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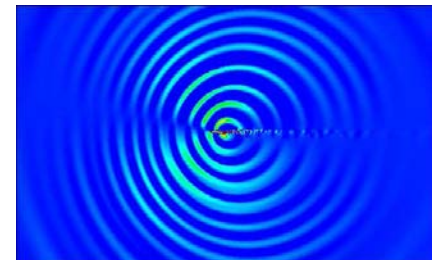
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Accurate wind turbine aero-acoustics by high-order schemes

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Introduction

- Objective
 - to develop a CAA tool for predicting *flow induced noise*
- Method
 - High-order Flow/Acoustics splitting technique
 - computational fluid dynamics + computational aero-acoustics
- Challenges
 - small amplitude of sound waves, e.g., 75dB $\rightarrow p' = 10^{-6} p_0$
 - wide range of frequencies , 20Hz-20kHz
 - long computing time

CFD - EllipSys Flow Solver

- Incompressible flow solver - EllipSys
 - Finite volume method
 - Cell-centred / Multi-block
 - Five levels multi-grid for the pressure equation
 - SIMPLE / SIMPLEC with Rhie-Chow interpolation
 - Second-order both in space and in time
- RANS / $k-\omega$, $k-\epsilon$, SA, etc.
- LES - The filtered incompressible Navier-Stokes equations

momentum equations:
$$\frac{\partial \bar{U}_i}{\partial t} + \frac{\partial (\bar{U}_i \bar{U}_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{P}}{\partial x_i} + \nu \frac{\partial^2 \bar{U}_i}{\partial x_j^2} + \frac{\partial \tau_{ij}}{\partial x_j}$$

turbulent stress terms:
$$\tau_{ij} = \nu_t \left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right) - \frac{2}{3} k \delta_{ij}$$

the eddy viscosity:
$$\nu_t = C \left| \bar{\omega} \right|^\alpha k^{(1-\alpha)/2} \Delta^{(1+\alpha)}$$

CAA - EllipSys Aeroacoustics Solver

- High-order CAA solver
 - Wavenumber optimized finite difference schemes
 - 4th, 6th, 8th, 10th, 12th - order explicit and compact schemes in space
 - 4th - order R-K for time advancing
- CAA equations:

$$\frac{\partial Q}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} + \frac{\partial G}{\partial z} = S$$

$$Q = \begin{pmatrix} \rho' \\ \rho u' + \rho' U \\ \rho v' + \rho' V \\ \rho w' + \rho' W \\ p' \end{pmatrix}, E = \begin{pmatrix} \rho u' + \rho' U \\ \rho(2Uu' + u'^2) + \rho' U^2 + p' \\ \rho(Vu' + Uv' + u'v') + \rho' UV \\ \rho(Wu' + Uw' + u'w') + \rho' UW \\ c^2(\rho u' + \rho' U) \end{pmatrix}$$

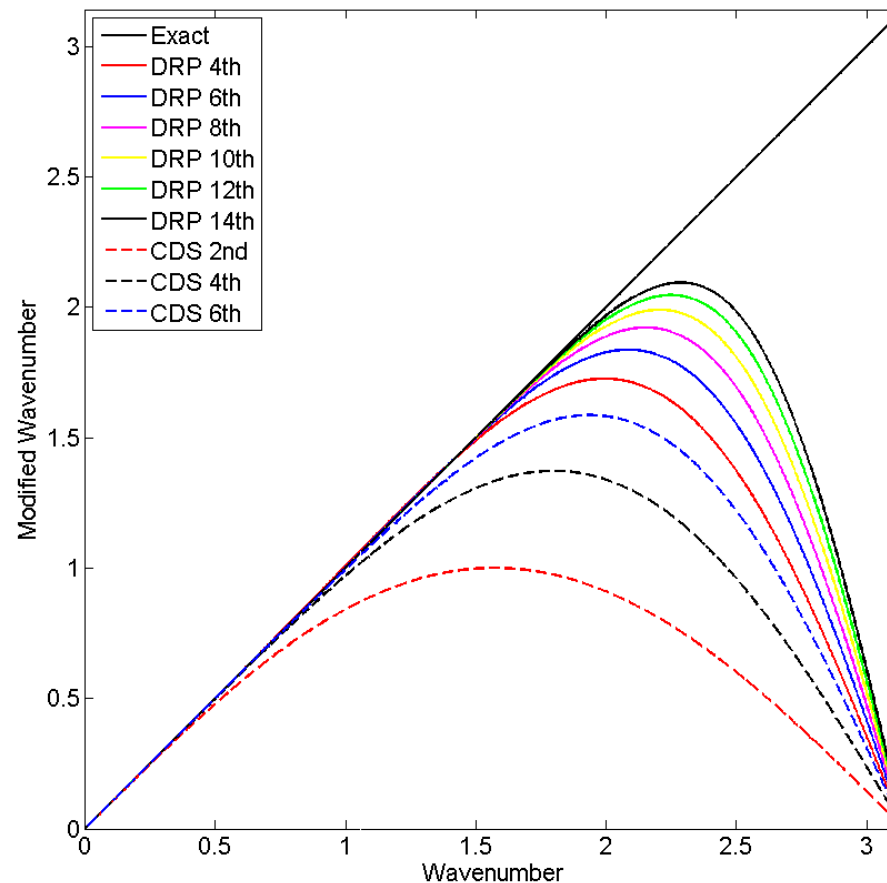
$$F = \begin{pmatrix} \rho v' + \rho' V \\ \rho(Vu' + Uv' + u'v') + \rho' UV \\ \rho(2Vv' + v'^2) + \rho' V^2 + p' \\ \rho(Vw' + Wv' + v'w') + \rho' VW \\ c^2(\rho v' + \rho' V) \end{pmatrix}$$

