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# Computation of Engine Noise Propagation and Scattering off an Aircraft

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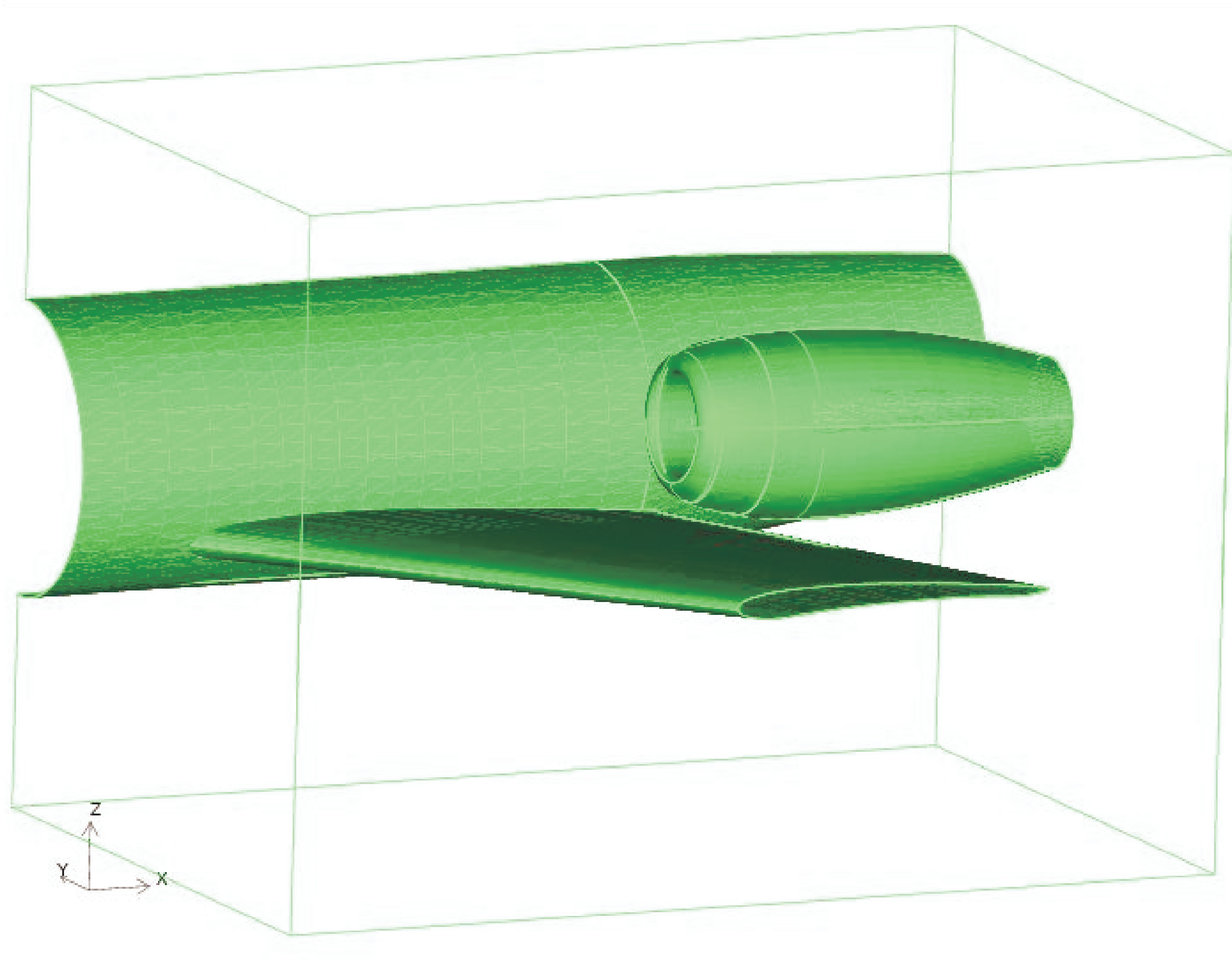
- NASA

# Introduction

- Noise signature of an aircraft
  – fan inlet and exhaust noise
- Influenced by
  – flow around the wing and fuselage
  – scattering from aircraft surface
- Reduce noise footprint by
  – optimizing engine and wing location
  – manipulating flow
- Methodology
  – experimental study (extremely expensive)
  – numerical simulation

# Computational Domain



# Governing Equations

$$\frac{\partial \tilde{Q}}{\partial t} + \sum_{d=1}^{3} \frac{\partial \tilde{F}_d}{\partial x_d} = 0$$

where,

$$\tilde{Q} = \begin{pmatrix} \rho \\ \rho v_1 \\ \rho v_2 \\ \rho v_3 \\ \rho E \end{pmatrix}, \tilde{F} = \begin{bmatrix} \rho v_d \\ \rho v_1 v_d + p\delta_{1d} \\ \rho v_2 v_d + p\delta_{2d} \\ \rho v_3 v_d + p\delta_{3d} \\ (\rho E + p) v_d \end{bmatrix}$$

