A Preliminary Analysis of Wing Flutter Using Moving Grid Finite Volume Method

Hiromasa Hayashi, Daisuke Takayama, Shohei Matsuoka

Department of Aerospace Engineering, Tohoku University

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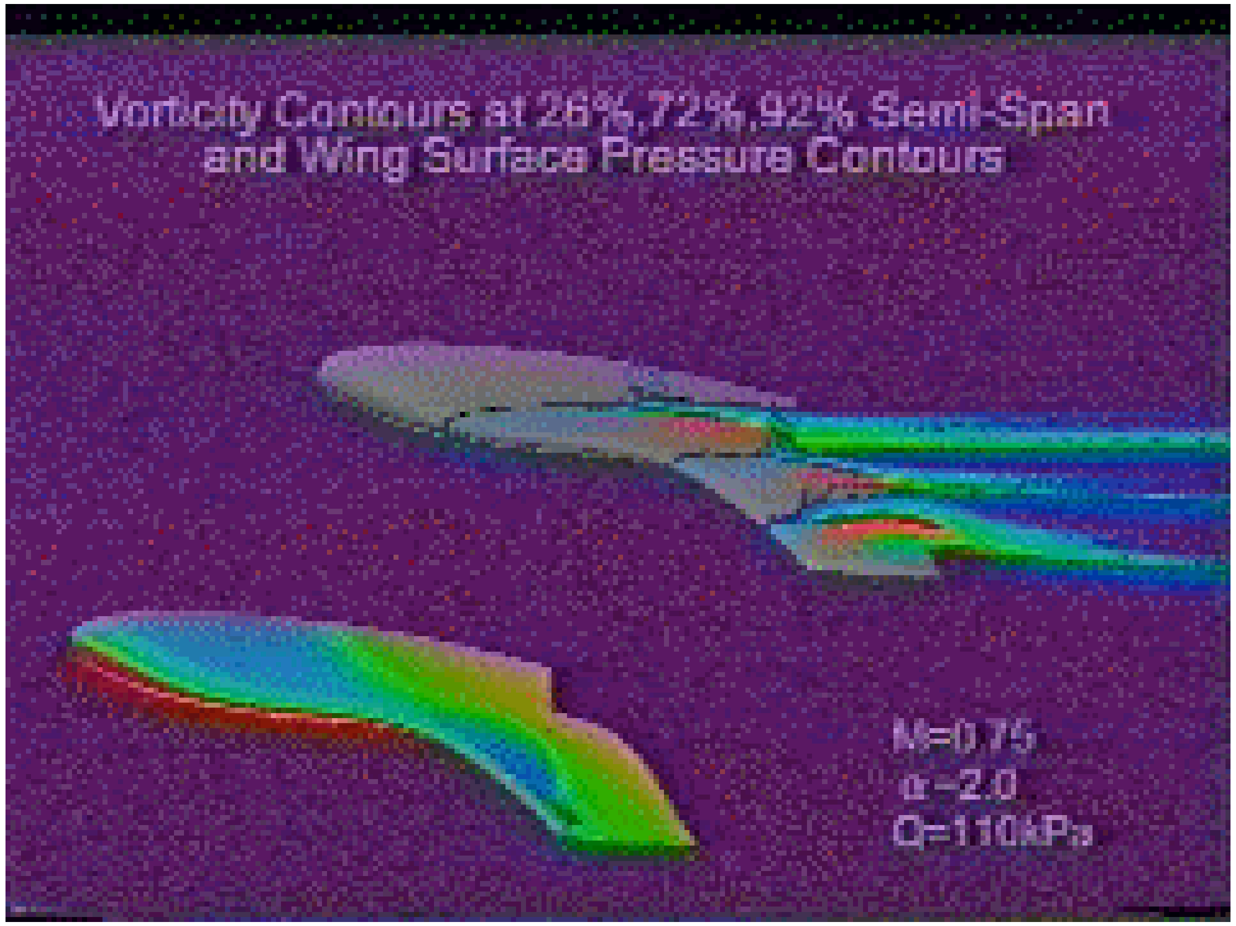
Wing flutter

- Aeroelastic phenomenon
- Diverging oscillation of a wing possibly causes wing destruction

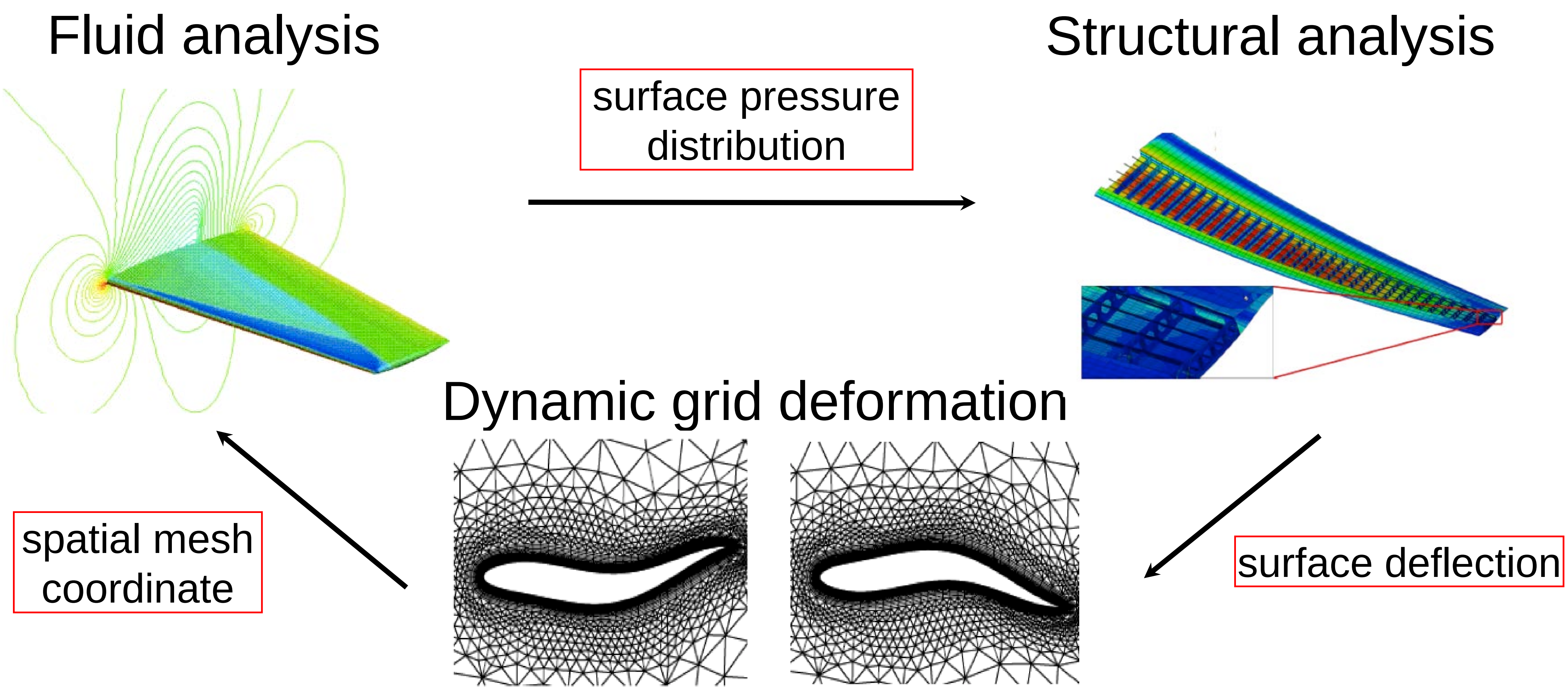


http://www.ard.jaxa.jp/research/kitai/ki-kuuriki.html

Flutter Analysis

Fluid-structure interaction simulation

- Three numerical methods are combined
  - Fluid analysis
  - Structural analysis
  - Dynamic grid deformation

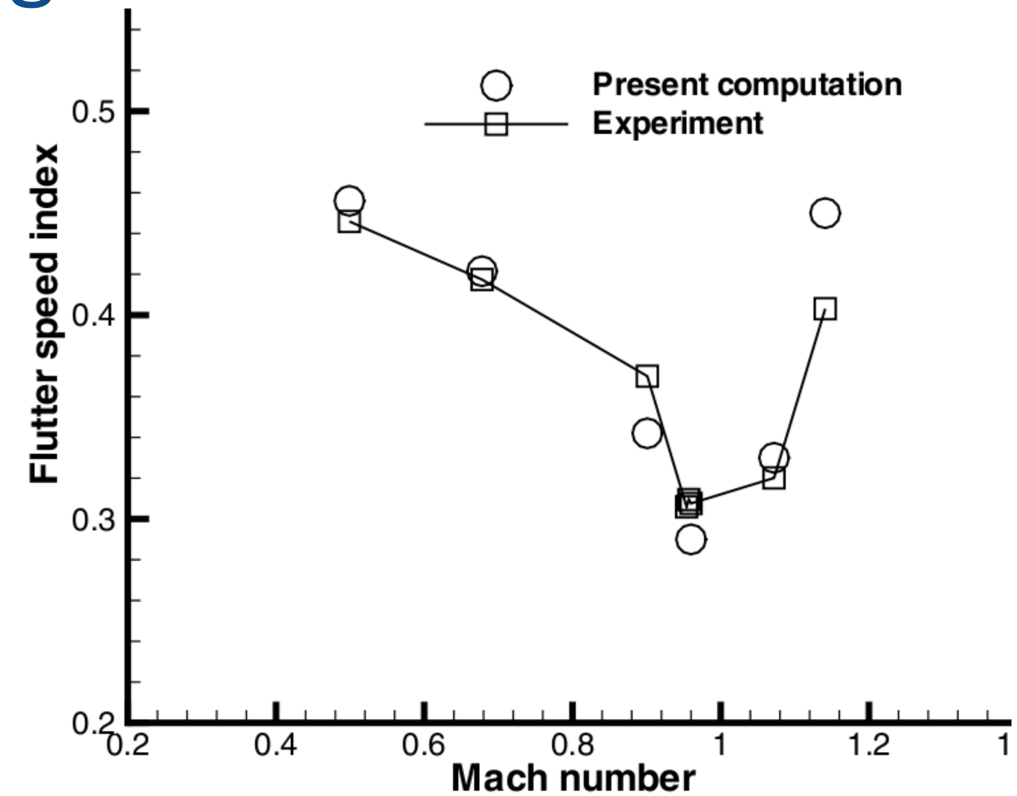


Past Flutter Analyses

Conservation equations for fluid flows

- Geometric conservation law
- Generalized curvilinear coordinate system

$$\text{Flutter Speed Index (FSI)} = \frac{V_\infty}{b_s \omega_a \sqrt{\mu}}$$



Comparison of computed results by Chen et al and experimental data for AGARD wing 445.6

Geometrical flexibility is required for problems having engine nacelles

- New CFD code based on Moving Grid FVM is developed
- Control volume is extended in 4D space and time

My Objective in Our Project

Develop an unsteady flow calculation code based on Moving Grid FVM

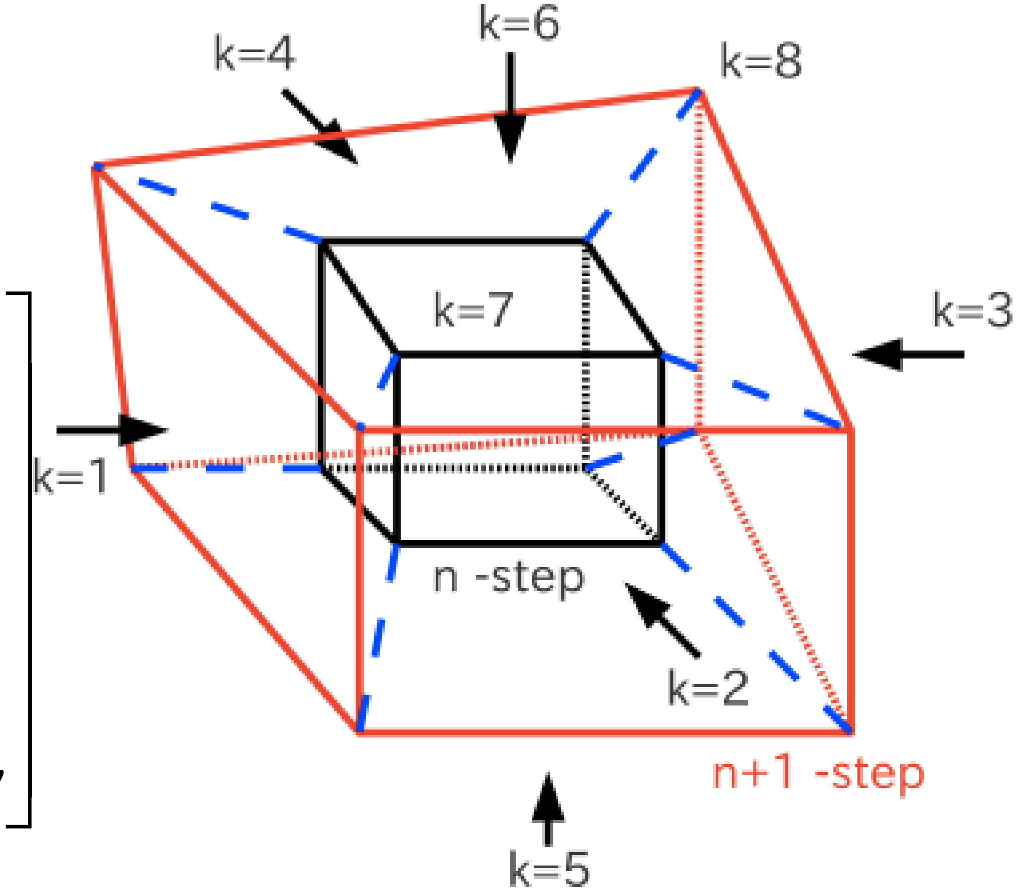
- Conservation law in 4D space and time
- Validation of developed CFD code
  - Steady flow-field over ONERA-M6 wing
  - Unsteady flow-field over NACA 0012 wing in pitching motion
- Attempt to compute flutter of AGARD wing 445.6

Moving Grid FVM

Conservation law in 4D space and time

$$\iiiint_{\Omega}\left(\frac{\partial \mathbf{Q}}{\partial t}+\frac{\partial \mathbf{E}}{\partial x}+\frac{\partial \mathbf{F}}{\partial y}+\frac{\partial \mathbf{G}}{\partial z}\right)d\Omega=\mathbf{0}$$

$$\mathbf{Q}=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ e\end{bmatrix},\mathbf{E}=\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ \rho uw\\ (e+p)u\end{bmatrix},\mathbf{F}=\begin{bmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ \rho vw\\ (e+p)v\end{bmatrix},\mathbf{G}=\begin{bmatrix}\rho w\\ \rho uw\\ \rho vw\\ \rho w^2+p\\ (e+p)w\end{bmatrix}$$



Discretized equation for moving and deforming cell

$$\mathbf{Q}^{n+1}V_8-\mathbf{Q}^{n}V_7$$

$$+\sum_{k=1}^{6}\left(\mathbf{Q}^{n+\frac{1}{2}}n_t+\mathbf{E}^{n+\frac{1}{2}}n_x+\mathbf{F}^{n+\frac{1}{2}}n_y+\mathbf{G}^{n+\frac{1}{2}}n_z\right)_k V_k=\mathbf{0}$$

Implicit integration form for Moving Grid FVM

$$[\mathbf{I}+\frac{1}{2V_8}\sum_{k=1}^{6}(\mathbf{I}n_t+\mathbf{A}^{(m)}n_x+\mathbf{B}^{(m)}n_y+\mathbf{C}^{(m)}n_z)_k V_k]\Delta\mathbf{Q}^{(m)}=$$

$$-\frac{1}{V_8}[\mathbf{Q}^{(m)}V_8-\mathbf{Q}^{n}V_7+\sum_{k=1}^{6}\frac{1}{2}(\mathbf{Q}^{(m)}n_t+\mathbf{E}^{(m)}n_x+\mathbf{F}^{(m)}n_y+\mathbf{G}^{(m)}n_z)_k V_k$$

$$+\sum_{k=1}^{6}\frac{1}{2}(\mathbf{Q}^{n}n_t+\mathbf{E}^{n}n_x+\mathbf{F}^{n}n_y+\mathbf{G}^{n}n_z)_k V_k]$$