$$G = \begin{pmatrix} \rho w' + \rho' W \\ \rho(Wu' + Uw' + u'w') + \rho' UW \\ \rho(Wv' + Vw' + v'w') + \rho' VW \\ \rho(2Ww' + w'^2) + \rho' W^2 + p' \\ c^2(\rho w' + \rho' W) \end{pmatrix}, S = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -\frac{\partial P}{\partial t} \end{pmatrix}$$

$$c^2 = \frac{\gamma p}{\rho} = \frac{\gamma(P + p')}{\rho_0 + \rho'}$$

CAA – High order scheme

- Example of high-order schemes – DRP schemes and CDS schemes

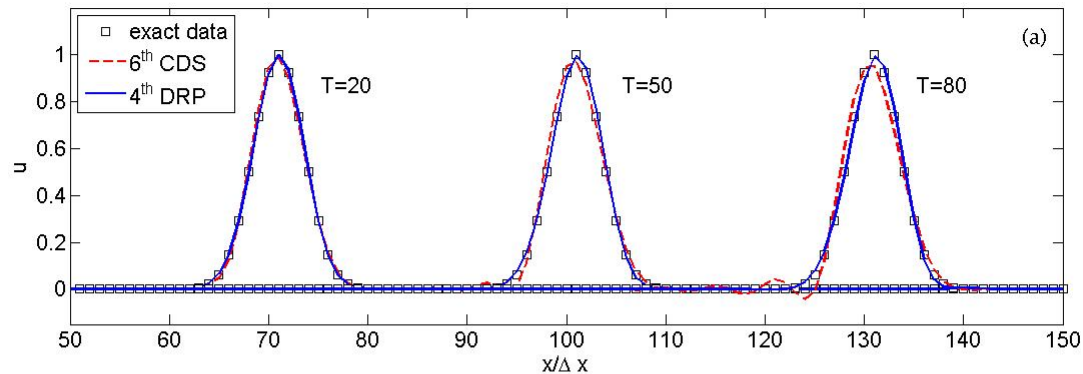


Simulation 1.– *Wave convection*

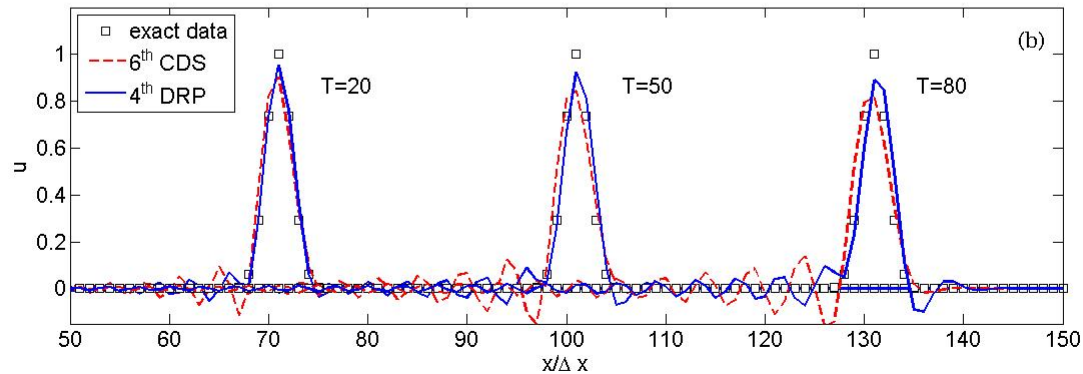
Wave convection: $\partial u / \partial t + \partial u / \partial x = 0$

$$u = \exp(-\ln(2)(x - x_0)^2 / b^2)$$

$b=3$



$b=1.5$



Simulation 2.– *Wave scattering*

Initial disturbance: $p(x, y, 0) = \exp\left[-\ln(2)\frac{(x-4)^2 + y^2}{(0.2)^2}\right]$

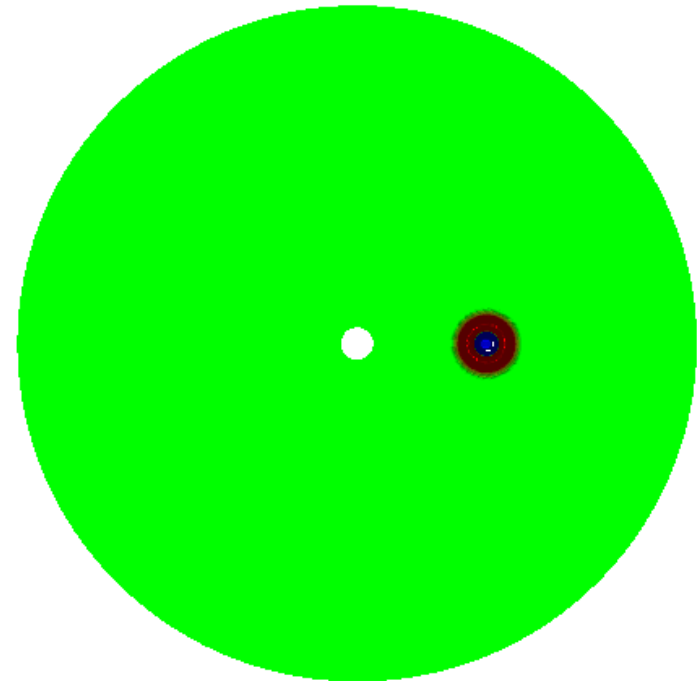
Initial velocity: $v_r = v_\theta = 0$

Euler equation in polar frame:

