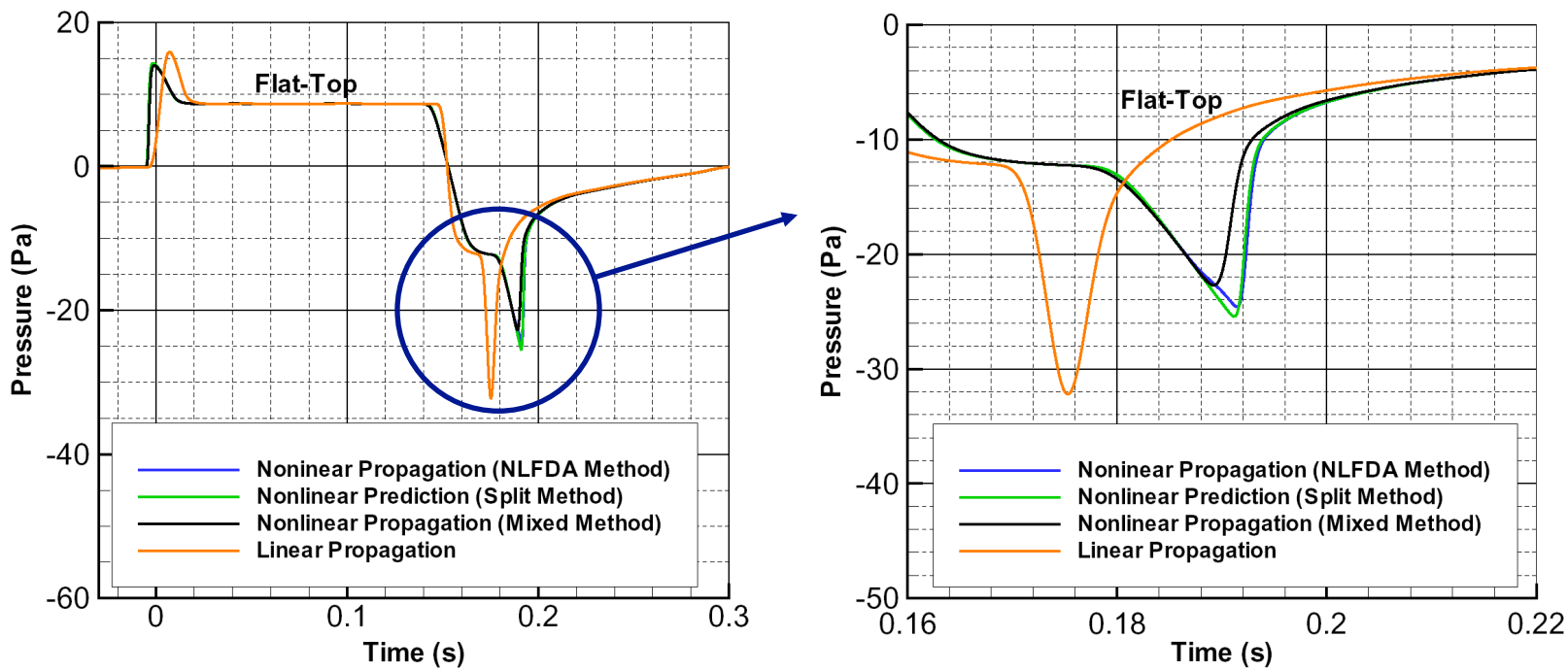
Application Problem : Sonic Boom

- Two sonic booms tested : Flat-top and Ramp (data generated at NASA Langley)
- Starting signal at 183m below the aircraft



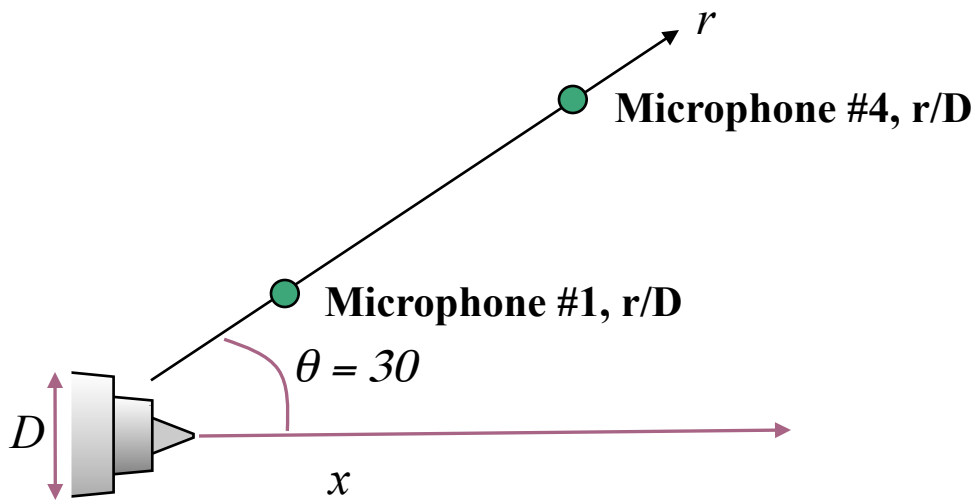
Application Problem : Sonic Boom

- Comparison of predictions at 14,630m below the aircraft
- T=273.15 K, relative humidity=20%, constant sound speed