Delta form : $\Delta\mathbf{Q}^{(m)}=\mathbf{Q}^{n+1}-\mathbf{Q}^{(m)}$

Number of inner iteration : m

Numerical Methods

Fluid analysis

- Governing equations : 3D Euler equations
- Spatial discretization : 3rd order Moving Grid FVM
- Convective numerical flux : SLAU (steady calculation)
  : Roe (unsteady calculation)
- Time integration : matrix-free LU-SGS method with inner iteration

Structure analysis

- Governing equations : equation of motion
- Modal analysis : accounting for 1st to 5th modes
- Modal damping : 0.02
- Time integration : three point backward difference

Computational grid

- Regenerated by algebraic method at each time step

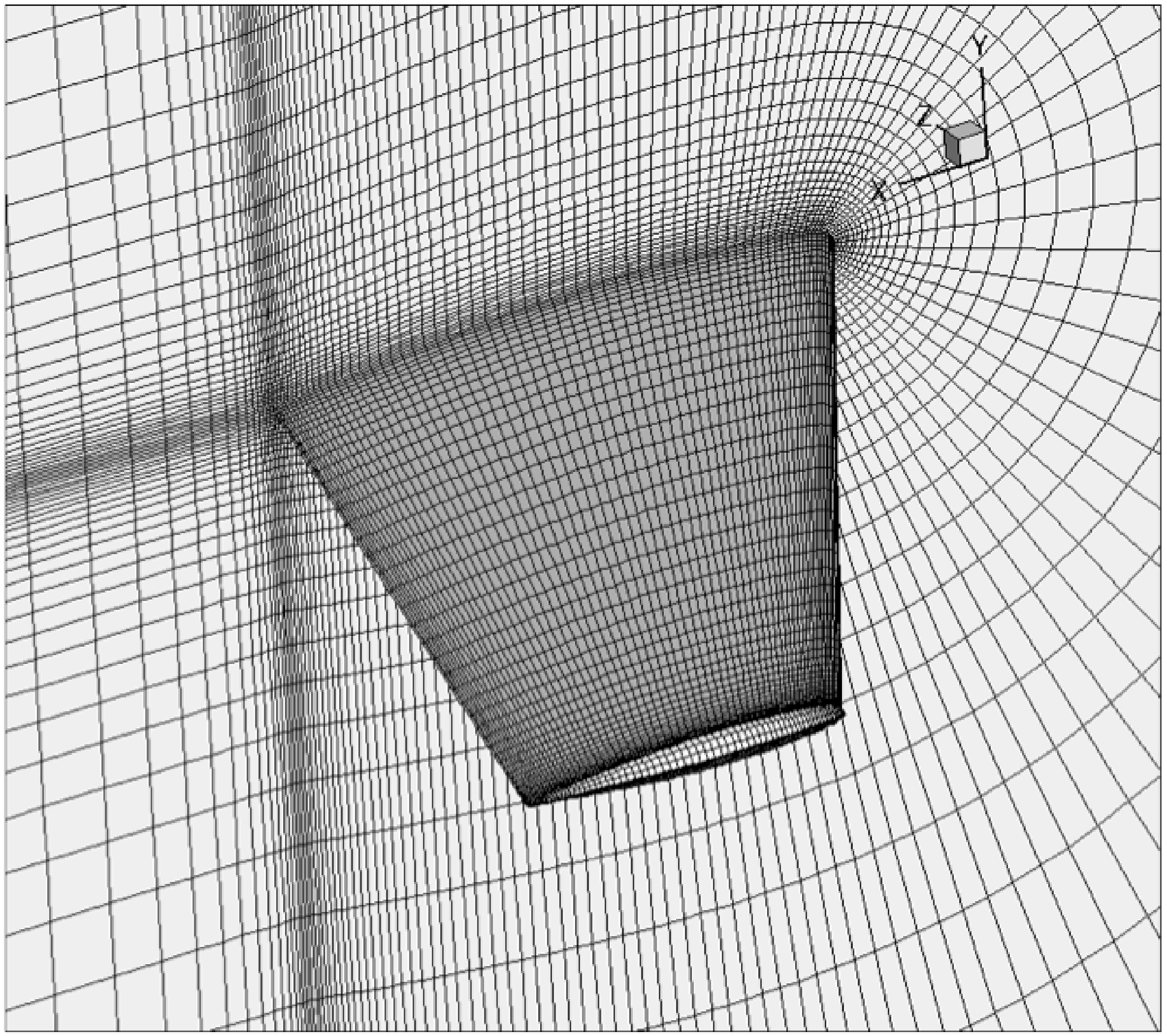
Steady flow-field over ONERA-M6 wing

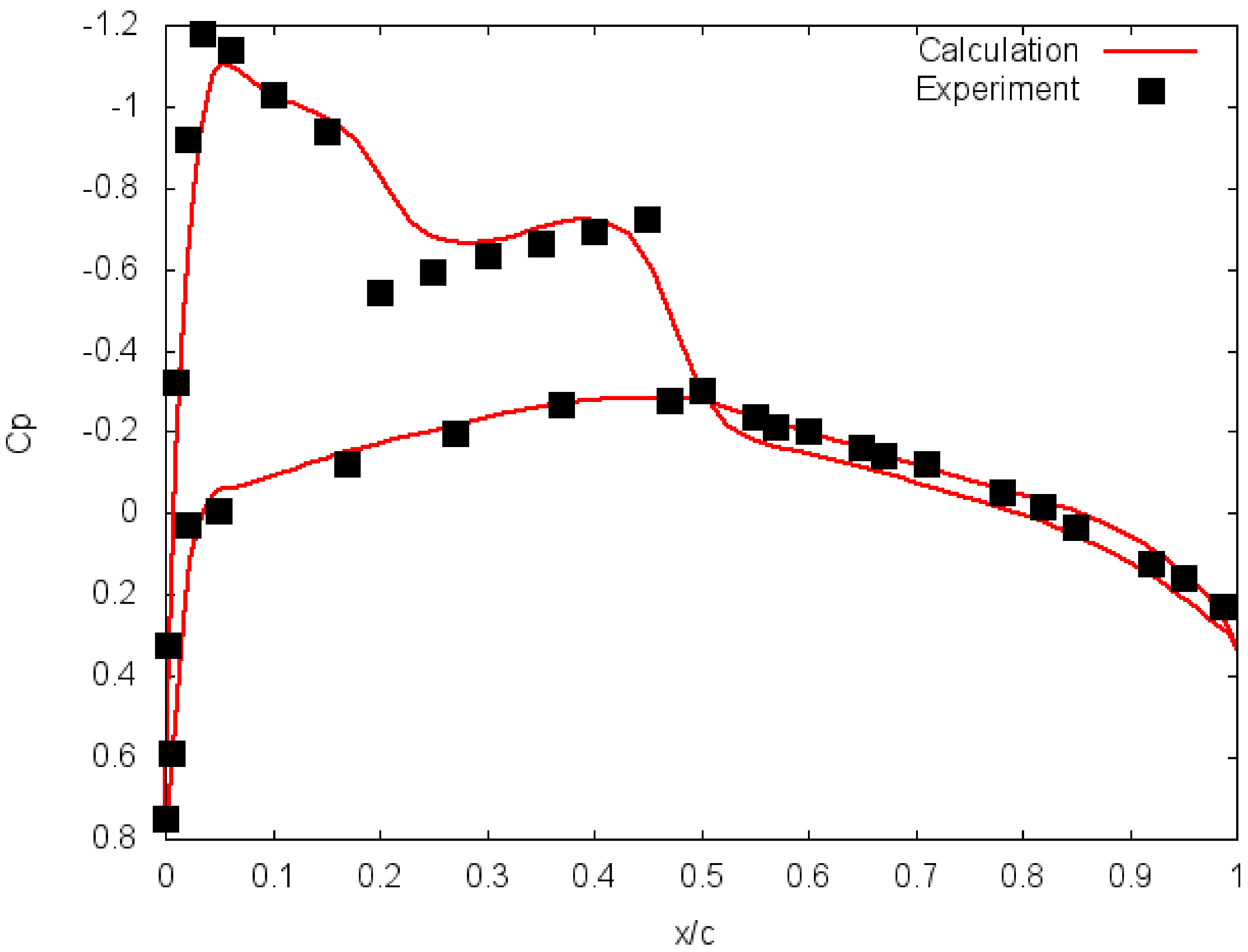
Computed result

ONERA M6 wing

- Grid type : C-H type
- Number of grid points
  : 197 × 50 × 82

- Flow conditions
  - Mach number : 0.84
  - Angle of attack : 3.06 [deg.]



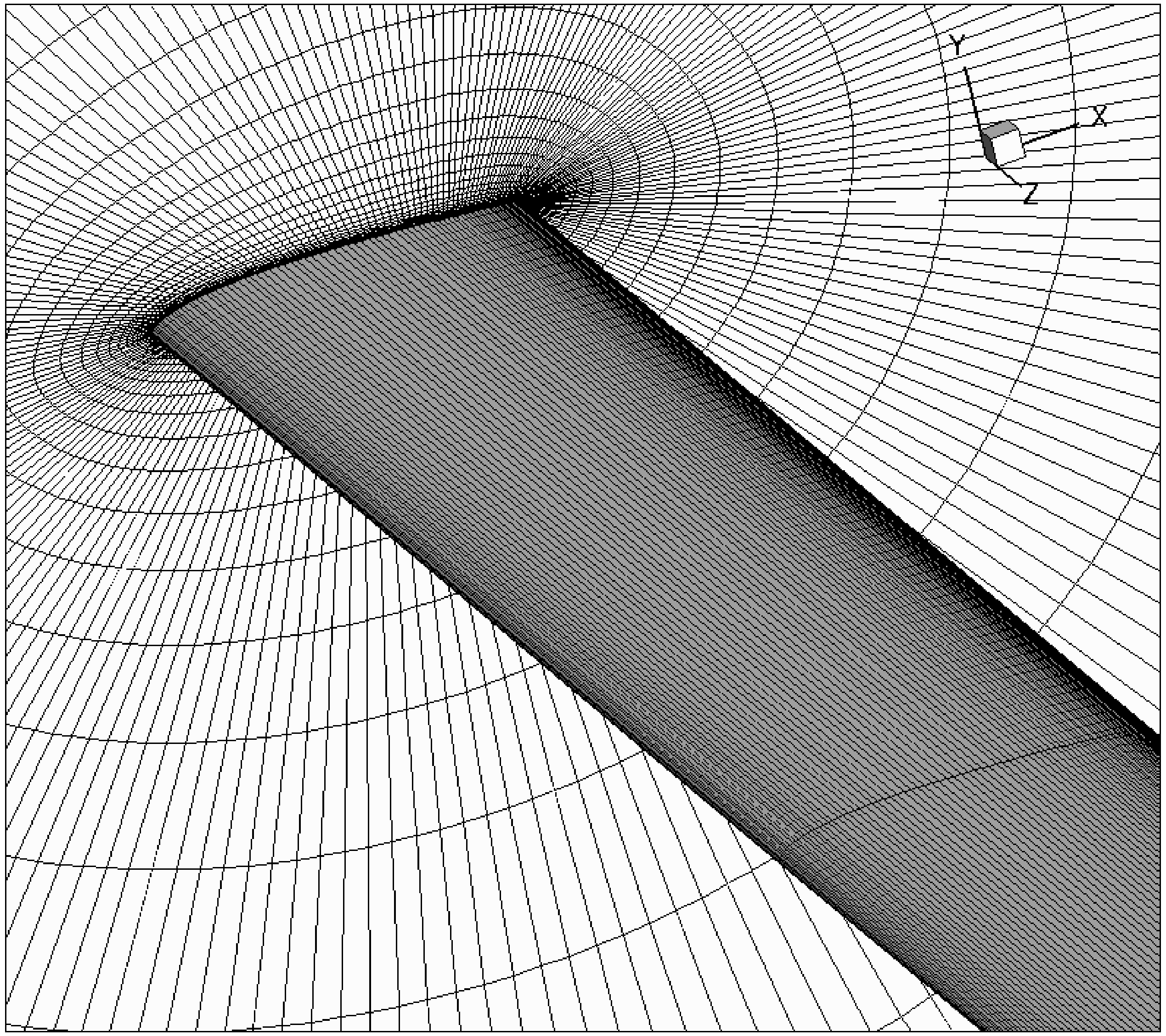


NACA 0012 wing in pitching motion

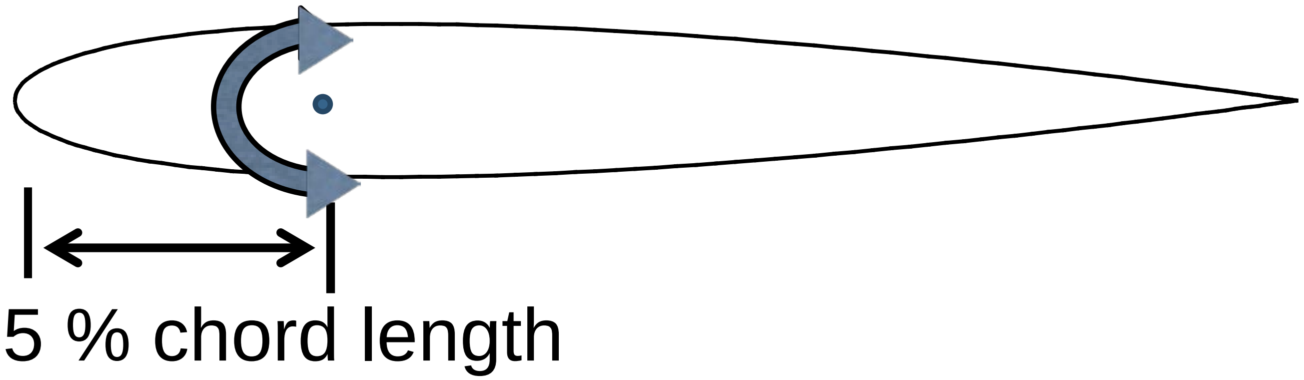
Computational grid for NACA 0012 wing

NACA 0012 wing

- Number of grid points
  : 202 × 40 × 10
- Computational domain
  : 40 root chord lengths
- Minimum grid spacing
  : 10^{-3} root chord length