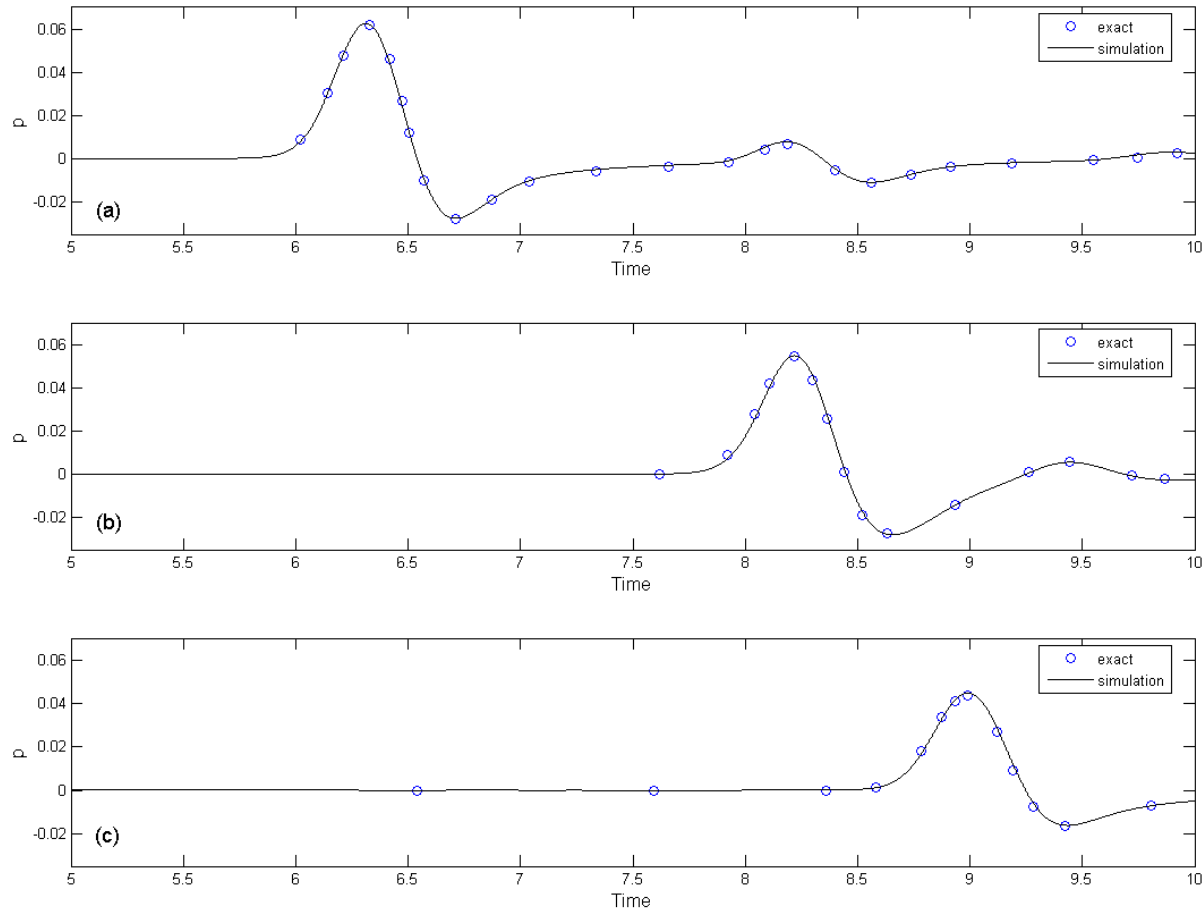
$$\frac{\partial}{\partial t} \begin{pmatrix} v_r \\ v_\theta \\ p \end{pmatrix} + \frac{\partial}{\partial r} \begin{pmatrix} p \\ 0 \\ v_r \end{pmatrix} + \frac{1}{r} \frac{\partial}{\partial \theta} \begin{pmatrix} 0 \\ p \\ v_\theta \end{pmatrix} + \frac{1}{r} \begin{pmatrix} 0 \\ 0 \\ v_r \end{pmatrix} = 0$$

Mesh configuration: 201x201 points in a half domain

Schemes: 4th-DRP and 4th-RK



Simulation 2.– Wave scattering



Time history sound pressure $p(t)$ measured at :
 $r = 5$, A ($\theta = 90^\circ$), B ($\theta = 135^\circ$), C ($\theta = 180^\circ$).

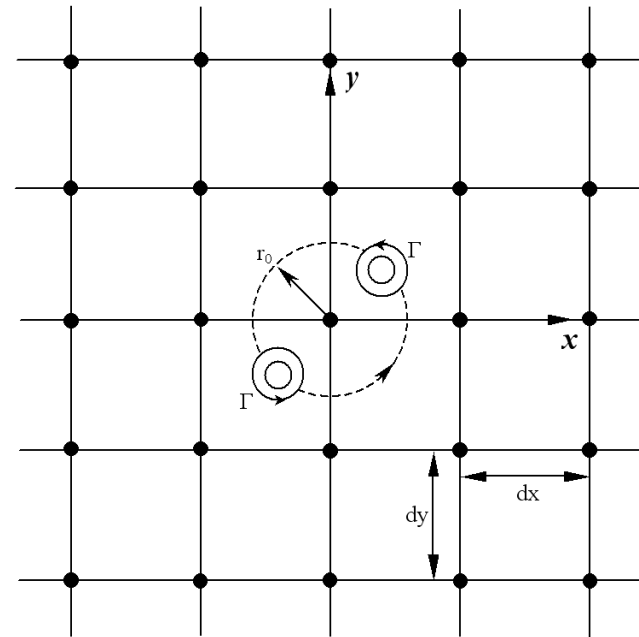
Simulation 3.– *Vortex sound*

The flow field variables U, V, P are given as:

$$U - iV = \frac{\Gamma}{i\pi} \frac{z}{z^2 - b^2}$$

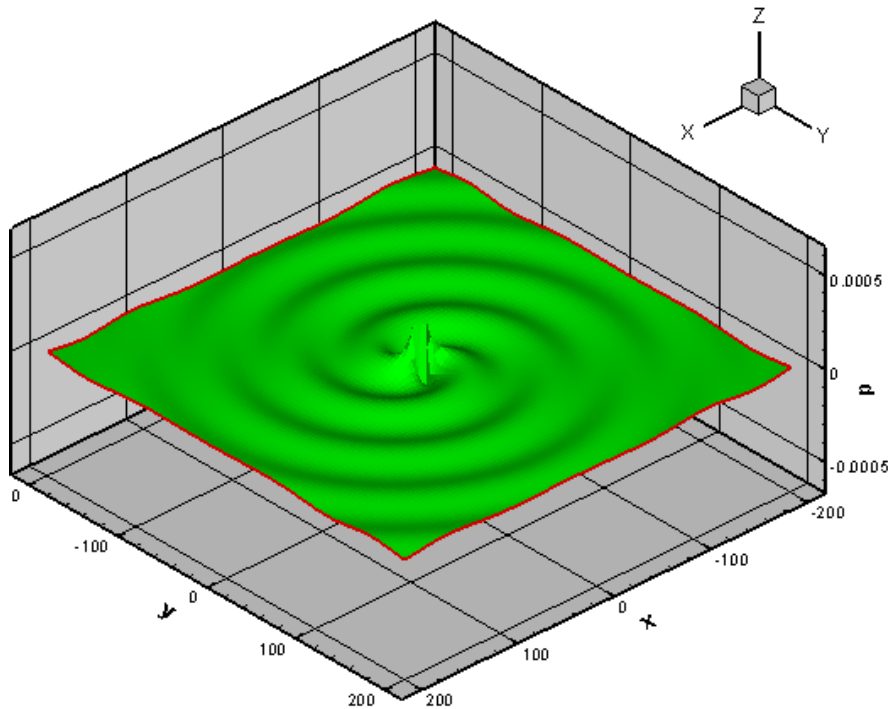
$$P = P_0 + \rho_0 \frac{\Gamma \omega}{\pi} \Re \left(\frac{b^2}{z^2 - b^2} \right) - \frac{1}{2} \rho_0 (U^2 + V^2)$$

u', v', ρ', p' are found from the 2D acoustic equations:

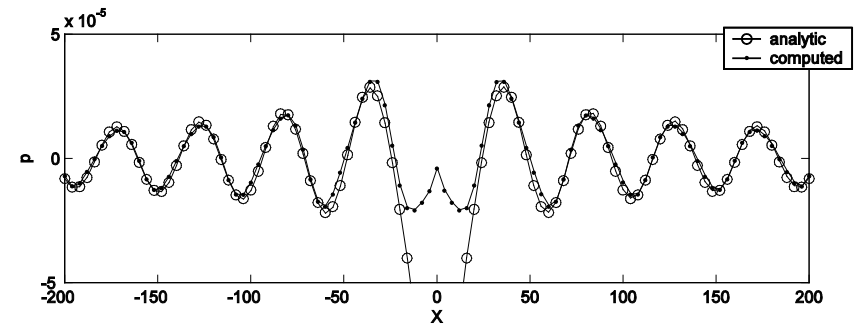
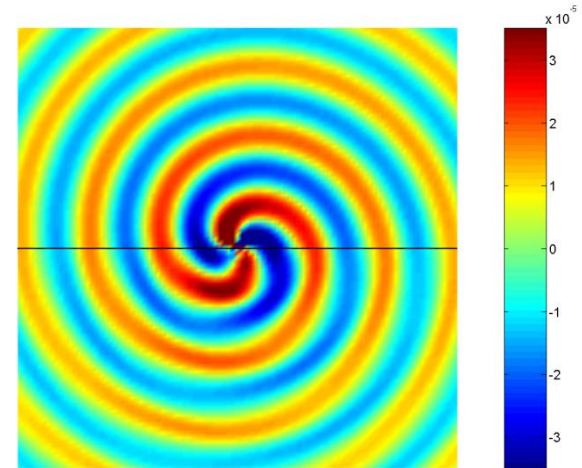


$$\frac{\partial}{\partial t} \begin{pmatrix} \rho' \\ \rho u' + \rho' U \\ \rho v' + \rho' V \\ p' \end{pmatrix} + \frac{\partial}{\partial x} \begin{pmatrix} \rho u' + \rho' U \\ \rho(2Uu' + u'^2) + \rho' U^2 + p' \\ \rho(Vu' + Uv' + u'v') + \rho' UV \\ c^2(\rho u' + \rho' U) \end{pmatrix} + \frac{\partial}{\partial y} \begin{pmatrix} \rho v' + \rho' V \\ \rho(Vu' + Uv' + u'v') + \rho' UV \\ \rho(2Vv' + v'^2) + \rho' V^2 + p' \\ c^2(\rho v' + \rho' V) \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ -\frac{\partial P}{\partial t} \end{pmatrix}$$