# Boundary Conditions

- Zero normal velocity BC on the symmetry plane, as well as on the fuselage, nacelle, and wing surfaces.
- Damping layers on other sides of the domain
  (D.Stanescu and D.Ait-Ali-Yahia, 1999)
- Engine noise source for spinning modes (*s, d*)
  (J.M.Tyler and T.G.Sofrin, 1962)

$$\begin{pmatrix} p-\bar{p} \\ \rho-\bar{\rho} \\ v_x-\bar{v}_x \\ v_r-\bar{v}_r \\ v_\theta-\bar{v}_\theta \end{pmatrix} = A \begin{bmatrix} E_s(k_{sd}r)\cos\Theta \\ \frac{1}{\bar{c}^2}\cdot E_s(k_{sd}r)\cos\Theta \\ \frac{k_x}{\omega_r\bar{\rho}}\cdot E_s(k_{sd}r)\cos\Theta \\ \frac{k_{xd}}{\omega_r\bar{\rho}}\cdot E_s^{'}(k_{sd}r)\sin\Theta \\ \frac{s}{\omega_r r}\cdot E_s(k_{sd}r)\cos\Theta \end{bmatrix}$$

# Solution Technique

- Spectral Methods
  - Require relatively few points per wavelength
  - Have low dispersion and dissipation errors
  - Have geometric flexibility
  - Are compact, robust and inherently parallelizable
- Time Domain and Frequency Domain Formulations
- Implemented in Distributed Memory Models

# Time Domain Formulation

- Mapping onto master element $\Omega_M=[-1,1]^3$

$$\frac{\partial Q}{\partial t}+\sum_{d=1}^{3}\frac{\partial F_d}{\partial \xi_d}=0$$

where,

$$Q = J\tilde{Q}, \text{ and } F_d = J\sum_{m=1}^{3}\frac{\partial \xi_d}{\partial x_m}$$

# Time Domain Formulation

- Discontinuous Galerkin spectral approximation

$$(Q_t, \varphi_{ijk}) + (\nabla_\xi \cdot F, \varphi_{ijk}) = 0$$

$$\frac{dQ_{ijk}}{dt} = -\left[D^\xi + D^\eta + D^\varsigma\right]F$$

where,

$$\varphi_{ijk} = h_i(\xi)h_j(\eta)h_k(\varsigma)$$

$$D^\xi F = \frac{1}{\omega_i}[F_1^*(1,\eta_j,\varsigma_k]h_i(1) - F_1^*(-1,\eta_j,\varsigma_k]h_i(-1) - d^\xi F)$$

- Low-storage Runge-Kutta scheme optimized for wave propagation (D. Stanescu and W.G. Habashi, 1998)

# Frequency Domain Formulation

- Equation governing the acoustic perturbations

$$\frac{\partial \rho'}{\partial t} + \nabla \cdot (\bar{\rho}\, \nabla \Phi' + \rho' \nabla \bar{\Phi}) = 0$$

$$\rho' = -\frac{\bar{\rho}}{\bar{c}^{2}} \left[ \frac{\partial \Phi'}{\partial t} + \nabla \bar{\Phi} \cdot \nabla \Phi' \right]$$

- Weak formulation: multiplied by $\psi(x, y, z)\mathrm{e}^{-i\omega t}$ and integrated using a divergence theorem.

$$\int_{\Omega} \psi \frac{\partial \rho'}{\partial t} r\,\mathrm{d}\Omega - \int_{\Omega} \nabla \psi \cdot (\bar{\rho} \nabla \phi + \rho' \nabla \bar{\phi}) r\,\mathrm{d}\Omega + \int_{\Gamma_f} \psi (\bar{\rho} \nabla \phi + \rho' \nabla \bar{\phi}) \cdot \mathbf{n}\, r\,\mathrm{d}s = 0$$

# Frequency Domain Formulation

- For $\Psi \in \mathrm{Z}_{\Gamma_f}$

$$
\begin{aligned}
&\int_\Omega \frac{\bar{\rho}}{\bar{c}^2}[\omega^2\phi\psi + i\omega\bar{u}(\phi\psi_x - \psi\phi_x) + i\omega\bar{v}(\phi\psi_y - \psi\phi_y) + i\omega\bar{w}(\phi\psi_z - \psi\phi_z) \\
&+ (\bar{u}^2 - \bar{c}^2)\phi_x\psi_x + (\bar{v}^2 - \bar{c}^2)\phi_y\psi_y + (\bar{w}^2 - \bar{c}^2)\phi_z\psi_z + \bar{u}\,\bar{v}(\phi_x\psi_y + \phi_y\psi_x) \\
&+ \bar{u}\,\bar{w}(\phi_x\psi_z + \phi_z\psi_x) + \bar{v}\,\bar{w}(\phi_y\psi_z + \phi_z\psi_y) - \psi\sigma(i\omega\phi + \bar{u}\phi_x + \bar{v}\phi_y + \bar{w}\phi_z)]\mathrm{d}\Omega \\
&= 0
\end{aligned}
$$