Pitching motion



Comparison of computed and experimental results

Freestream condition

- Mach number : 0.755

Oscillating condition

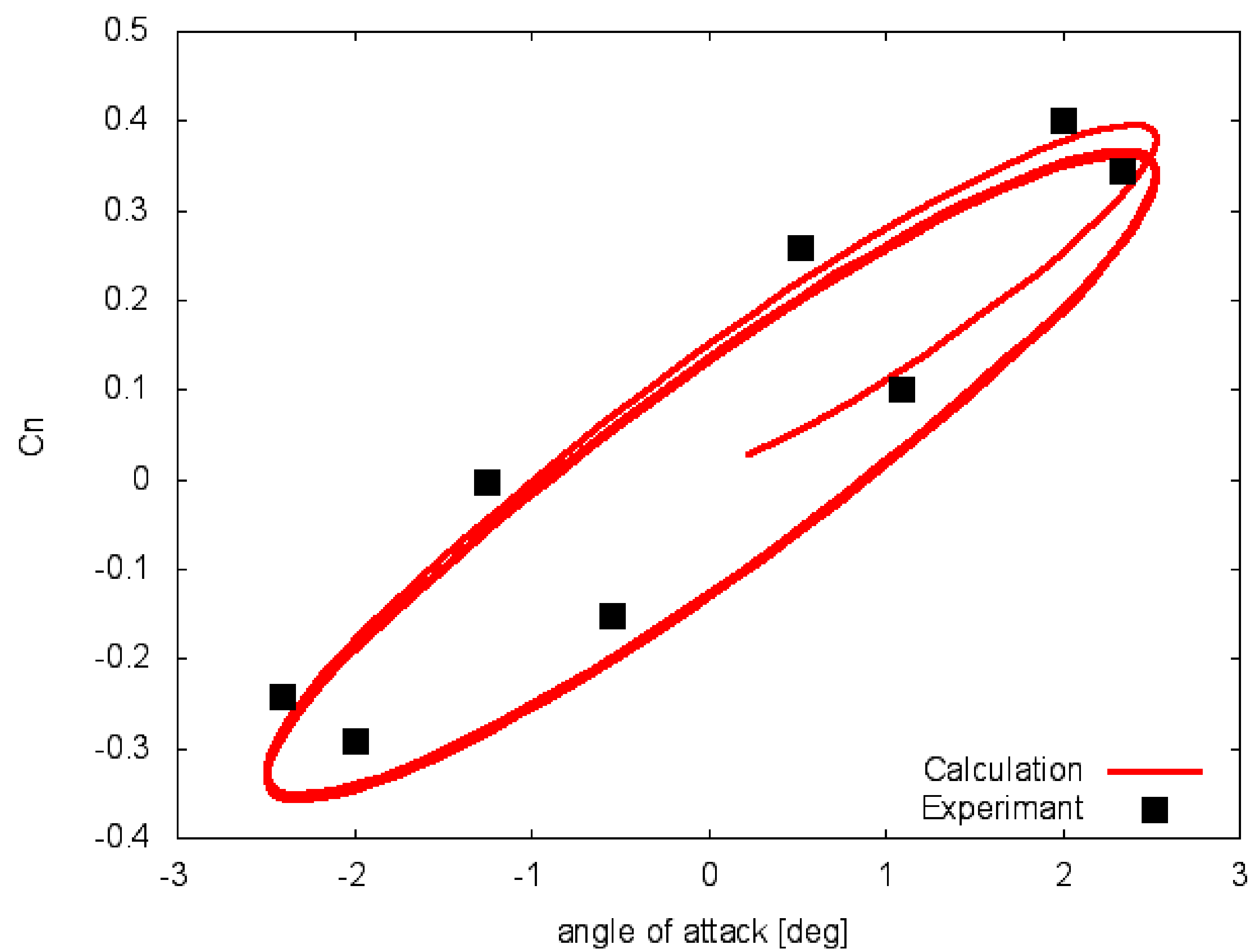
- Mean angle of attack : 0.016 [deg.]
- Amplitude of pitching angle : 2.51 [deg.]
- Reduced frequency *k* : 0.0814

$$k = \frac{\omega c}{2U_\infty}$$

ω : frequency

c : root chord length

U_∞ : freestream velocity



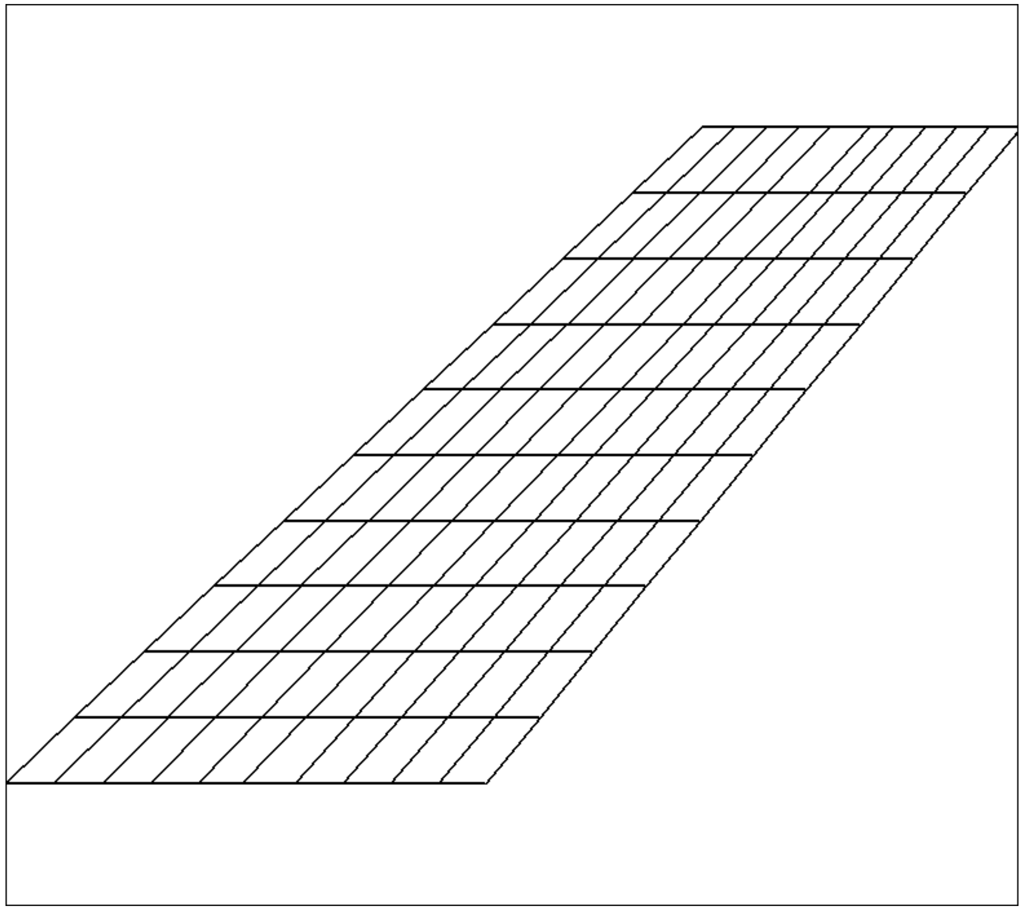
R. H. Landon, "Data set 3 NACA 0012 Oscillatory and Transient Pitching", Agard-r-702, 1982

Flutter analysis for AGARD wing 445.6

AGARD wing 445.6

Weakened wing model (model 3)

- Root chord length : 0.558 [m]
- Aspect ratio : 1.65
- Taper ratio : 0.658
- Swept angle : 45 [deg.]
- Cross-section airfoil : NACA 65A004

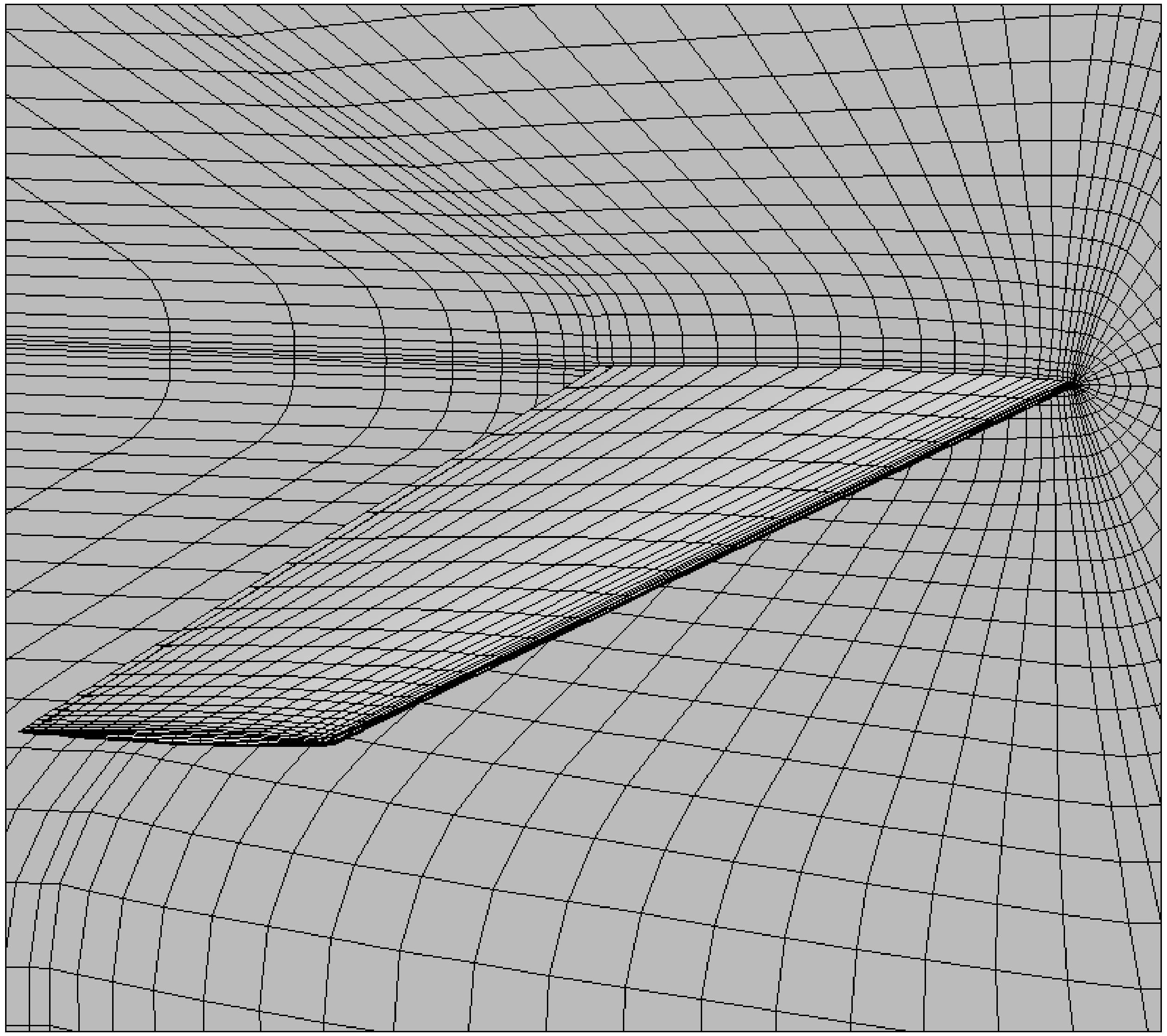


Mode	1st mode (bending)	2nd mode (torsion)	3rd mode (bending)	4th mode (torsion)	5th mode (bending)
Frequency [Hz]	9.6	38.2	48.3	91.5	118.1

Computational model and flow conditions

AGARD wing 445.6

- Number of grid points
  : 96 × 39 × 28
- Computational domain
  : 30 root chord lengths
- Minimum grid spacing
  : 10^{-2} root chord length

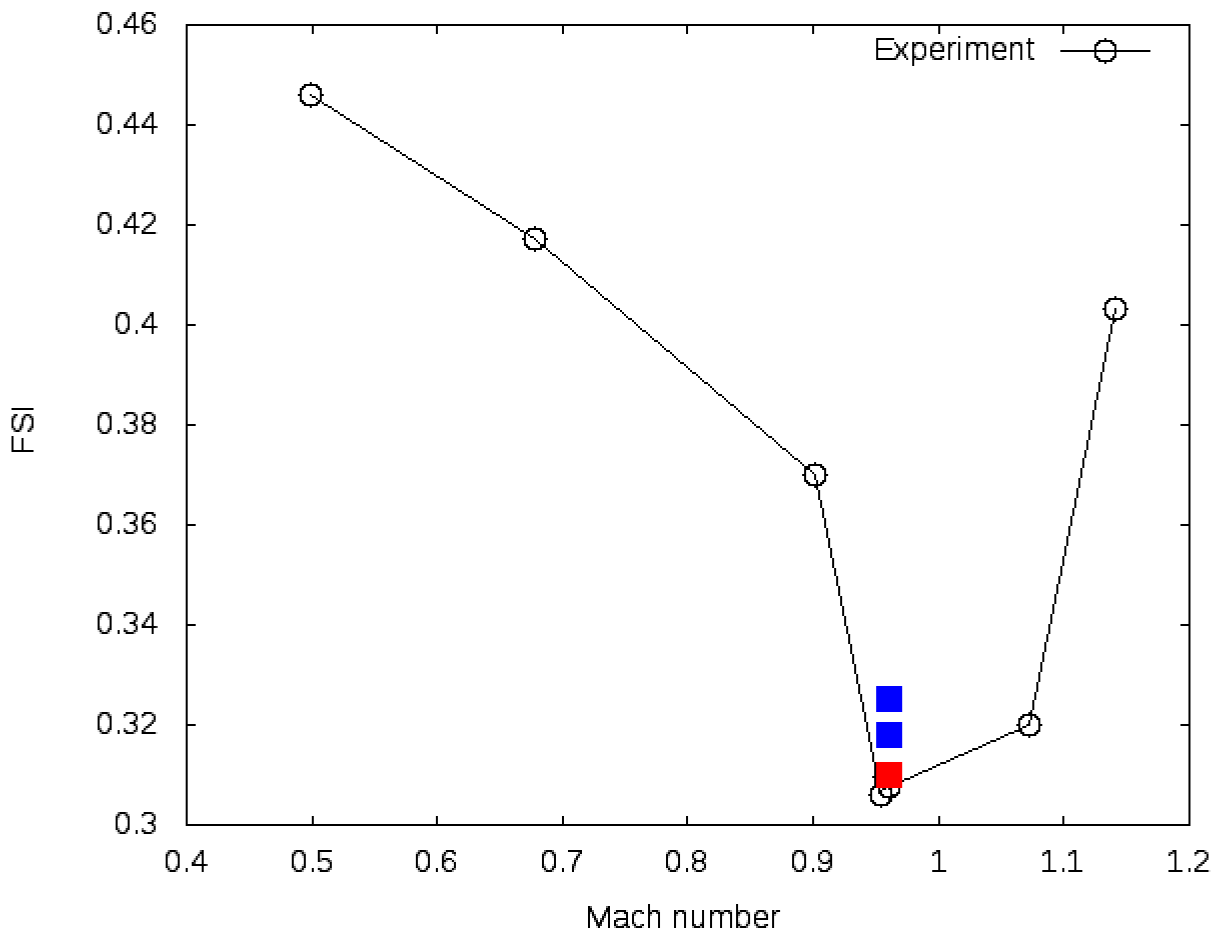


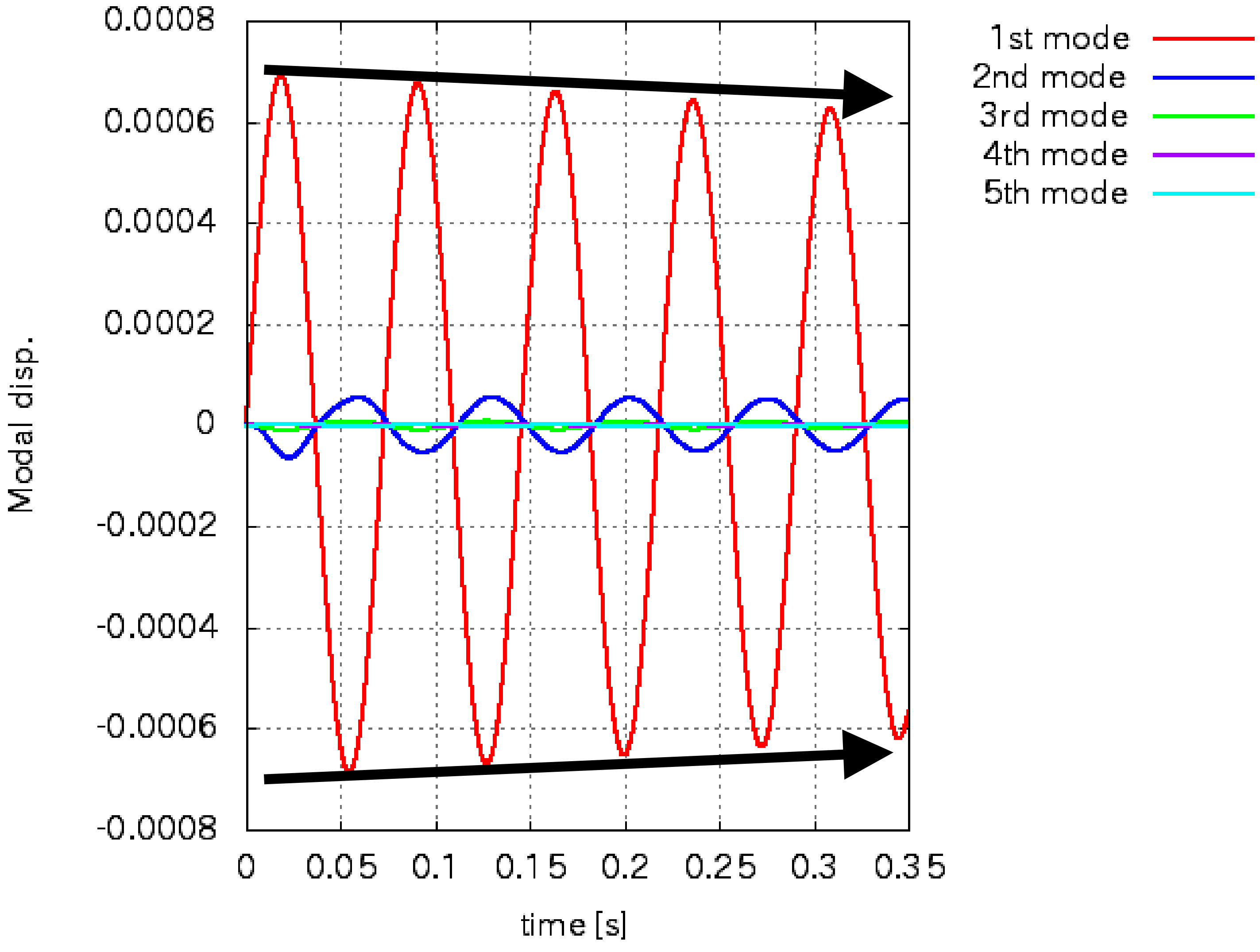
Flow conditions

- Mach number : 0.678, 0.901, 0.96, 1.072
- Angle of attack : 0.0 [deg.]