Simulation 3.— *Vortex sound*



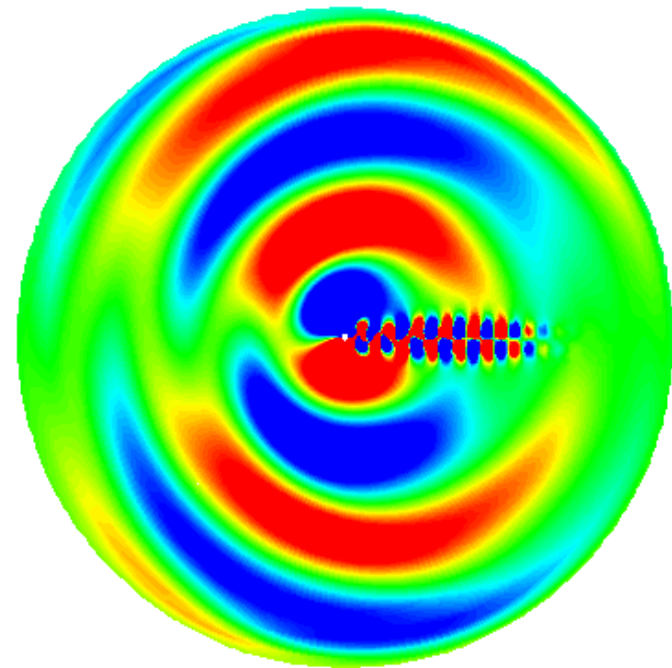
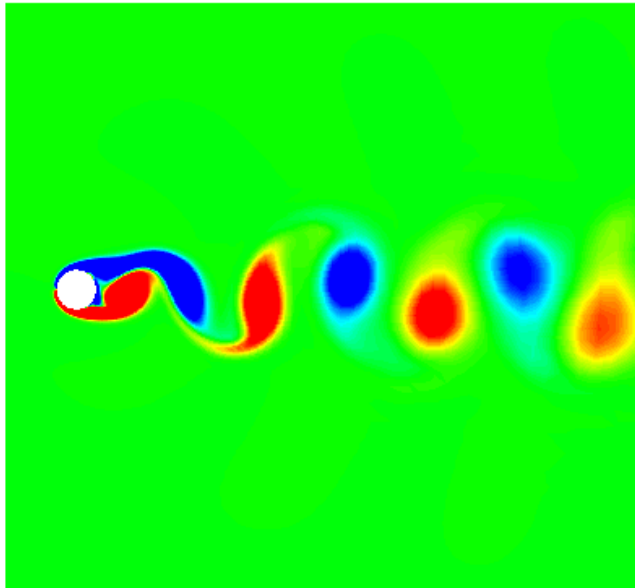
$$\Gamma = 2\pi / 10$$



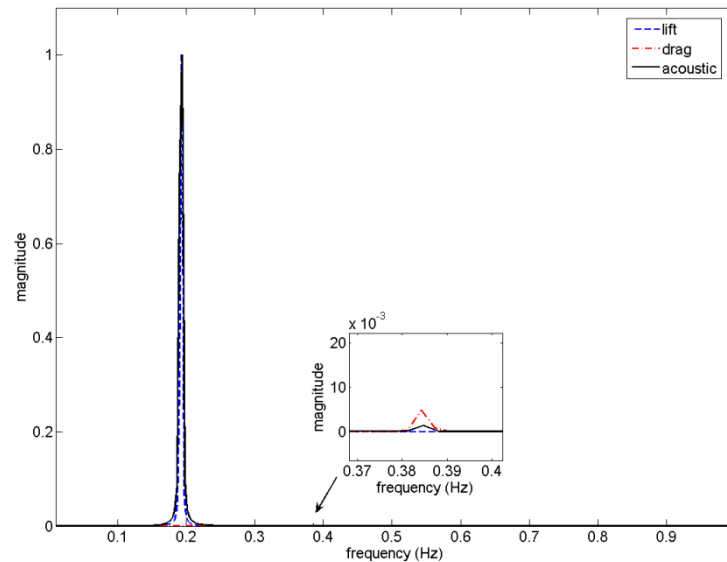
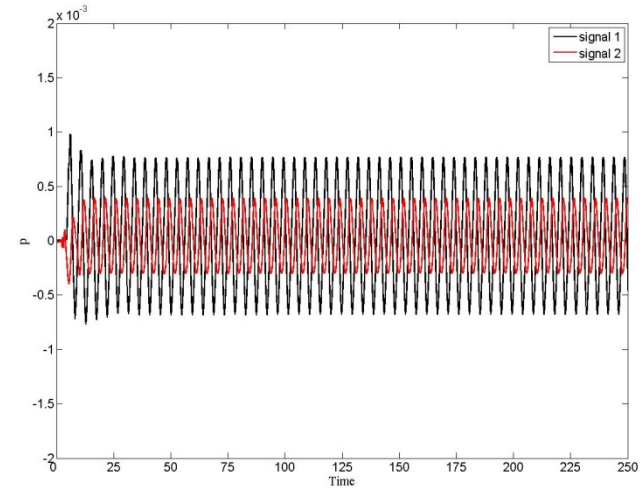
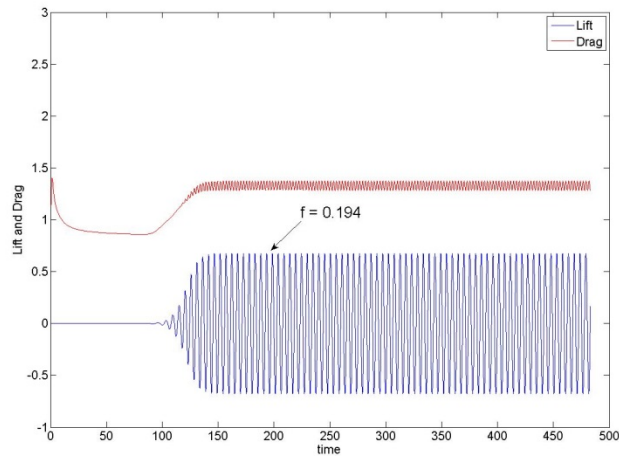
Simulation 4.— *Laminar flow over cylinder*

Flow over a cylinder at $Re = 200$ and $M = 0.2$.