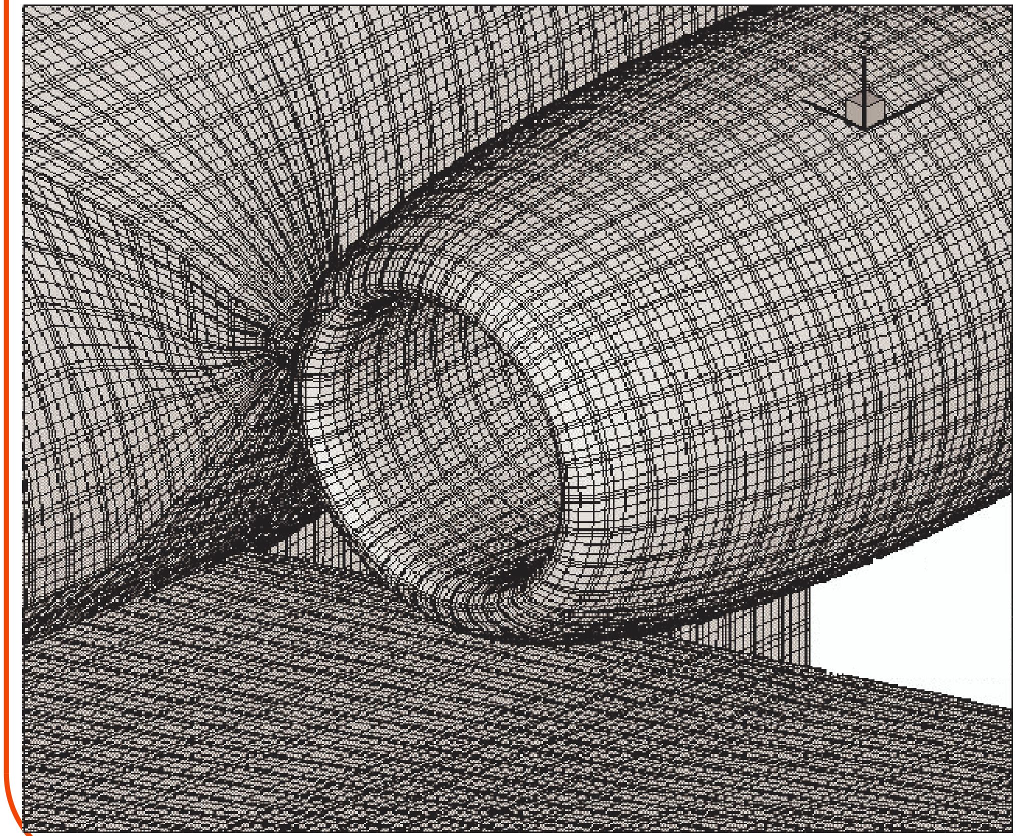
- Discretized by a Chebyshev spectral element method

$$A\{\phi\} = \{b\}$$

- Parallel Schur complement domain decomposition method

- PETSc package is used for high-level primitives (S. Balay, W.D. McInnes, etc., 2001)

# Grid Generation



- Non-overlapping hexahedral elements
- ICEMCFD
- Hexahedral representation of underlying geometry with G-L point distribution

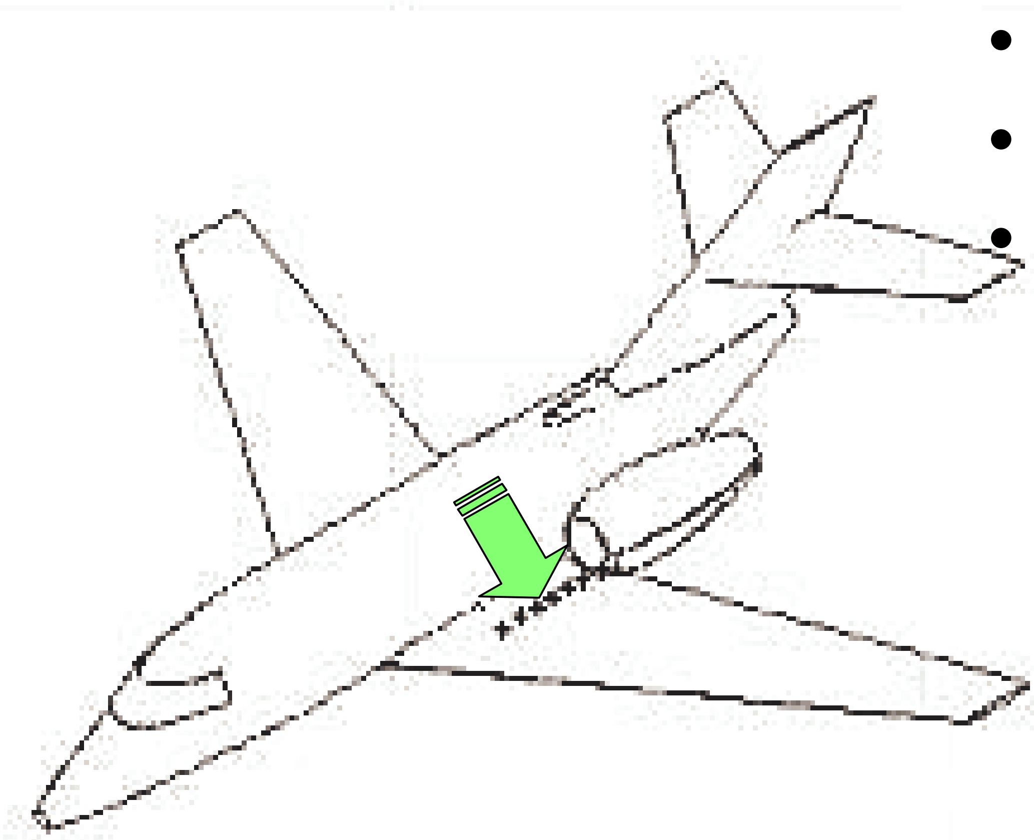
# Computation (Time Domain)