Computed results of damping response

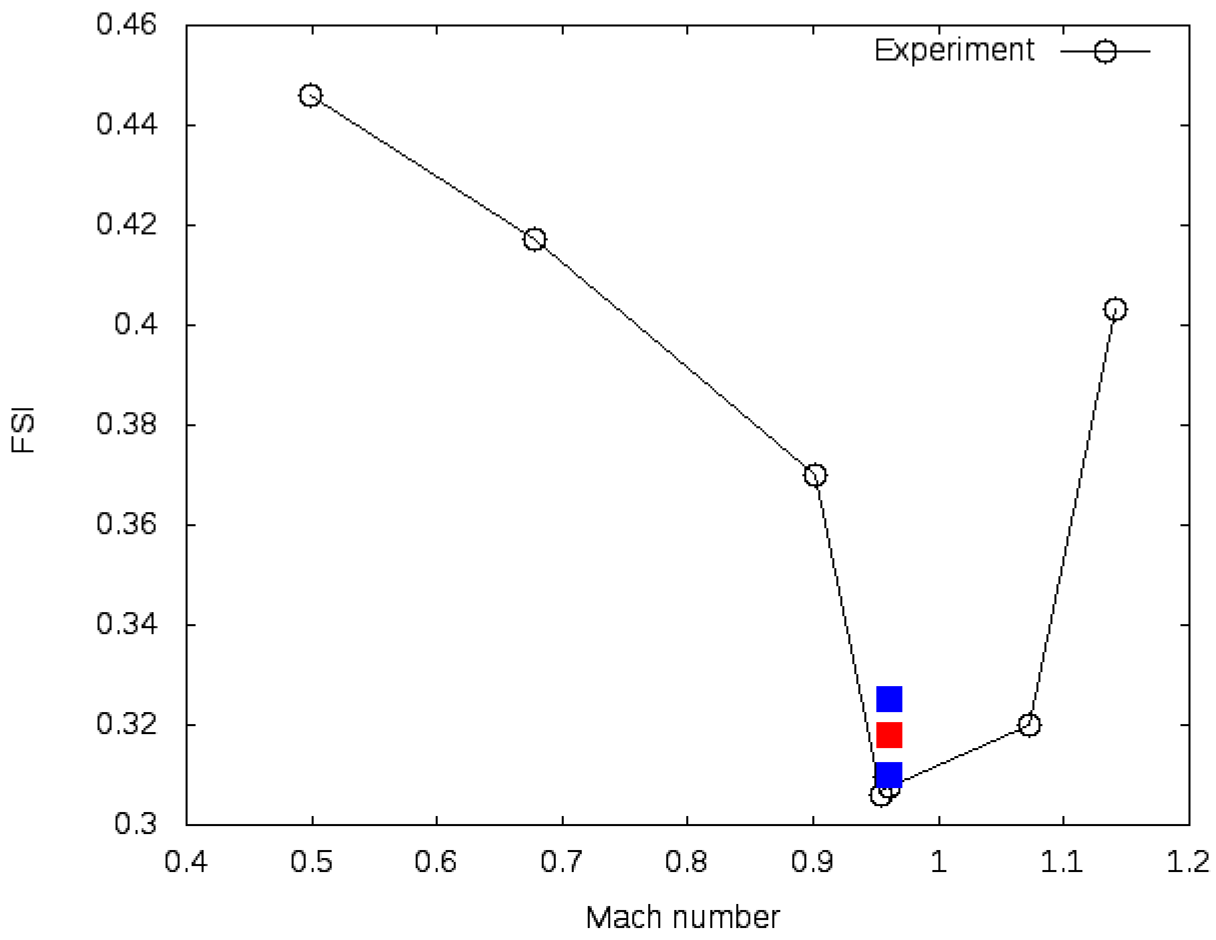
Mach number=0.96, FSI=0.31

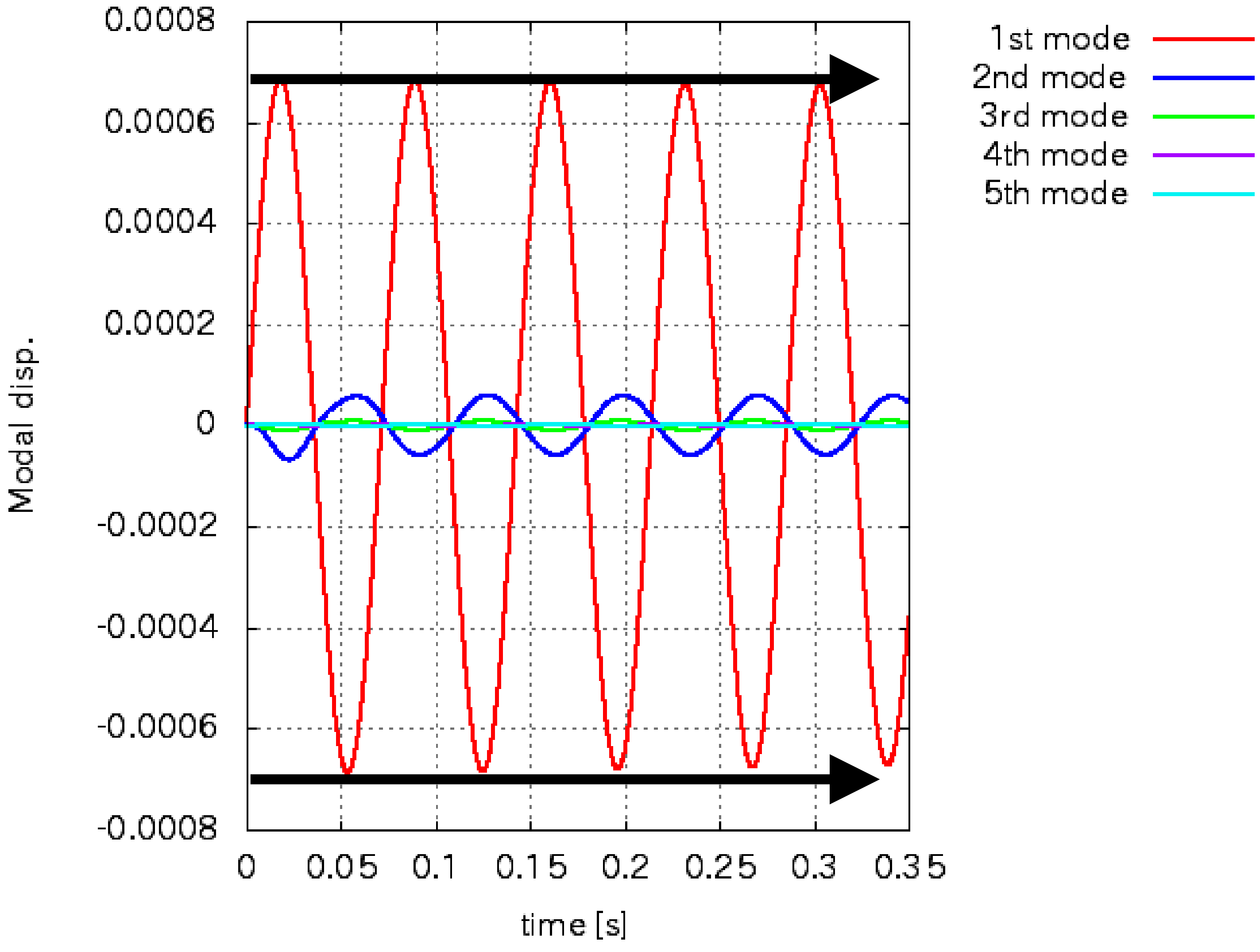




Computed results of neutral response

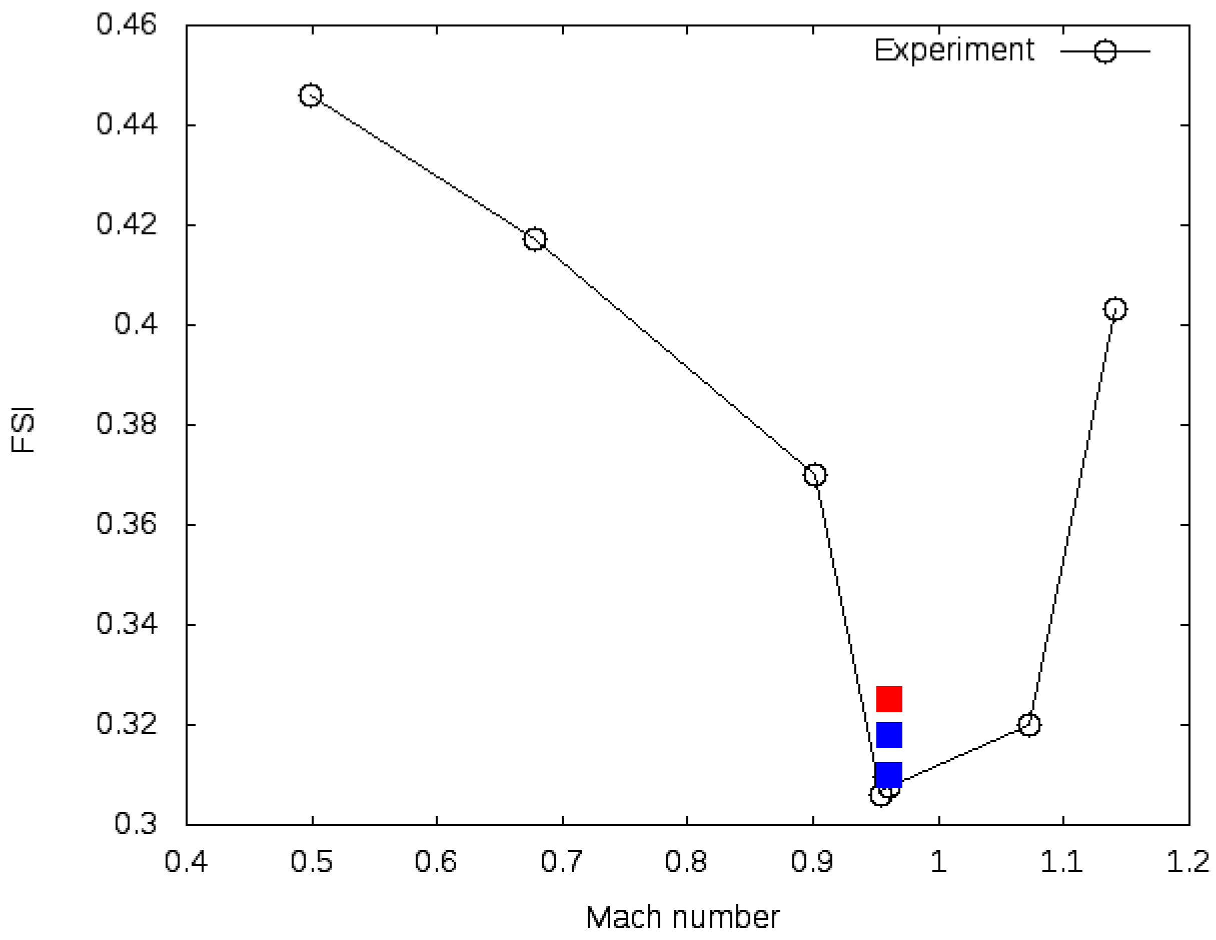
Mach number=0.96, FSI=0.318

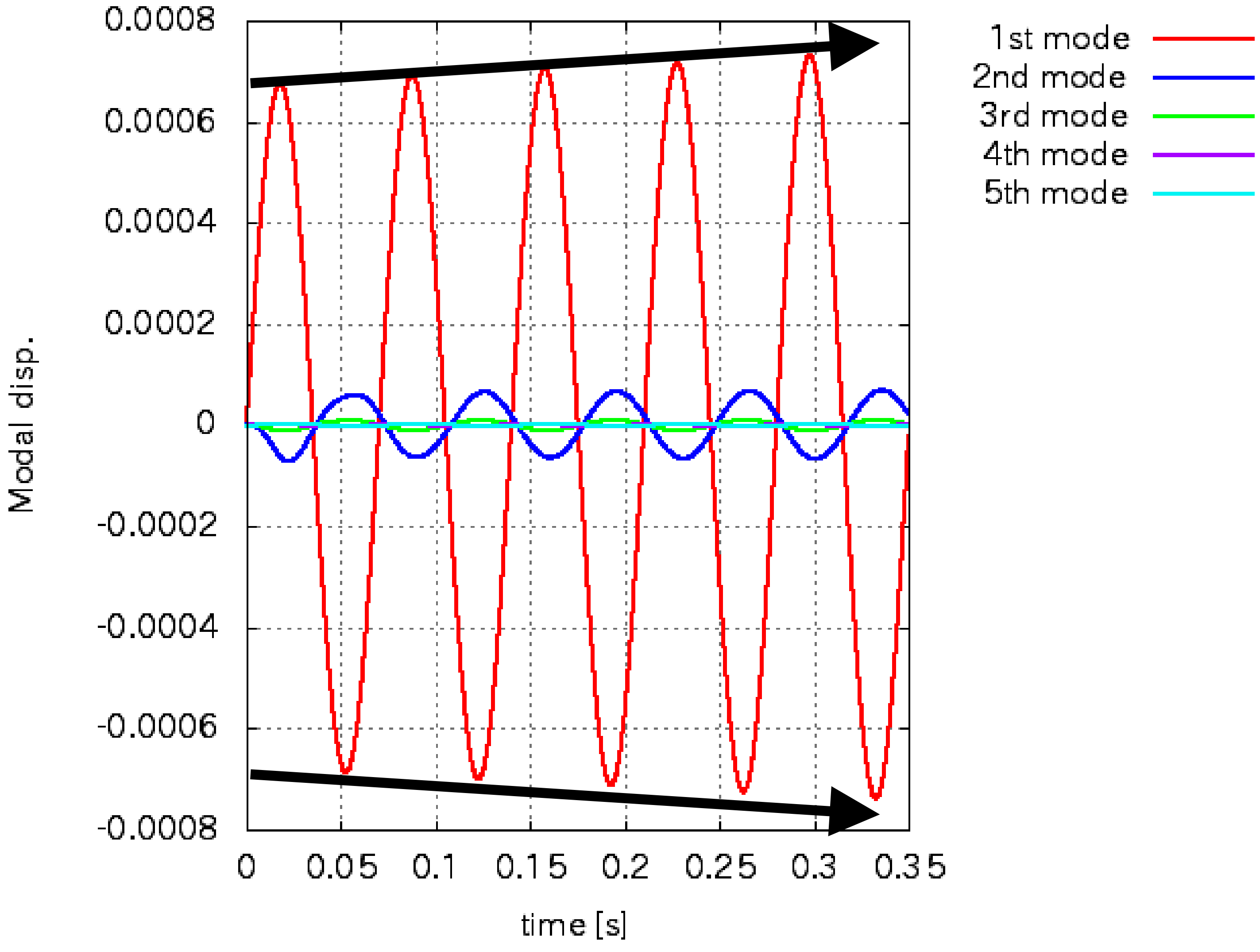




Computed results of diverging response

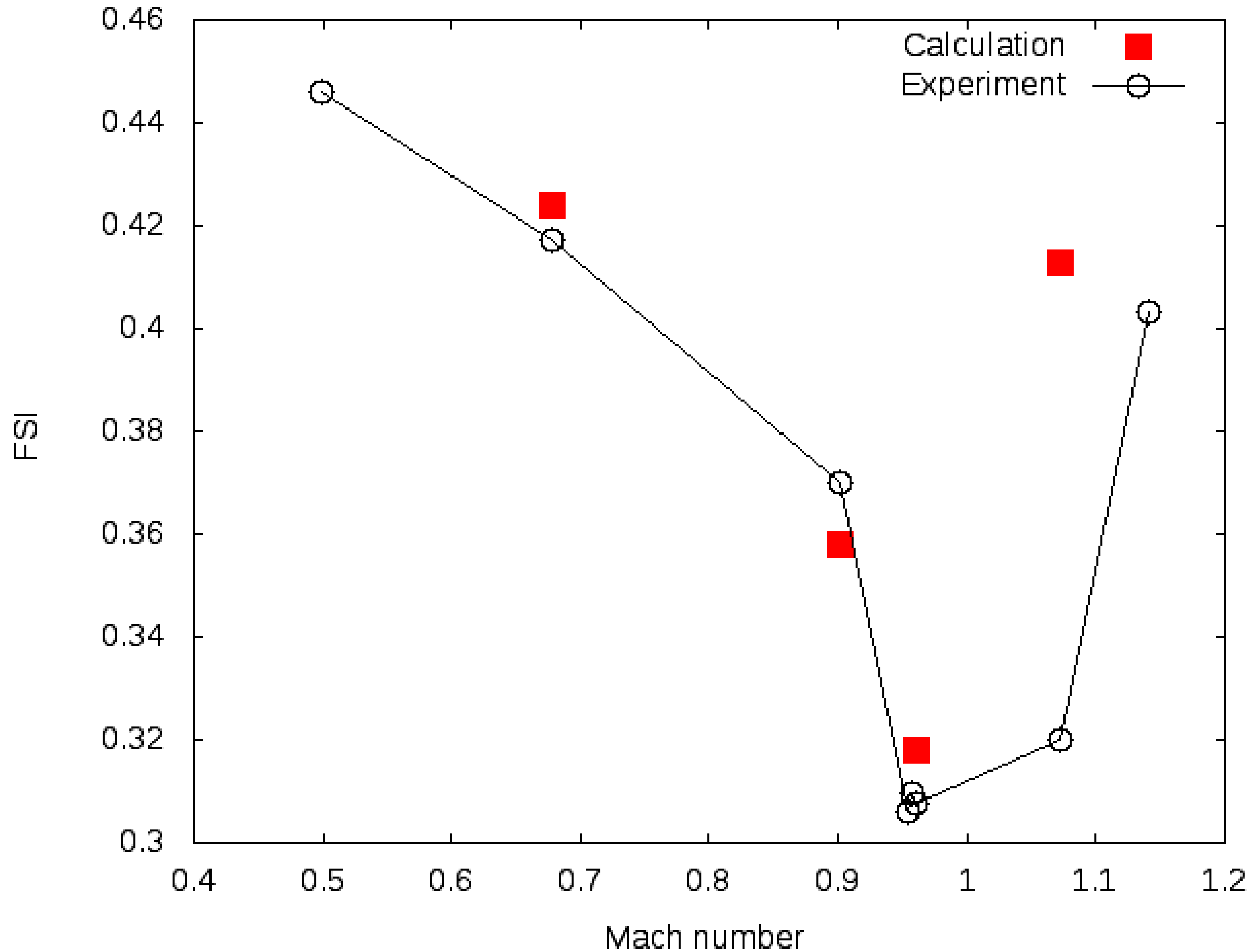
Mach number=0.96, FSI=0.325





Flutter analysis results for AGARD wing 445.6

For other Mach numbers, FSI calculations are conducted in the same way



Summary

- Successfully developed an unsteady flow calculation code based on Moving Grid Finite Volume Method
- Code validation studies for steady and unsteady flows
  - Reasonable agreements are indicated
- Preliminary flutter analysis is attempted
  - Computed flutter boundaries show reasonable agreements with experimental data

Future works

- Account for viscous effects
- Unstructured grid for including engine nacelles
- Composite wing

Back up

Background

Wing flutter

- Aeroelastic phenomenon
- Diverging vibration of a wing which possibly causes wing destruction

Airplane design with a composite wing

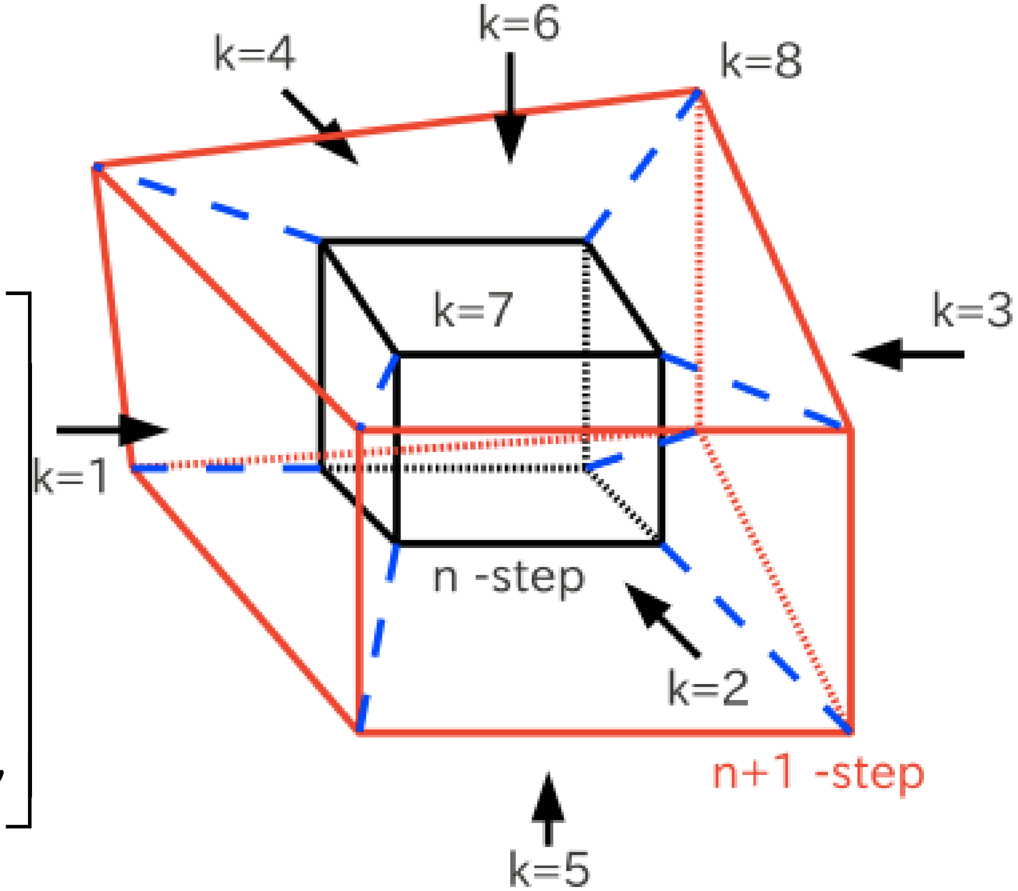
- Flutter characteristics can be degraded by decreased stiffness
- Accurate prediction capability for flutter boundary needs to be established
  - Numerical simulation
  - Wing tunnel testing

Moving Grid FVM

Integrate three-dimensional Euler eqs. in time and space

$$\iiiint_{\Omega}\left(\frac{\partial \mathbf{Q}}{\partial t}+\frac{\partial \mathbf{E}}{\partial x}+\frac{\partial \mathbf{F}}{\partial y}+\frac{\partial \mathbf{G}}{\partial z}\right)d\Omega=\mathbf{0}$$

$$\mathbf{Q}=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ e\end{bmatrix},\mathbf{E}=\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ \rho uw\\ (e+p)u\end{bmatrix},\mathbf{F}=\begin{bmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ \rho vw\\ (e+p)v\end{bmatrix},\mathbf{G}=\begin{bmatrix}\rho w\\ \rho uw\\ \rho vw\\ \rho w^2+p\\ (e+p)w\end{bmatrix}$$