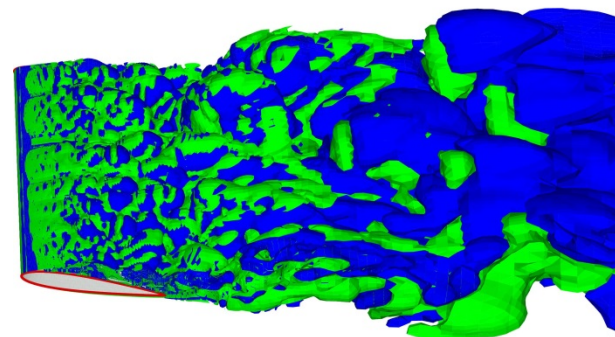
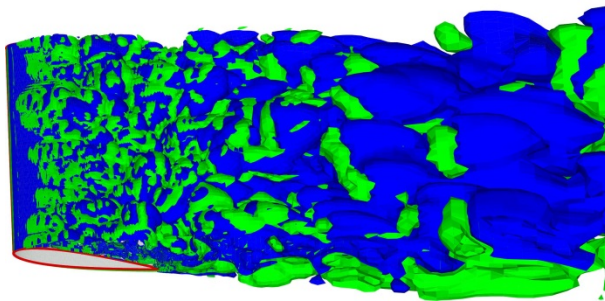
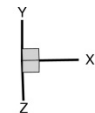
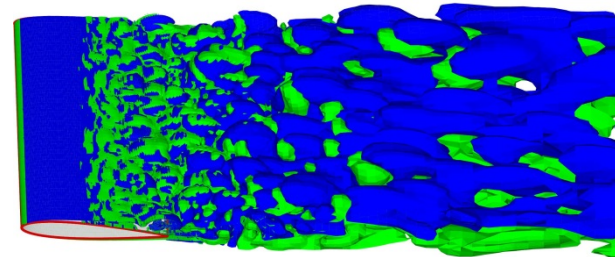
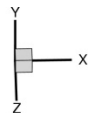
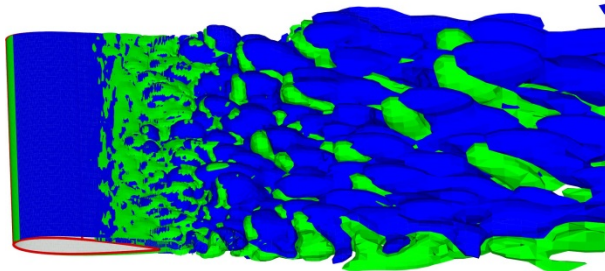
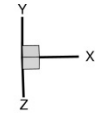
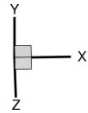
O-mesh: 256x128 points in the tangential and radial directions; $dt = 1e-3$



Simulation 4.— *Laminar flow over a cylinder*

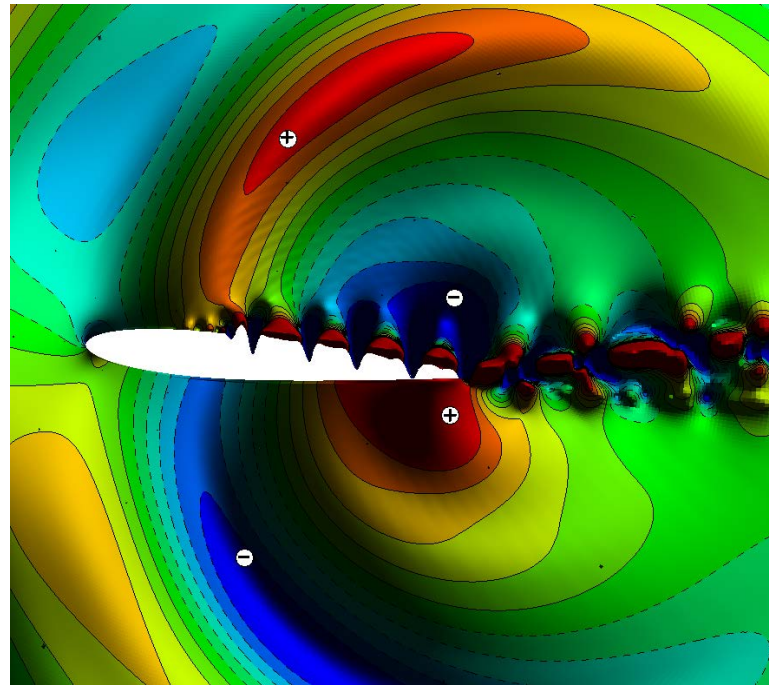
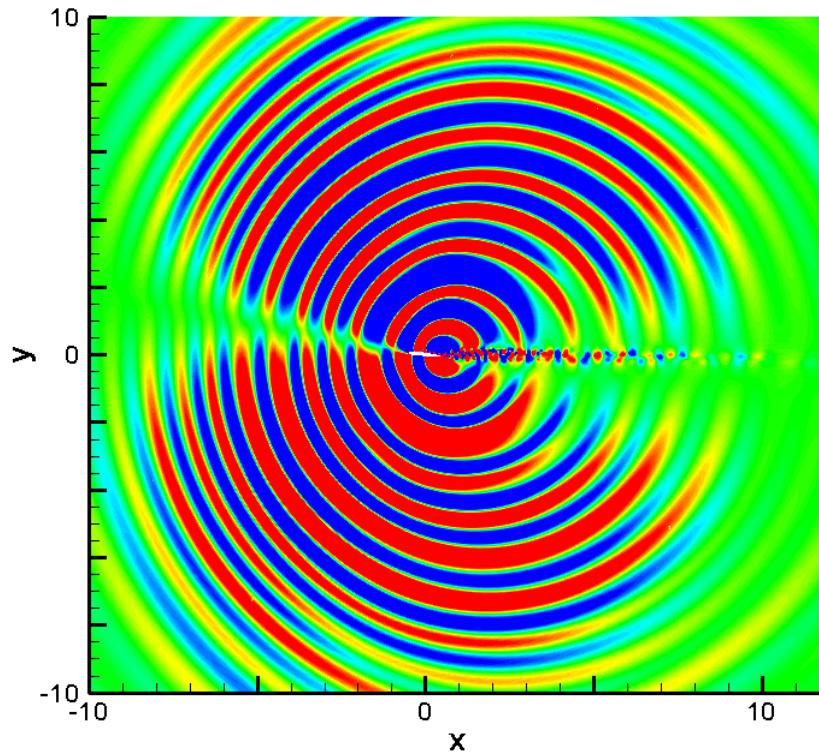