- Tone at $\omega$=3650 Hz, $M_\infty$=0.0
- Reduced frequency $\omega_r$=26.3
- Spinning mode (18, 0) and (22, 0)
- 103,105 hexahedral elements
- 22,270,680 G-L points (N=6)
- 32 processors of an IBM Regatta-type SP4 machine for 10 days

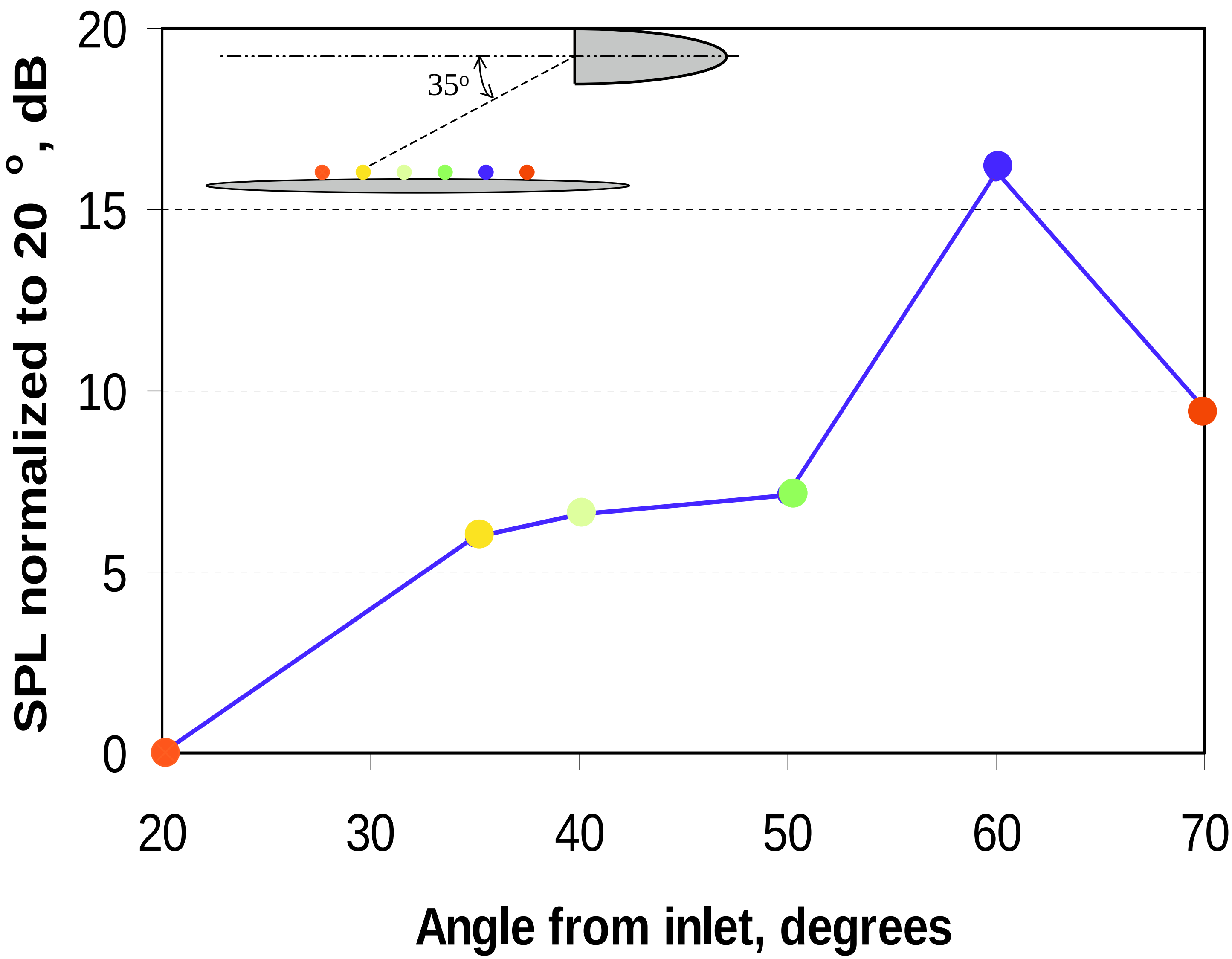
# Computation (Frequency Domain)