Apply Gauss's divergence theorem to above eqs.

$$\mathbf{Q}^{n+1}V_8-\mathbf{Q}^{n}V_7$$

$$+\sum_{k=1}^{6}(\mathbf{Q}^{n+\frac{1}{2}}n_t+\mathbf{E}^{n+\frac{1}{2}}n_x+\mathbf{F}^{n+\frac{1}{2}}n_y+\mathbf{G}^{n+\frac{1}{2}}n_z)_k V_k=\mathbf{0}$$

Take average of n -step and n+1 –step

$$\mathbf{Q}^{n+1}V_8 - \mathbf{Q}^n V_7$$

$$+\sum_{k=1}^{6}[\frac{1}{2}(\mathbf{Q}^{n+1}n_t + \mathbf{E}^{n+1}n_x + \mathbf{F}^{n+1}n_y + \mathbf{G}^{n+1}n_z)_k V_k$$

$$+\frac{1}{2}(\mathbf{Q}^n n_t + \mathbf{E}^n n_x + \mathbf{F}^n n_y + \mathbf{G}^n n_z)_k V_k] = 0$$

Apply inner iteration method

$$\mathbf{Q}^{(m)}V_8 + \Delta\mathbf{Q}^{(m)}V_8 - \mathbf{Q}^n V_7$$

$$+\sum_{k=1}^{6}[\frac{1}{2}\{(\mathbf{Q}^{(m)} + \Delta\mathbf{Q}^{(m)})n_t + \mathbf{E}^{(m+1)}n_x + \mathbf{F}^{(m+1)}n_y + \mathbf{G}^{(m+1)}n_z\}_k V_k$$

$$+\frac{1}{2}(\mathbf{Q}^n n_t + \mathbf{E}^n n_x + \mathbf{F}^n n_y + \mathbf{G}^n n_z)_k V_k] = 0$$

Moving Grid FVM

Linearization of E, F and G

$$\mathbf{E}^{(m+1)} = \mathbf{E}^{(m)} + \left(\frac{\partial \mathbf{E}}{\partial \mathbf{Q}}\right)^{(m)} \Delta\mathbf{Q}^{(m)} = \mathbf{E}^{(m)} + \mathbf{A}^{(m)}\Delta\mathbf{Q}^{(m)}$$

$$\mathbf{F}^{(m+1)} = \mathbf{F}^{(m)} + \left(\frac{\partial \mathbf{F}}{\partial \mathbf{Q}}\right)^{(m)} \Delta\mathbf{Q}^{(m)} = \mathbf{F}^{(m)} + \mathbf{B}^{(m)}\Delta\mathbf{Q}^{(m)}$$

$$\mathbf{G}^{(m+1)} = \mathbf{G}^{(m)} + \left(\frac{\partial \mathbf{G}}{\partial \mathbf{Q}}\right)^{(m)} \Delta\mathbf{Q}^{(m)} = \mathbf{G}^{(m)} + \mathbf{C}^{(m)}\Delta\mathbf{Q}^{(m)}$$

Finally the eqs. below are solved

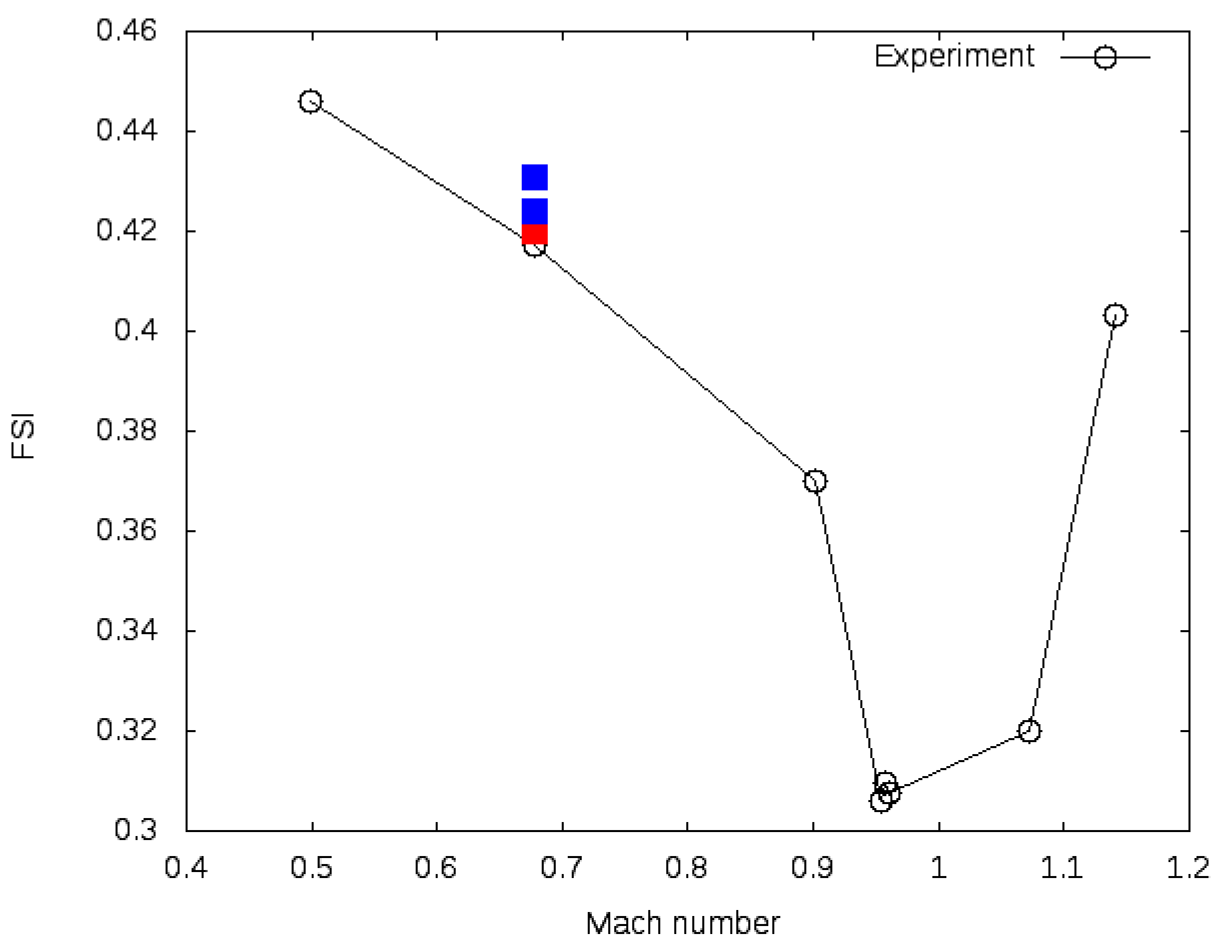
$$[\mathbf{I} + \frac{1}{2V_8}\sum_{k=1}^{6}(\mathbf{I}n_t + \mathbf{A}^{(m)}n_x + \mathbf{B}^{(m)}n_y + \mathbf{C}^{(m)}n_z)_k V_k]\Delta\mathbf{Q}^{(m)} =$$