Application Problem : Jet Noise

- Broadband data from Boeing Low Speed Aeroacoustic Facility



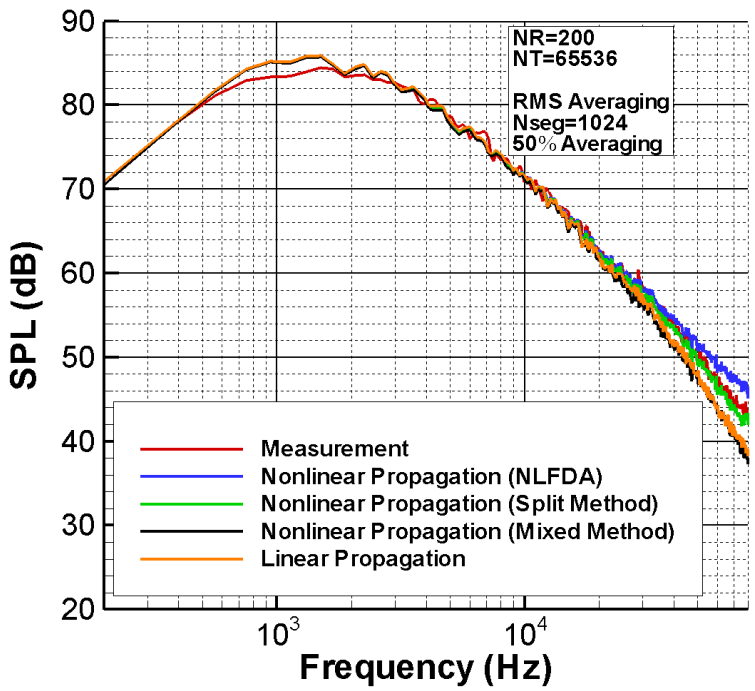
Case	M	Tj/Ta	D (inch)	r/D (mic 1)	r/D (mic 4)
Supersonic	1.9	1.65	1.27	100	289

Propagation of pressure signal from the initial measurement Mic. 1 to Mic. 4

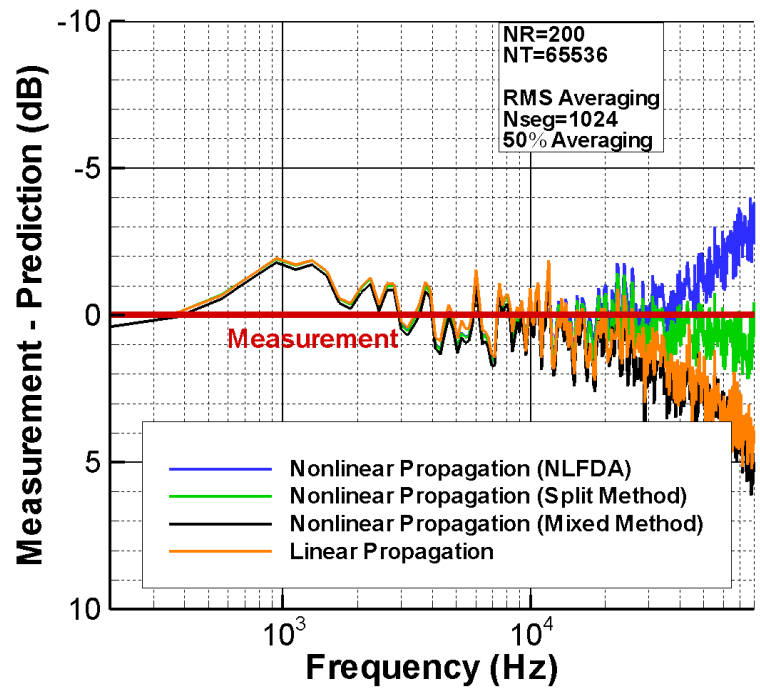
Application Problem : Jet Noise

- Sound Pressure Level at 289 Dj

SPL



Error



Conclusions

- Aeroacoustic research has advanced the knowledge and science of unsteady fluid mechanics and it helps to achieve NASA's green aviation vision. But noise reduction and accurate prediction of noise are still very challenging. We need to develop more accurate and efficient numerical methods
- Acoustic scattering problem has a wide range of applications. Analytic solution of the pressure gradient and time-domain equivalent source method were developed. More research is needed for the flow effects on scattering and robust algorithm
- Large amplitude sound waves propagate nonlinearly with the steepening of a waveform. A new split method shows accurate and efficient predictions for sonic boom and jet noise. More applications can be studied such as launch vehicle noise

- Thank you for your attention!
- Contact : skulee@ucdavis.edu