- Tone at $\omega$=3650 Hz, $M_\infty=0.1$
- Fan face Mach number $M_f=0.2$
- Spinning mode (18, 0)
- 103,105 hexahedral elements
- 6,746,736 points
- 192 processors of an IBM Regatta-type SP4 machine for 2.5 days
- Huge memory requirements

# Experiment



- $M_\infty = 0.3$
- AGL = 500 ft
- $M_f = 0.53$
- Mode (22, 0) likely
- Kulite microphones

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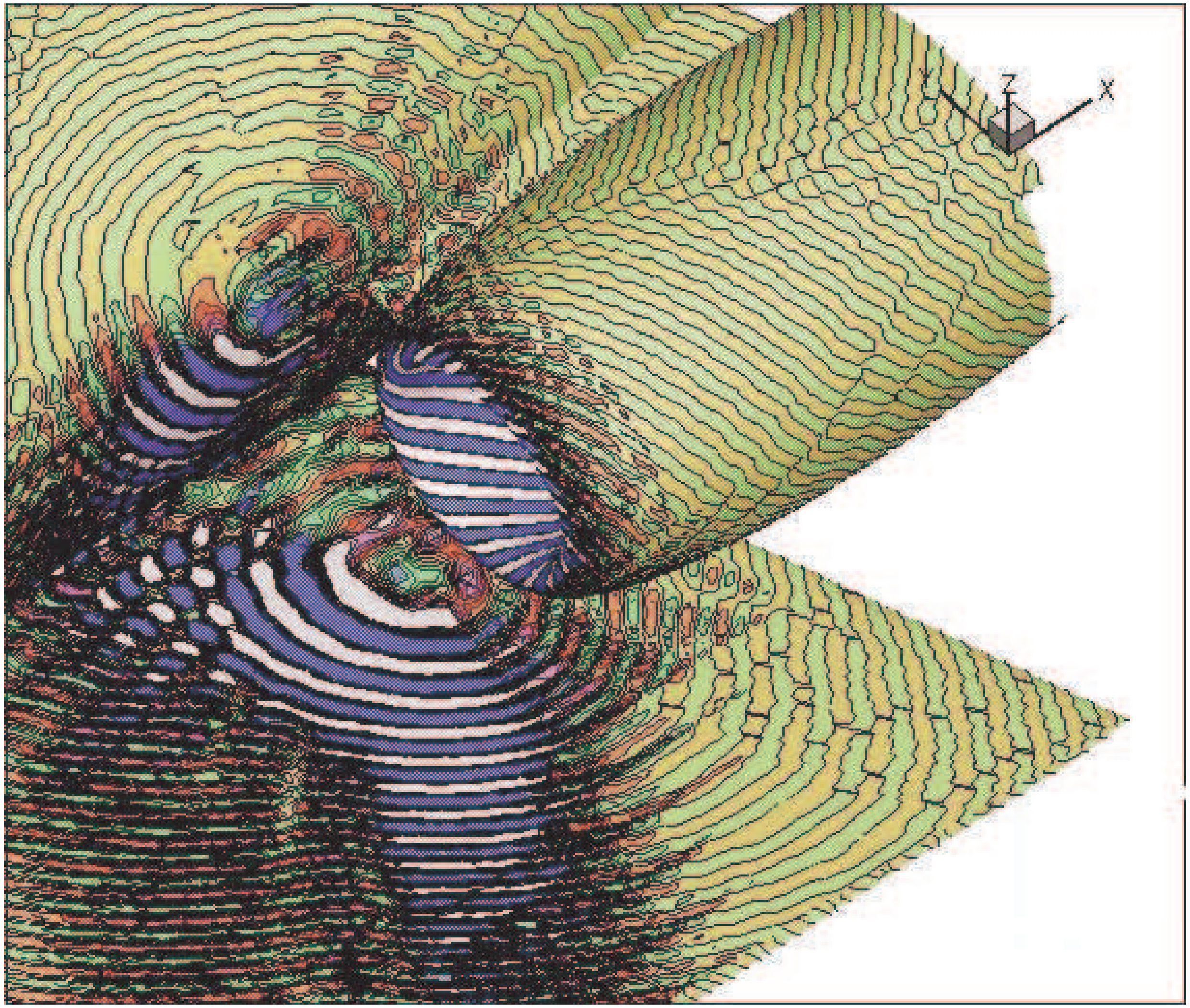
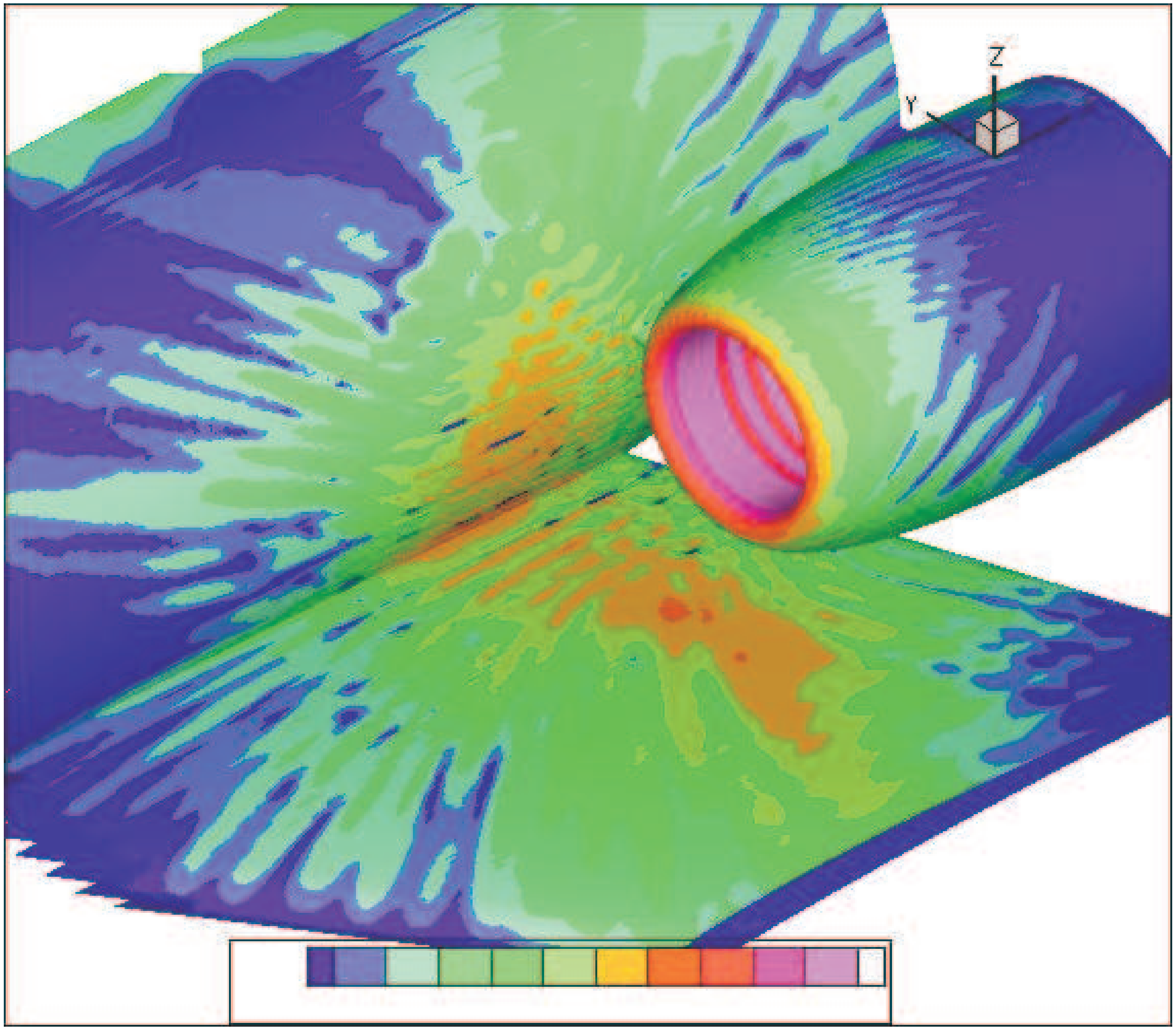
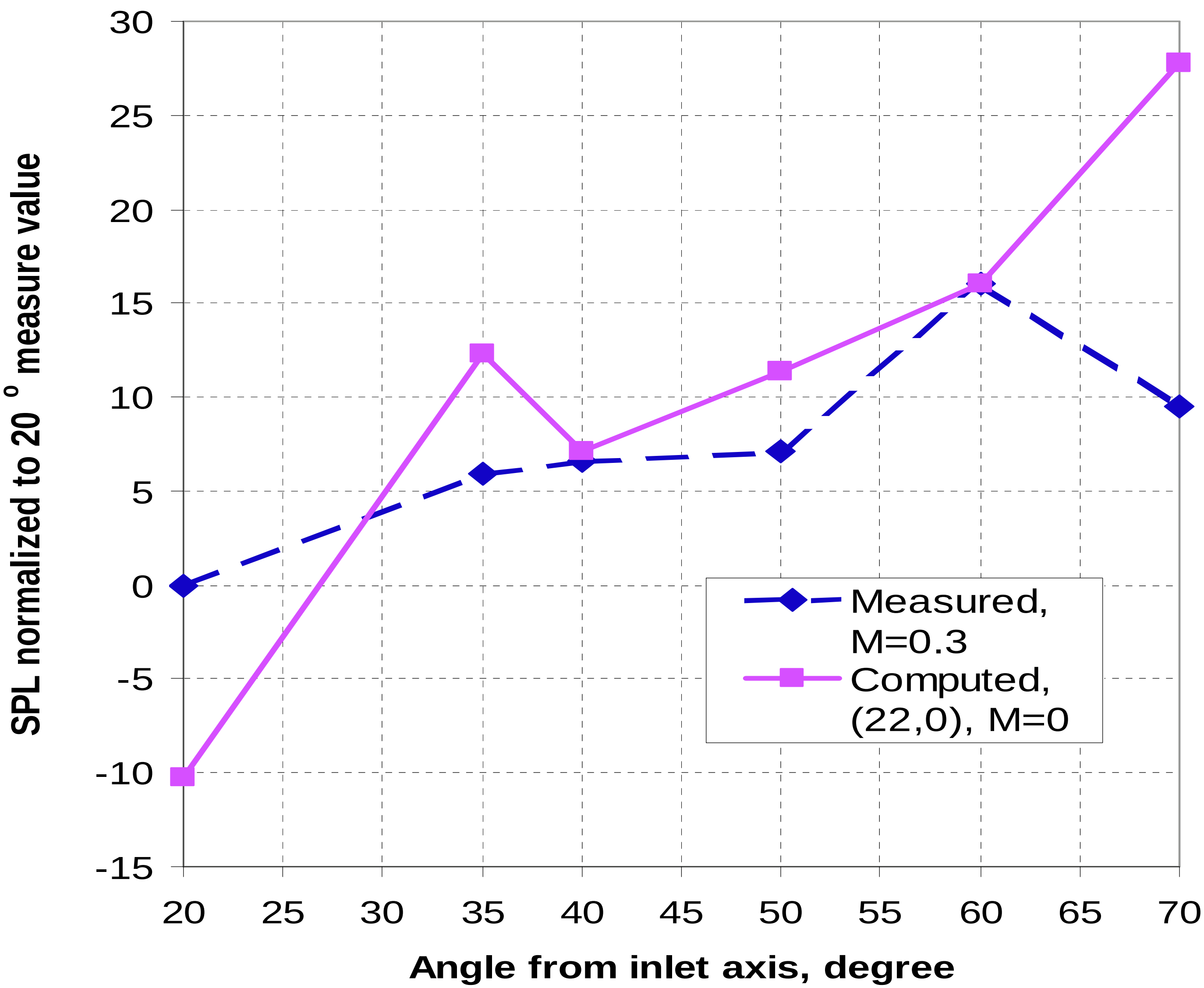