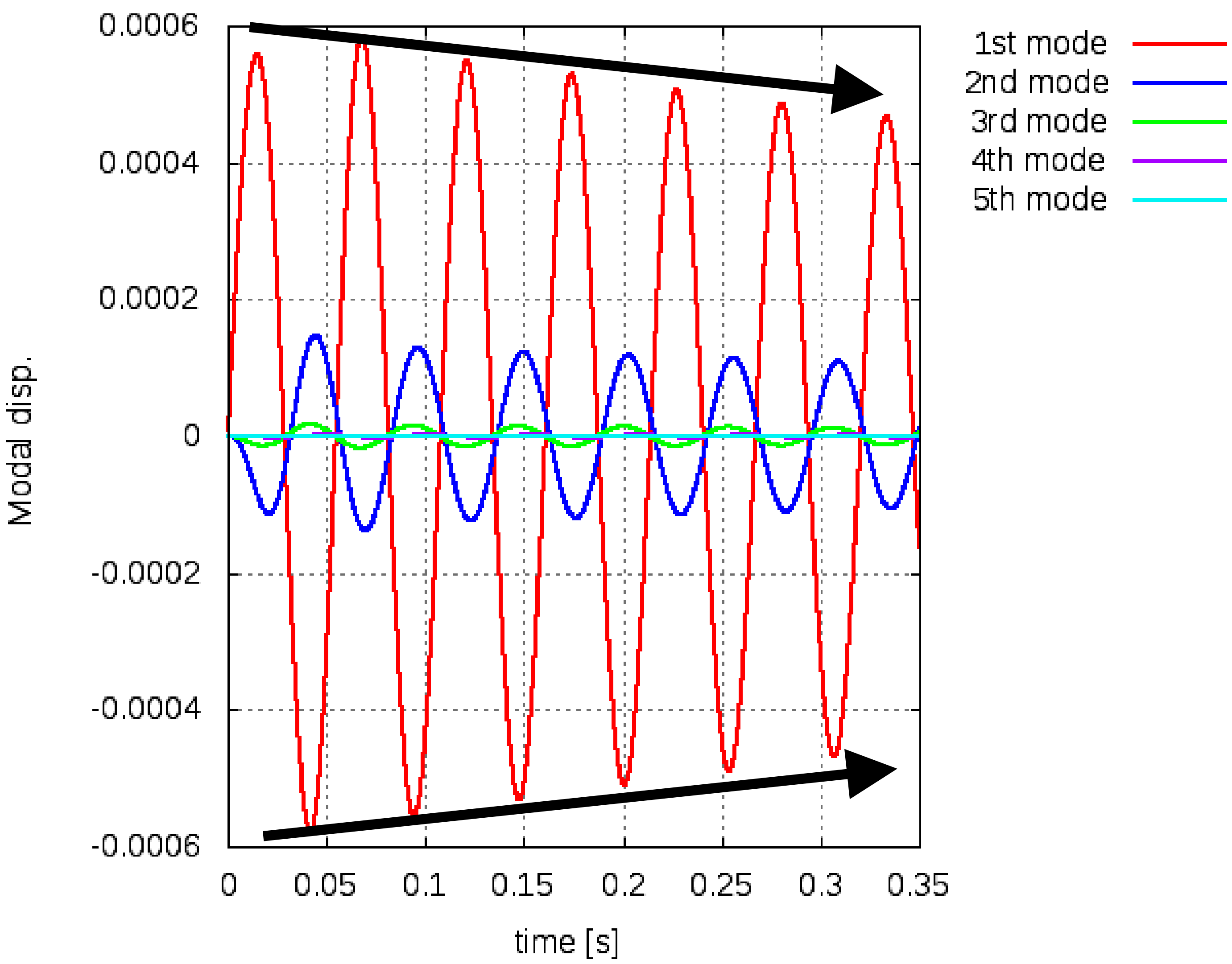
$$-\frac{1}{V_8}[\mathbf{Q}^{(m)}V_8 - \mathbf{Q}^{n}V_7 + \sum_{k=1}^{6}\frac{1}{2}(\mathbf{Q}^{(m)}n_t + \mathbf{E}^{(m)}n_x + \mathbf{F}^{(m)}n_y + \mathbf{G}^{(m)}n_z)_k V_k$$

$$+\sum_{k=1}^{6}\frac{1}{2}(\mathbf{Q}^{n}n_t + \mathbf{E}^{n}n_x + \mathbf{F}^{n}n_y + \mathbf{G}^{n}n_z)_k V_k]$$