Simulation 5.— *Turbulent flow over an airfoil*



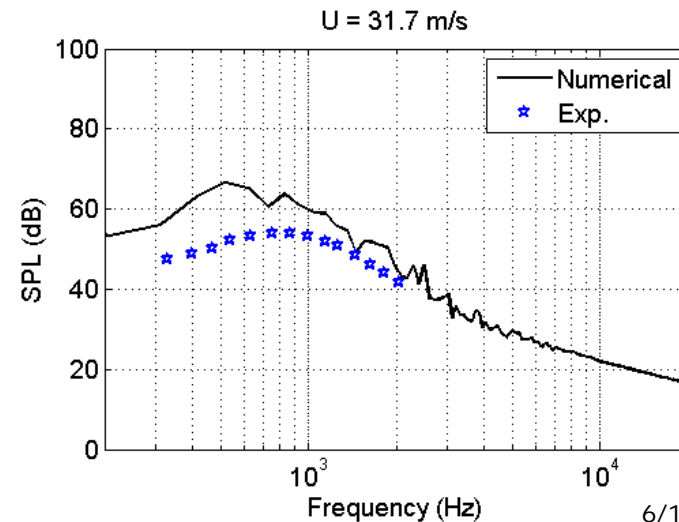
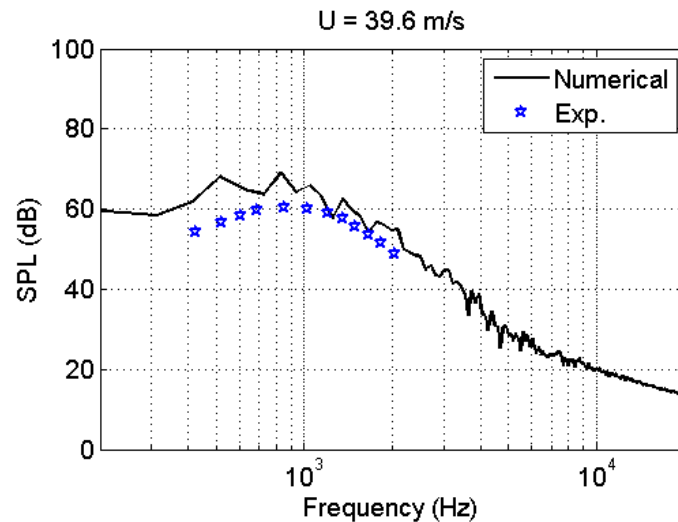
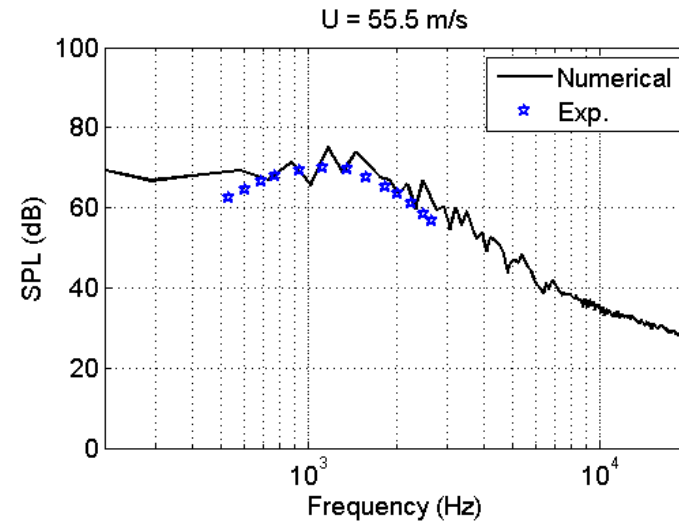
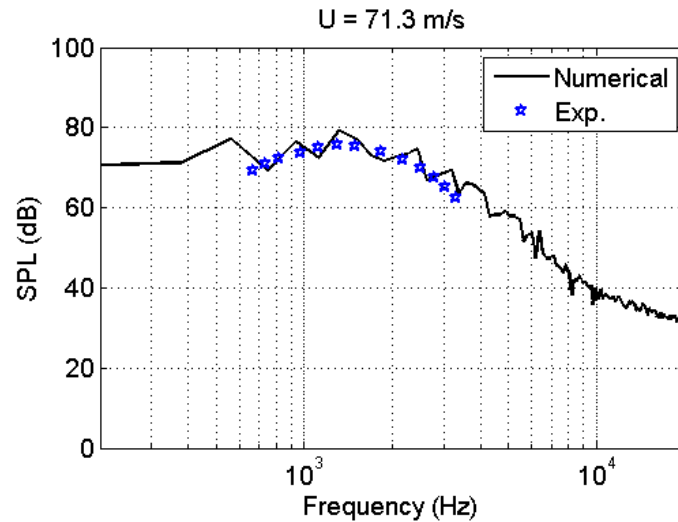
$Re = 160,000$ and $\alpha = 4^\circ, 6^\circ, 10^\circ, 12^\circ$.