Acoustic pressure contours on the aircraft surface. Mode(18, 0) radiated at $\omega_r$=26.3.




SPL contours on the aircraft surface.
Mode(18, 0) radiated at $\omega_r$=26.3.

# SPL Variation on the Wing Suction Side

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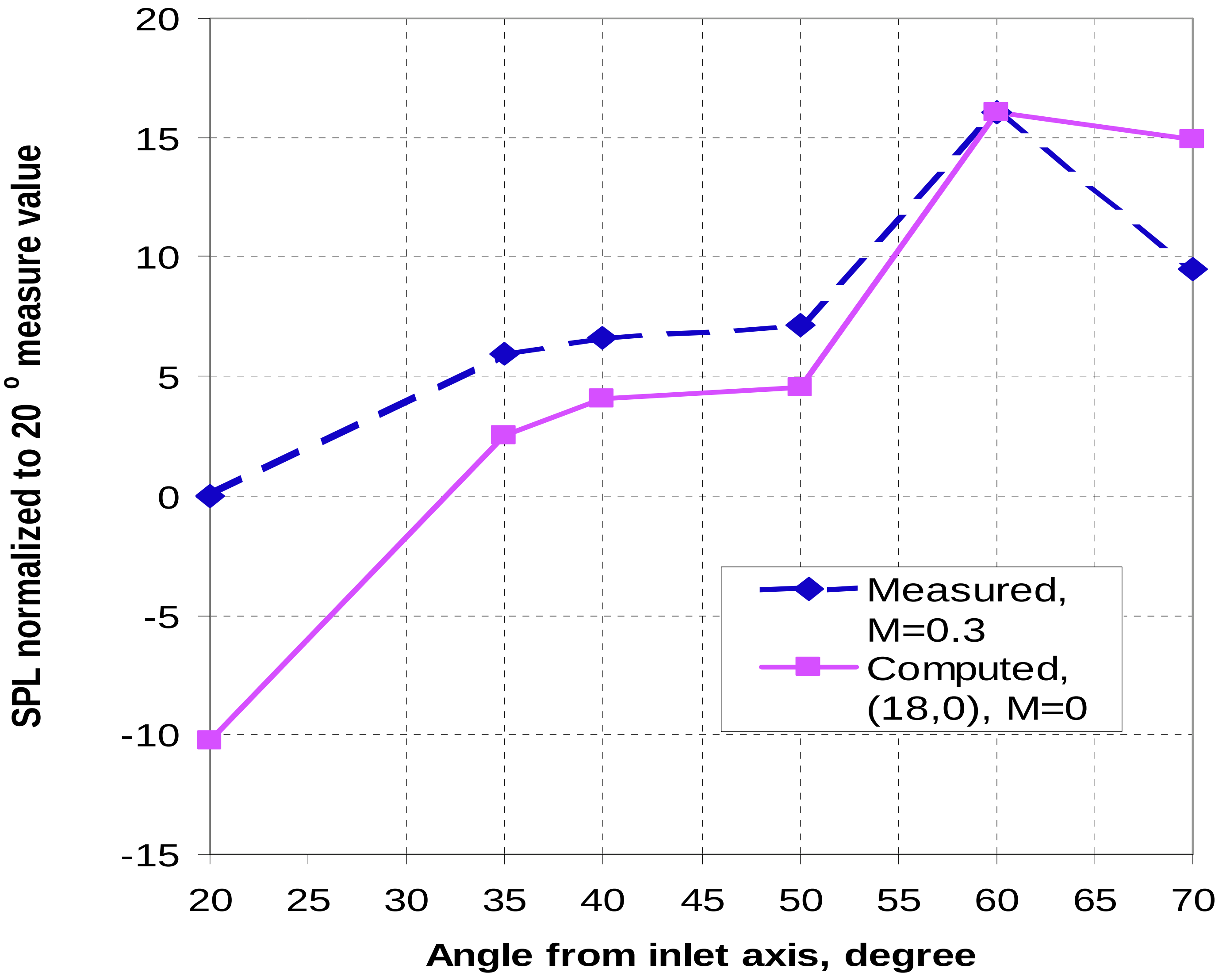