Computed results of damping response

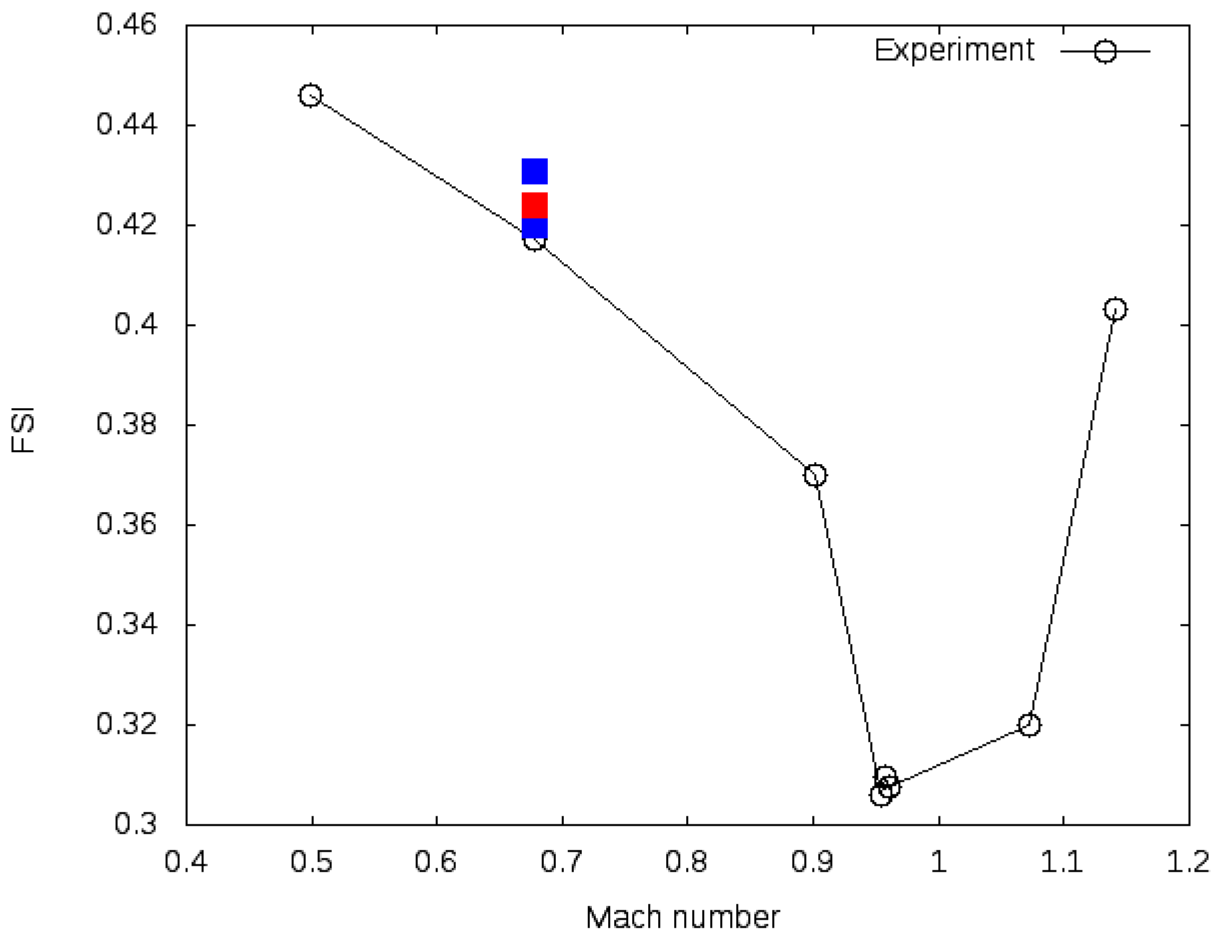
Mach number=0.678, FSI=0.421

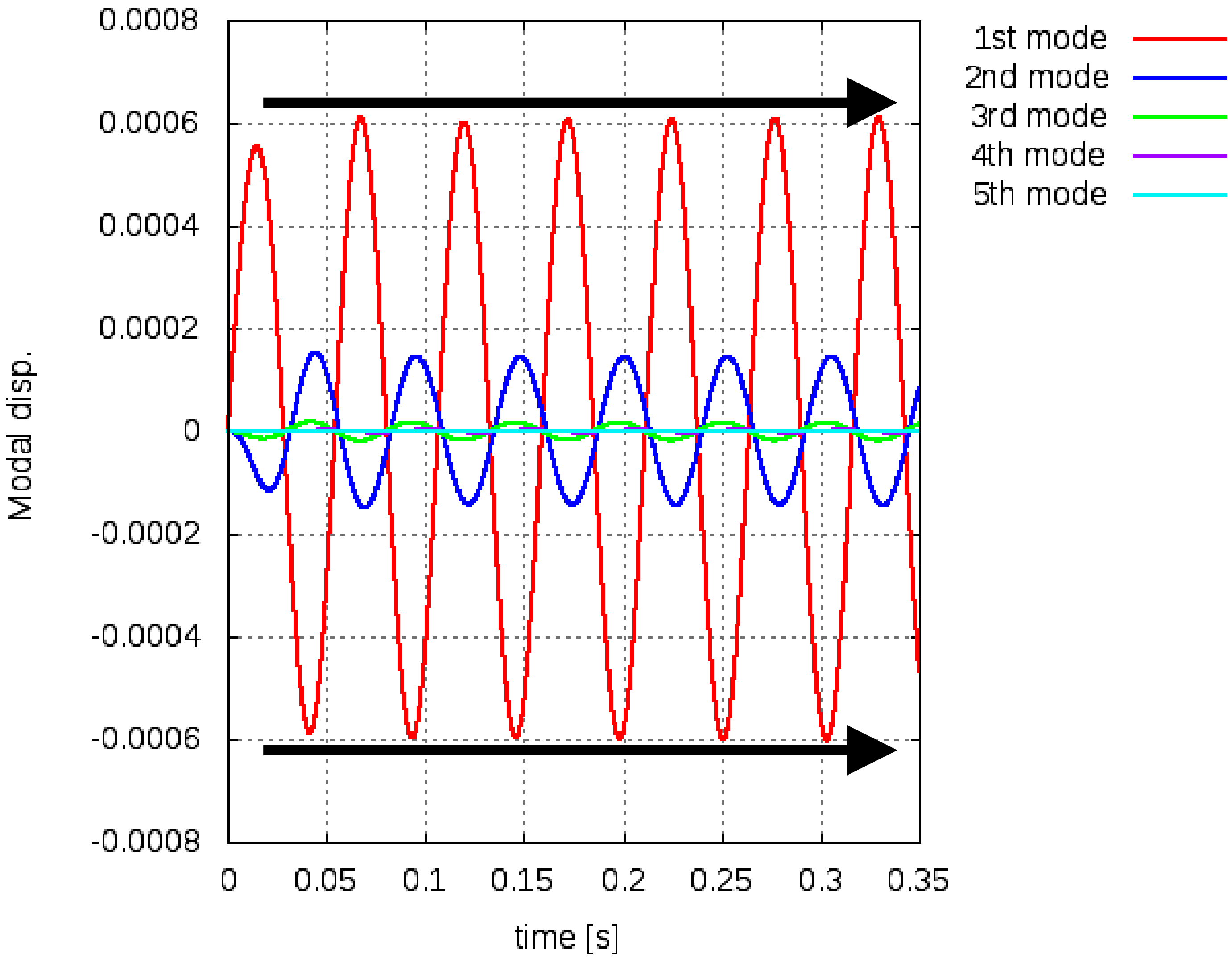




Computed results of neutral response

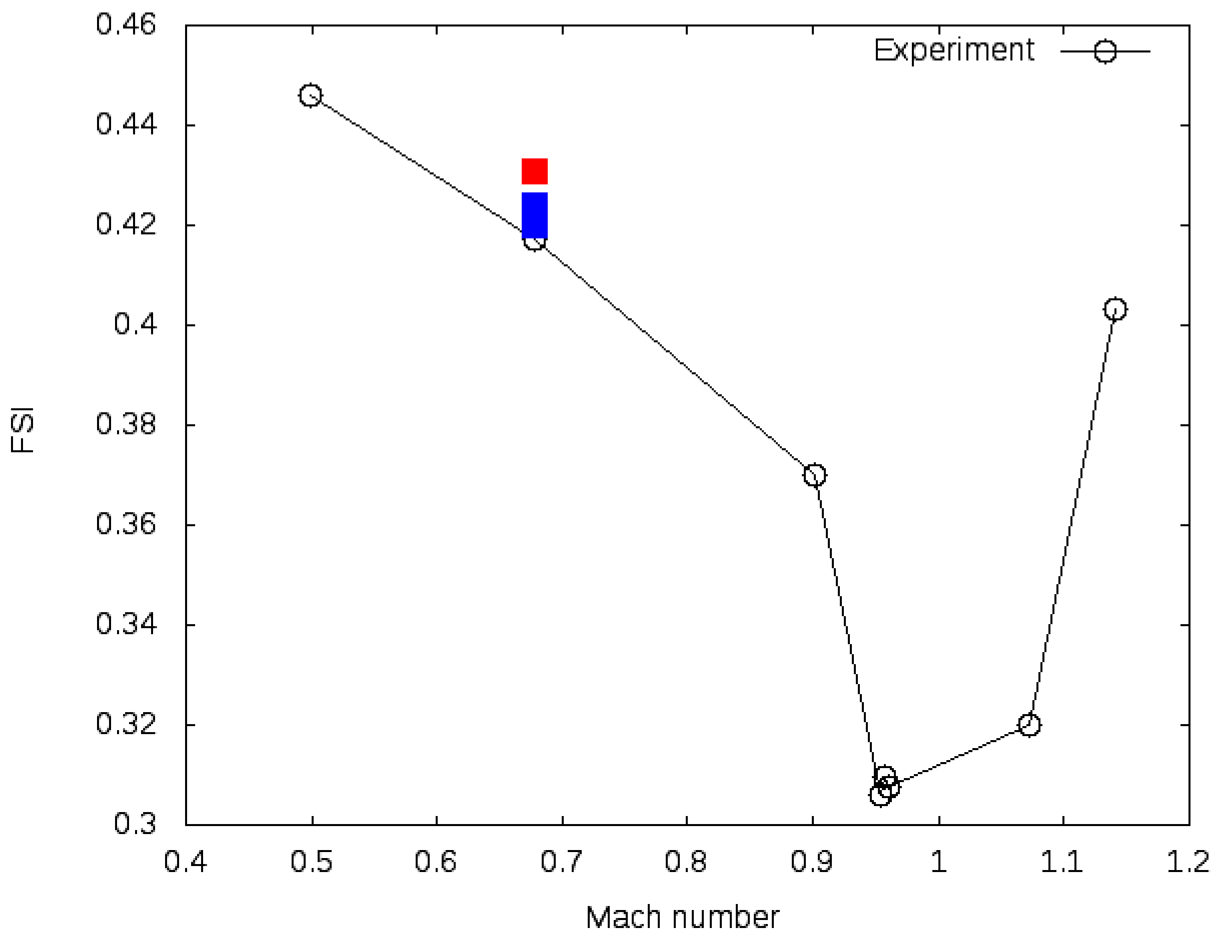
Mach number=0.678, FSI=0.424

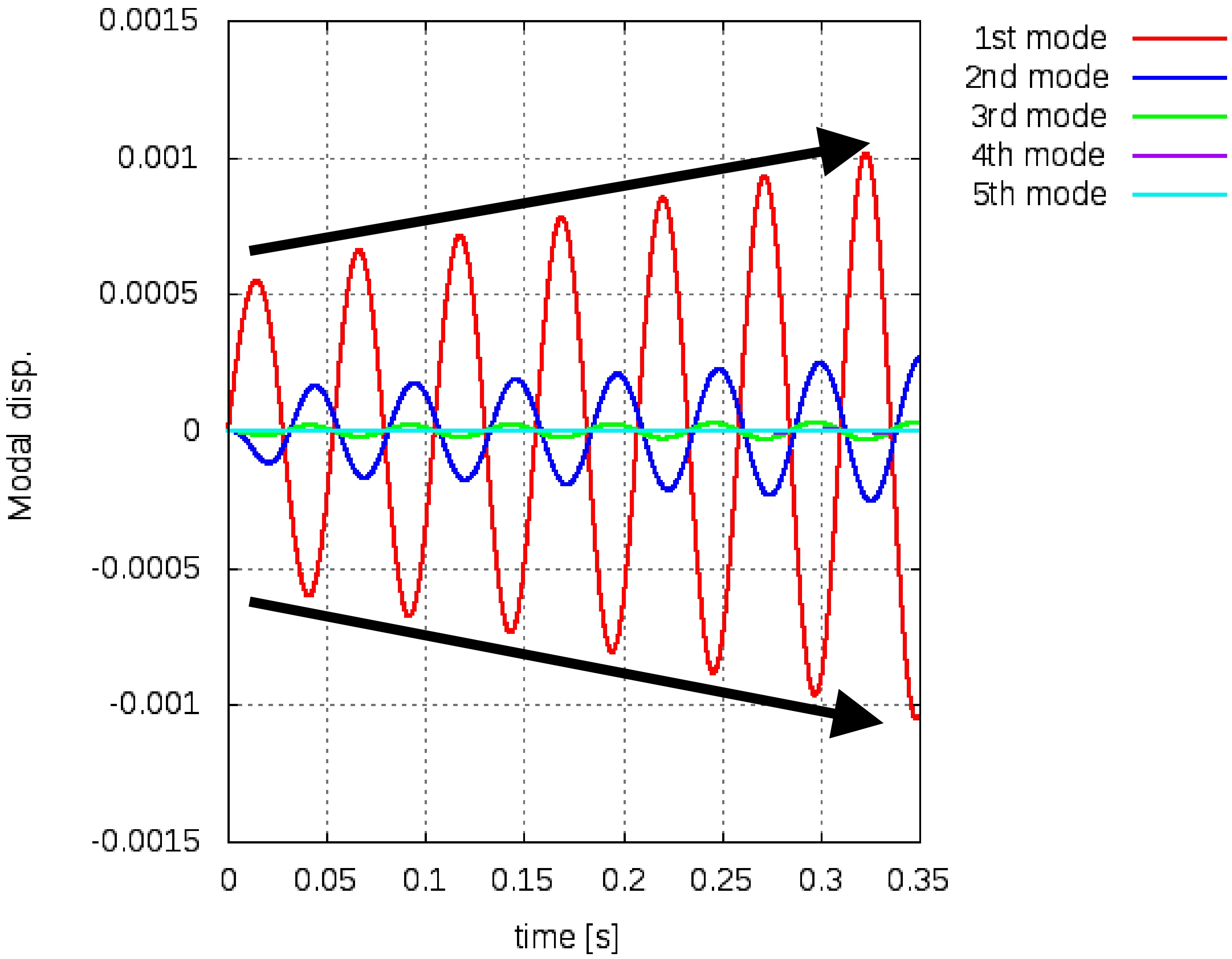




Computed results of diverging response

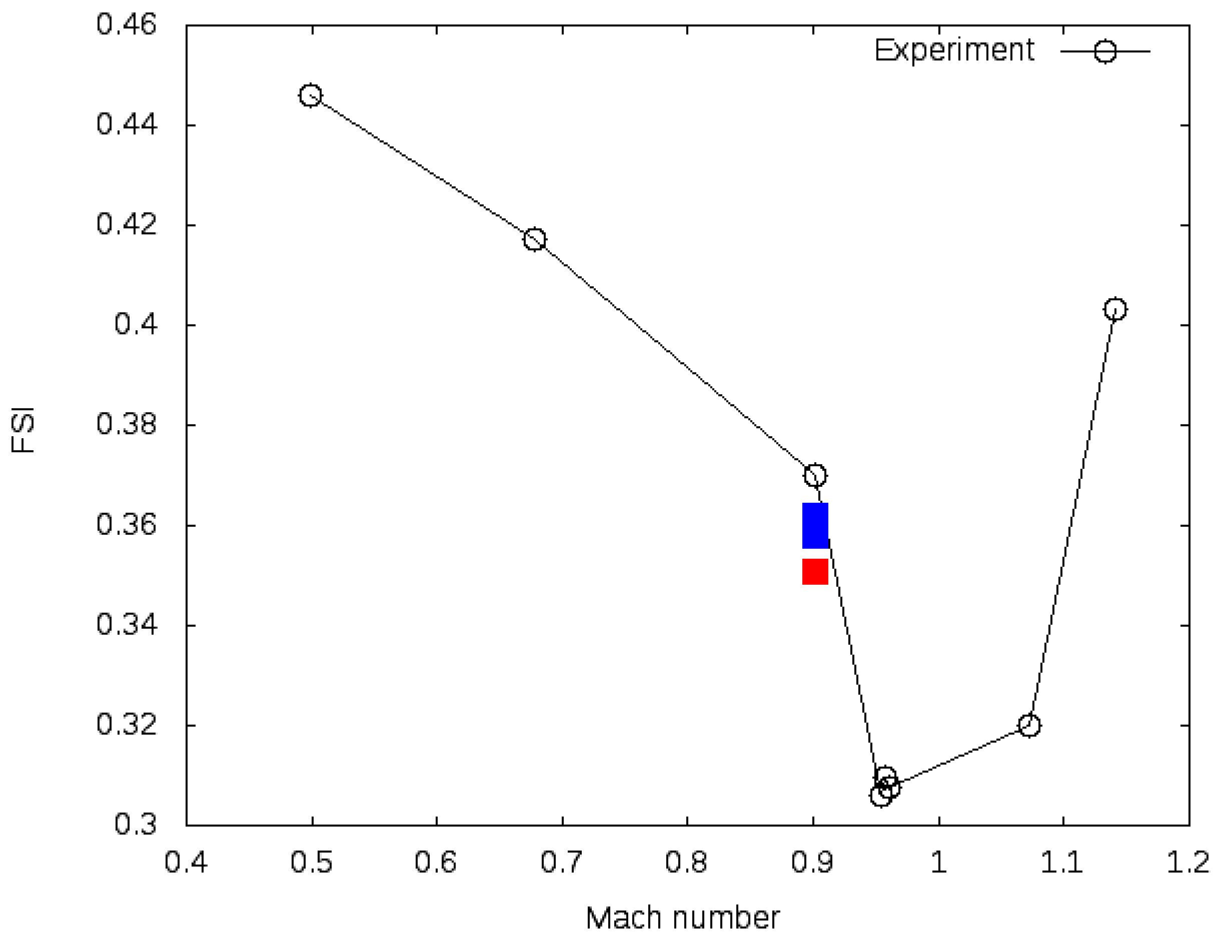
Mach number=0.678, FSI=0.430

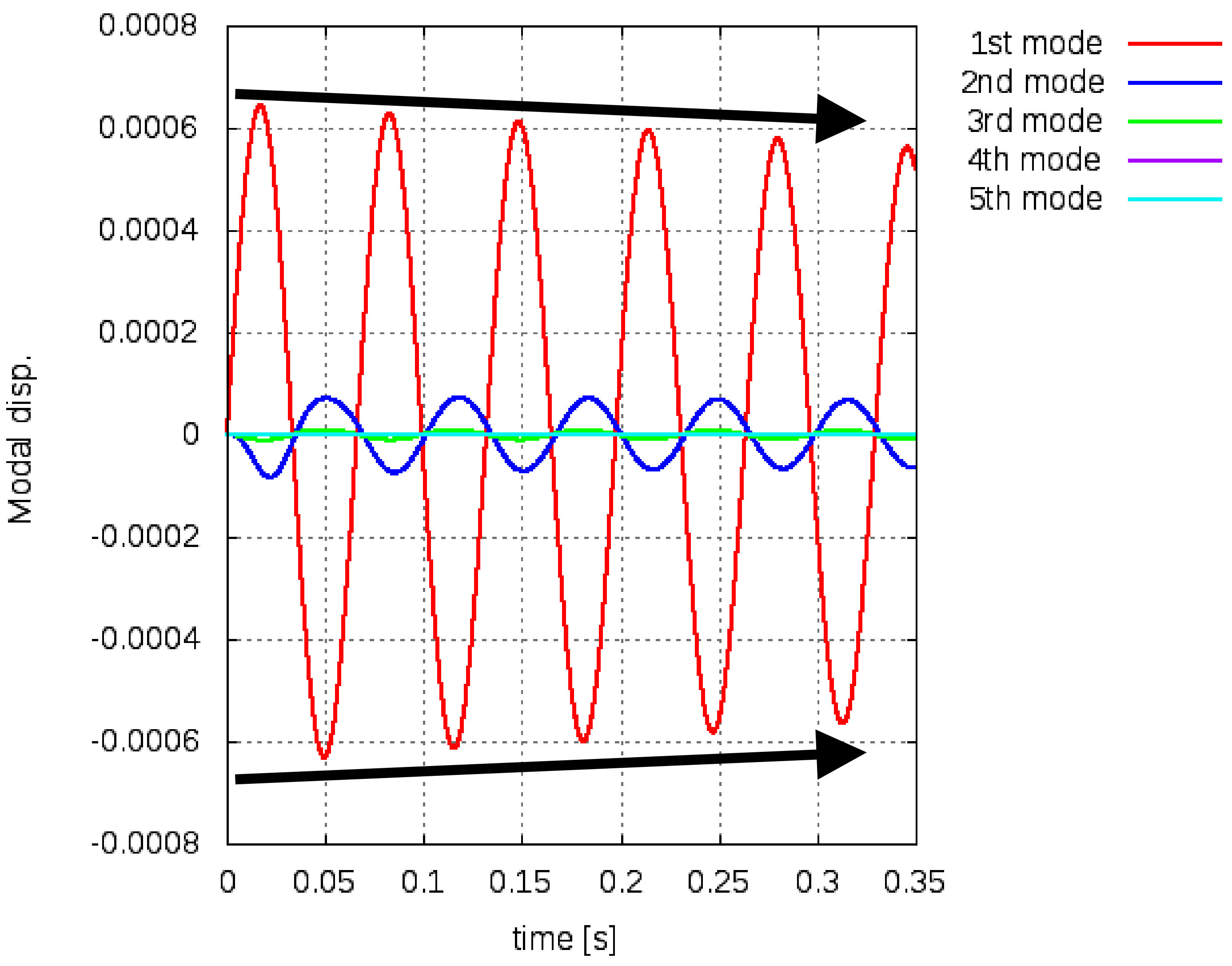