Simulation 5.— *Turbulent flow over an airfoil*



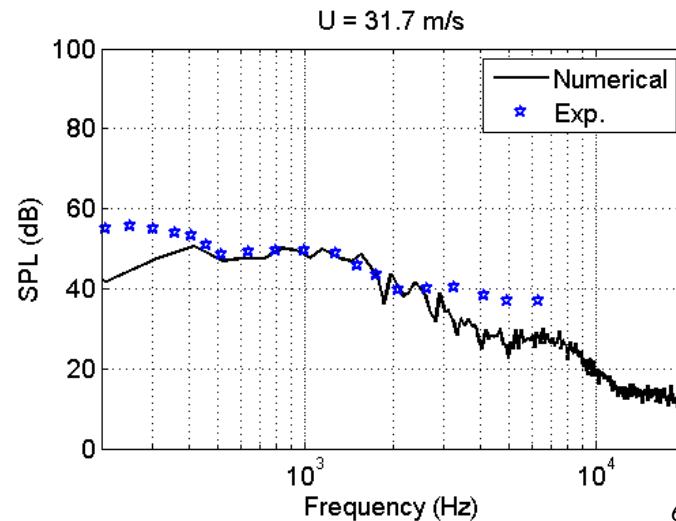
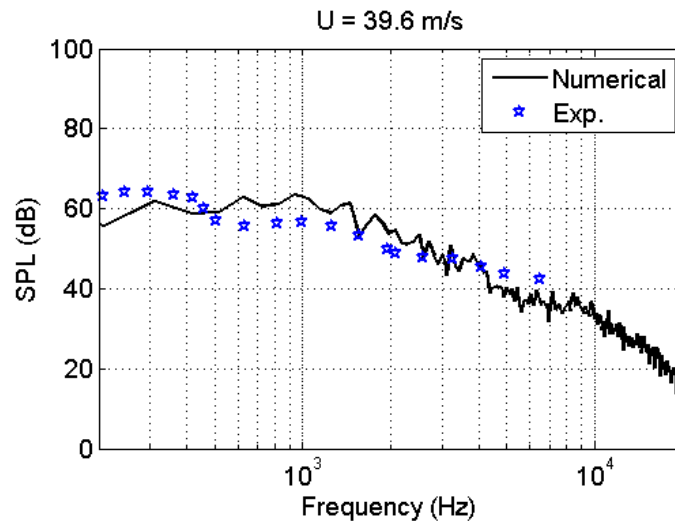
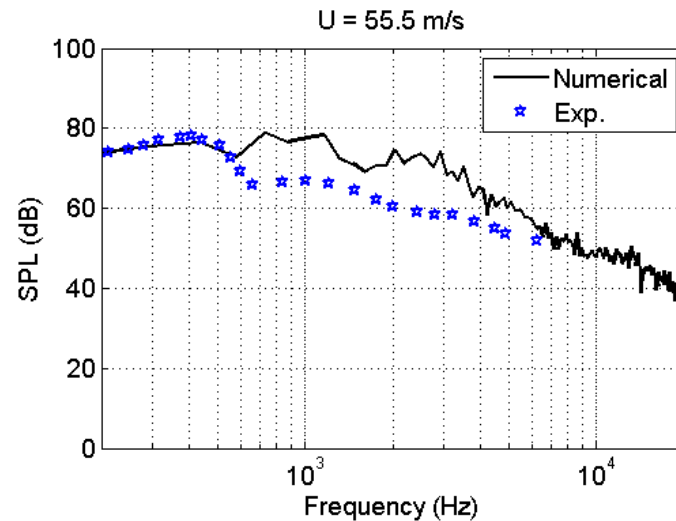
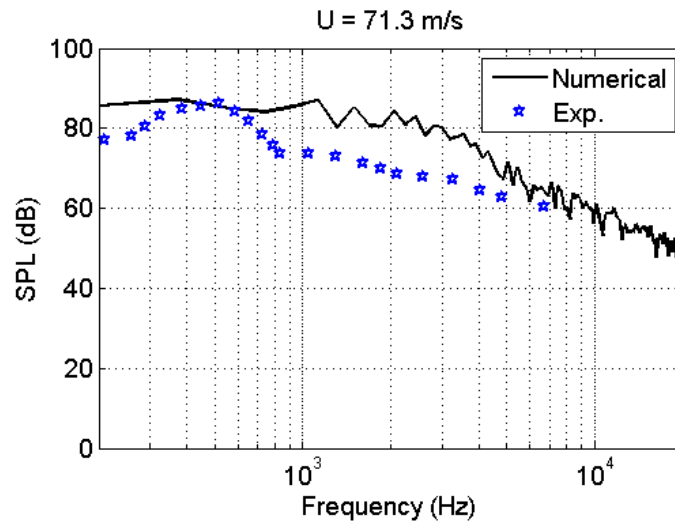
Simulation 5.— *Turbulent flow over an airfoil*

- Turbulent airfoil flow: $\alpha = 6.7^\circ$.



Simulation 5.— *Turbulent flow over an airfoil*

- Turbulent airfoil flows - $\alpha = 12.3^\circ$.



Conclusions

- Instead of directly solving the compressible NS equations, flow induced noise is predicted by the flow/acoustic splitting method.
- Flow and acoustic simulations were carried out by EllipSys using HPC (cluster with over 500 nodes).
- To reduce dispersion errors of sound waves, high-order schemes are used for CAA equations.
- It is observed that the aerodynamic force is related to the noise generation (some correlations are found from their spectra).
- For turbulent flows, LES is a good option for flow computations. However, for high-Reynolds-number-flow, LES becomes expensive.

Thank you very much for your attention!