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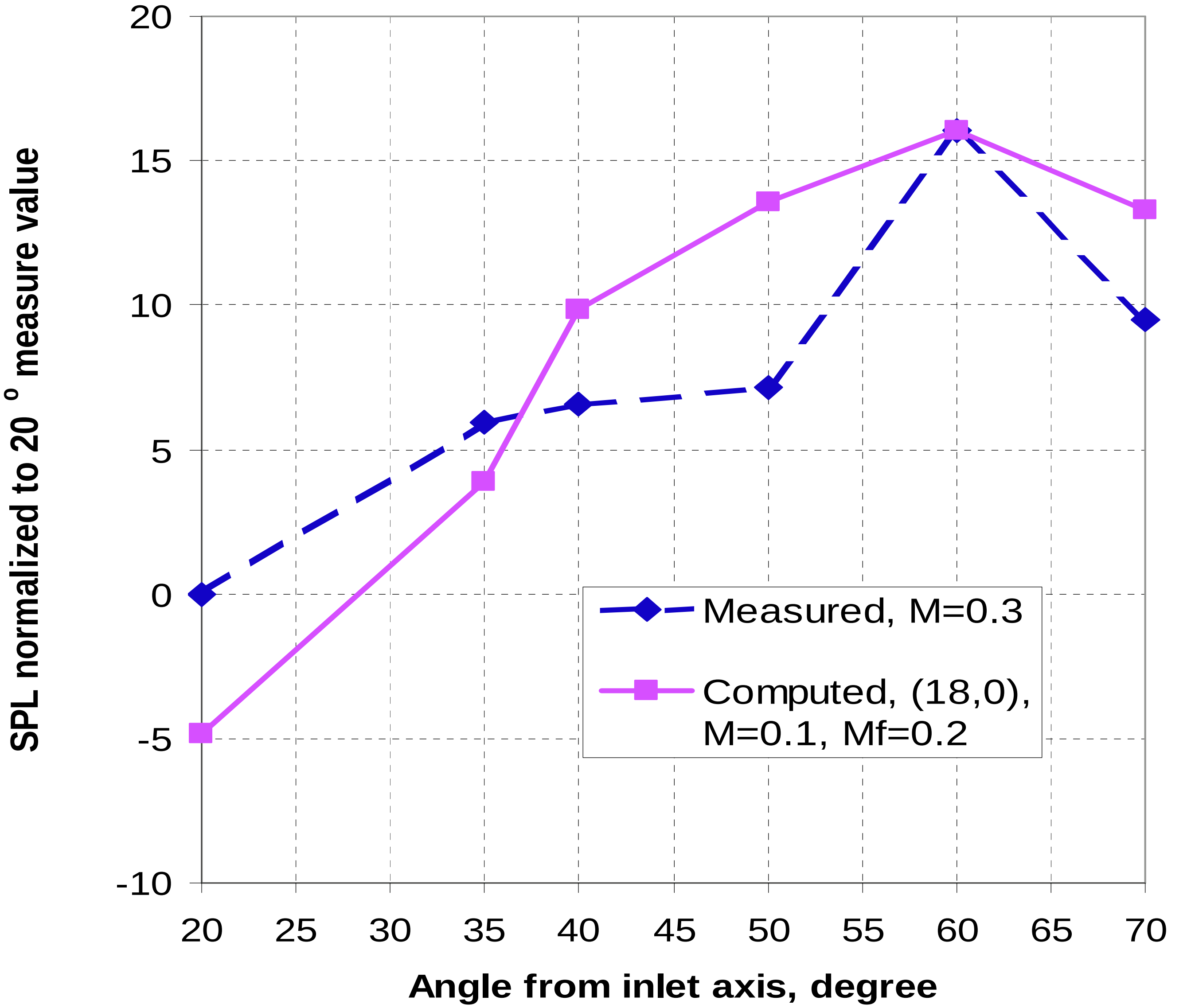

# Conclusion

- A realistic, complete and accurate modeling of propagation of aircraft engine noise, including the effect of scattering from fuselage, pylon, and wing, is now possible with the proposed methodology implemented on large distributed memory parallel computers.
- The computer code is flexible enough to accommodate even more complicated configurations.
- Still need to improve efficiency of parallel matrix solution (Schur complement )