Computed results of damping response

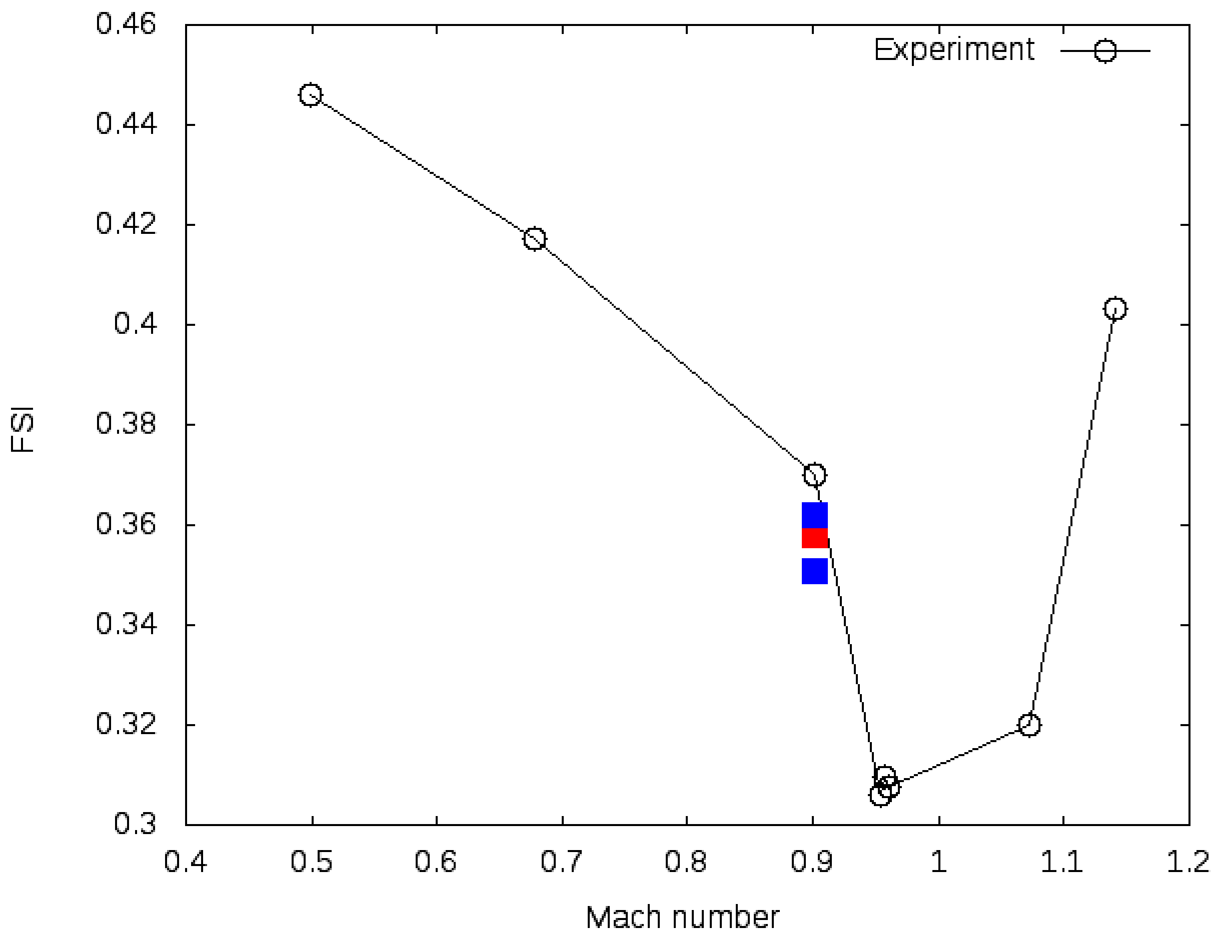
Mach number=0.901, FSI=0.351

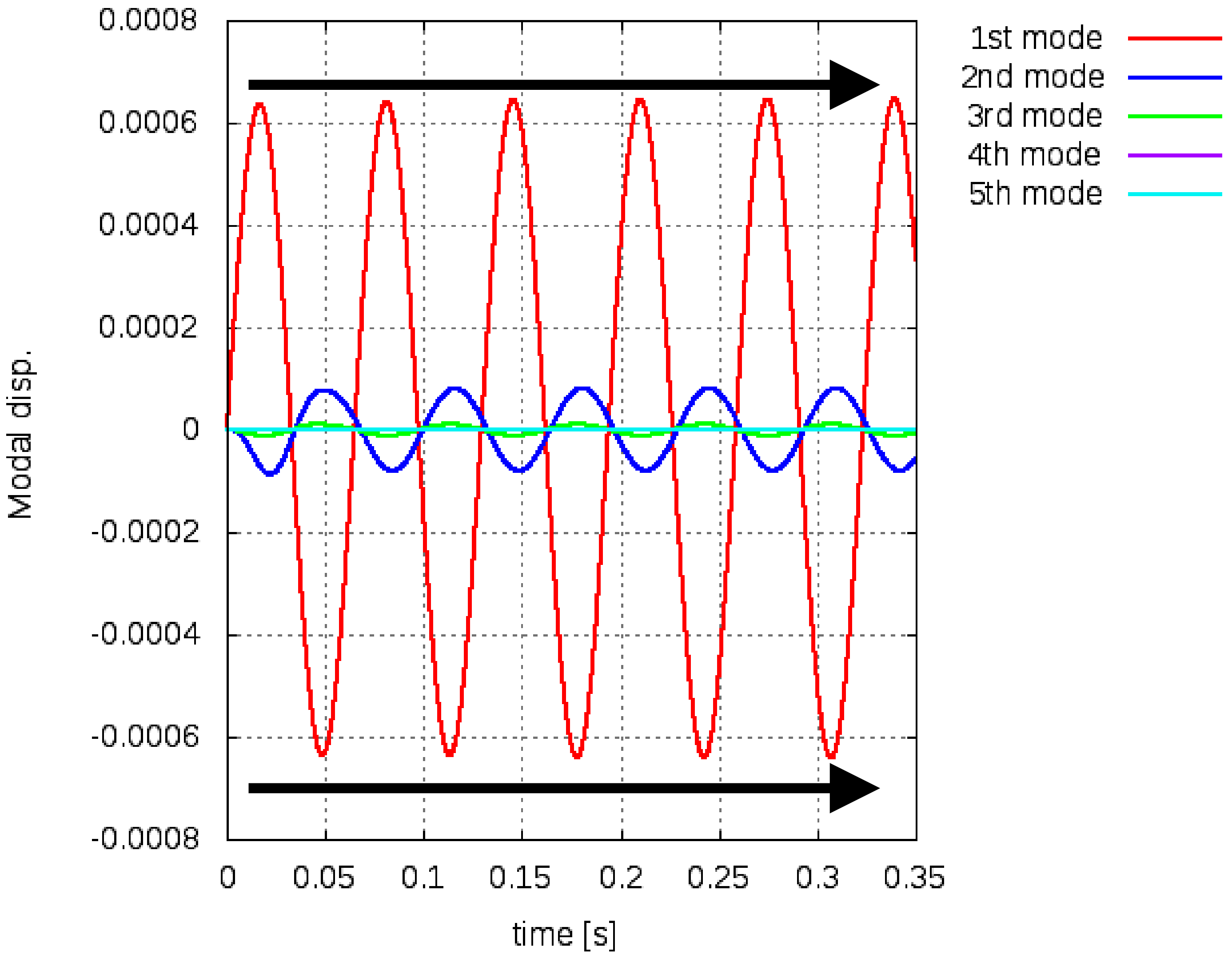




Computed results of neutral response

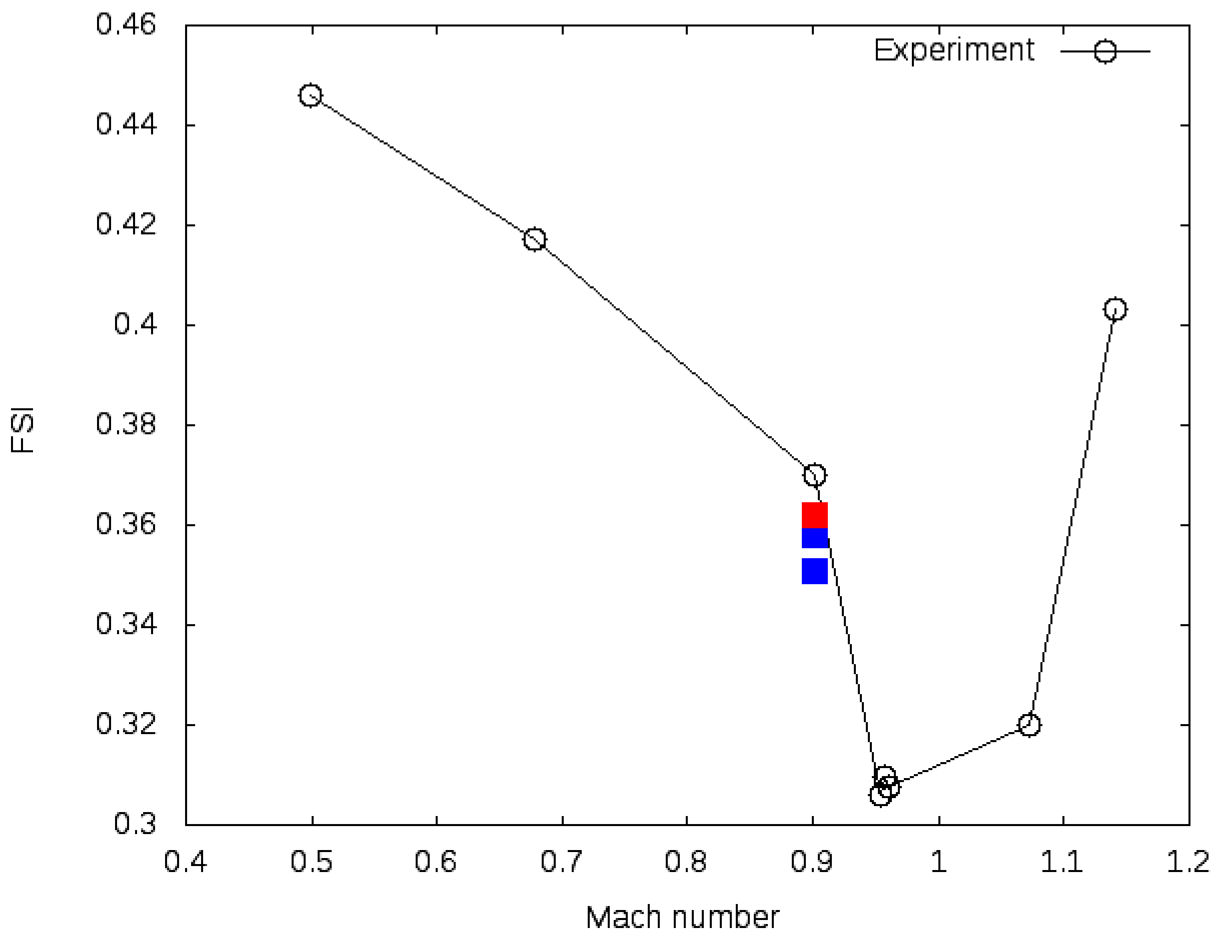
Mach number=0.901, FSI=0.358

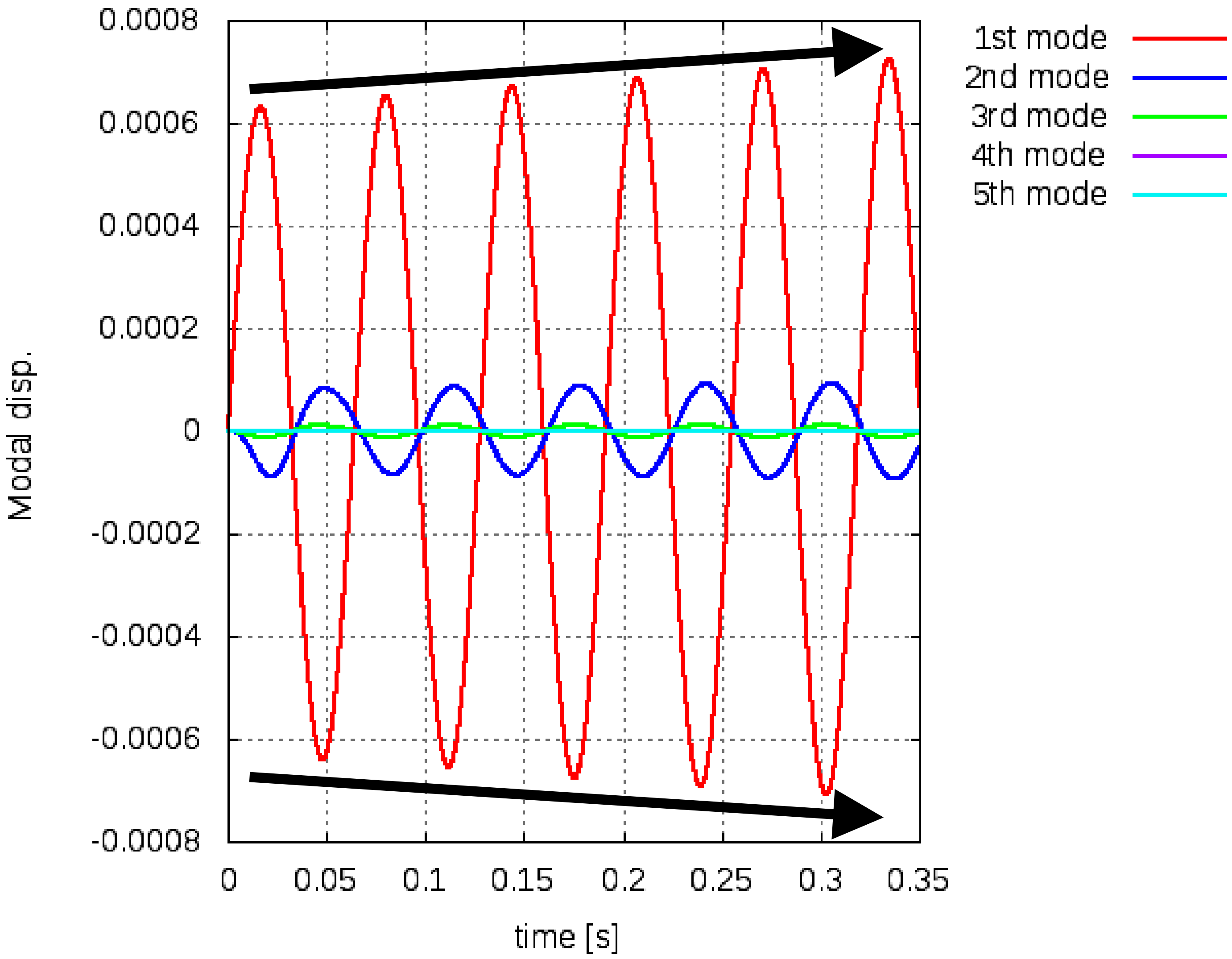




Computed results of diverging response

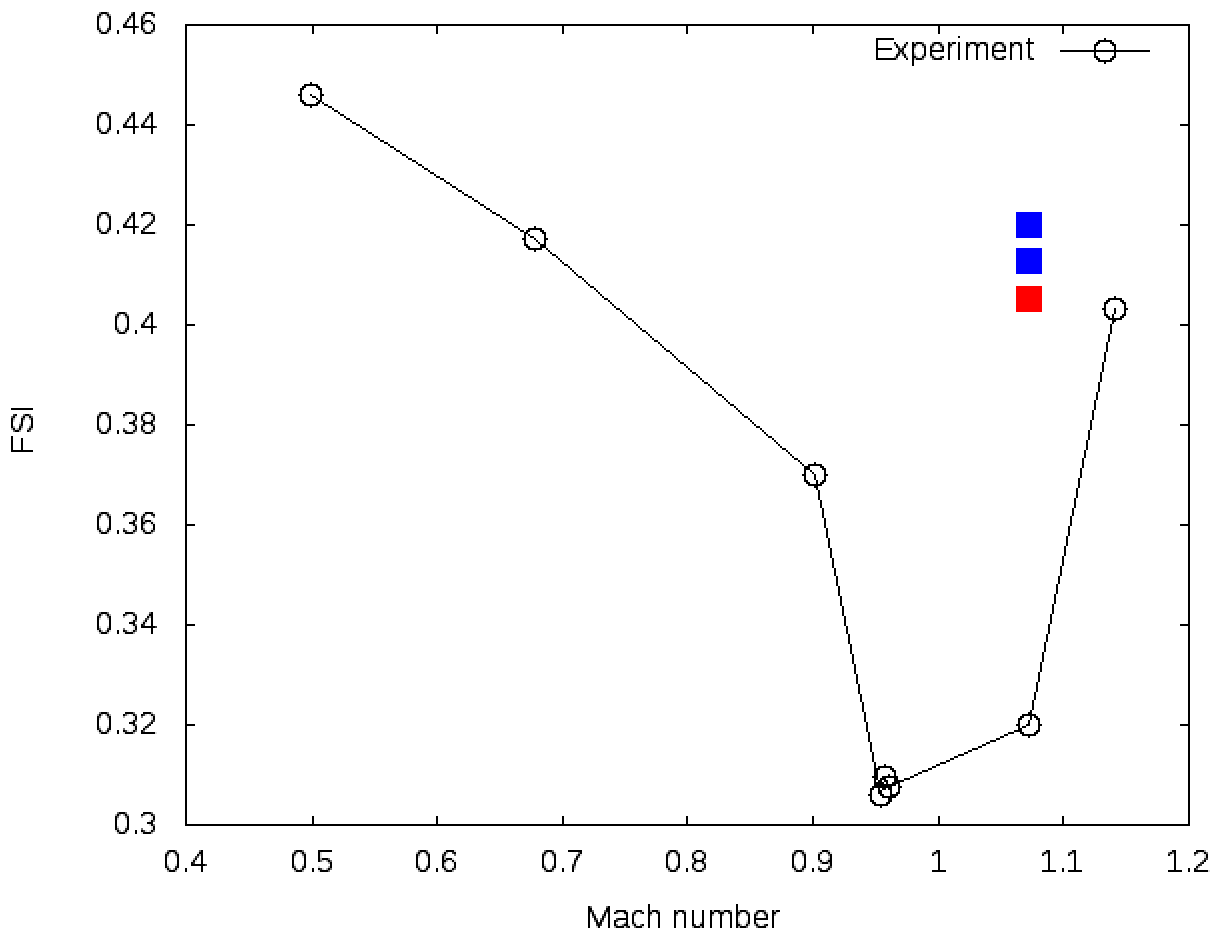
Mach number=0.901, FSI=0.362

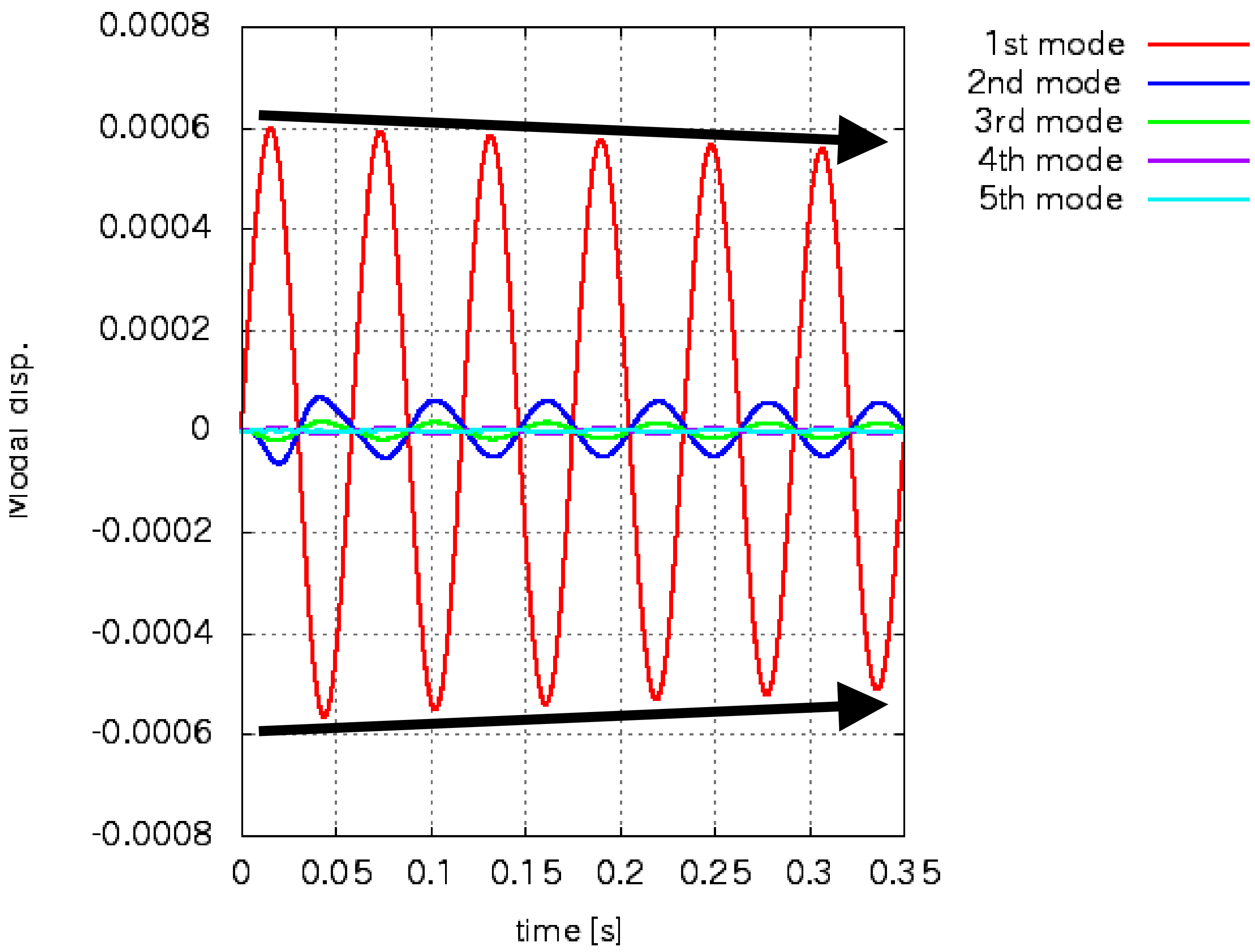




Computed results of damping response

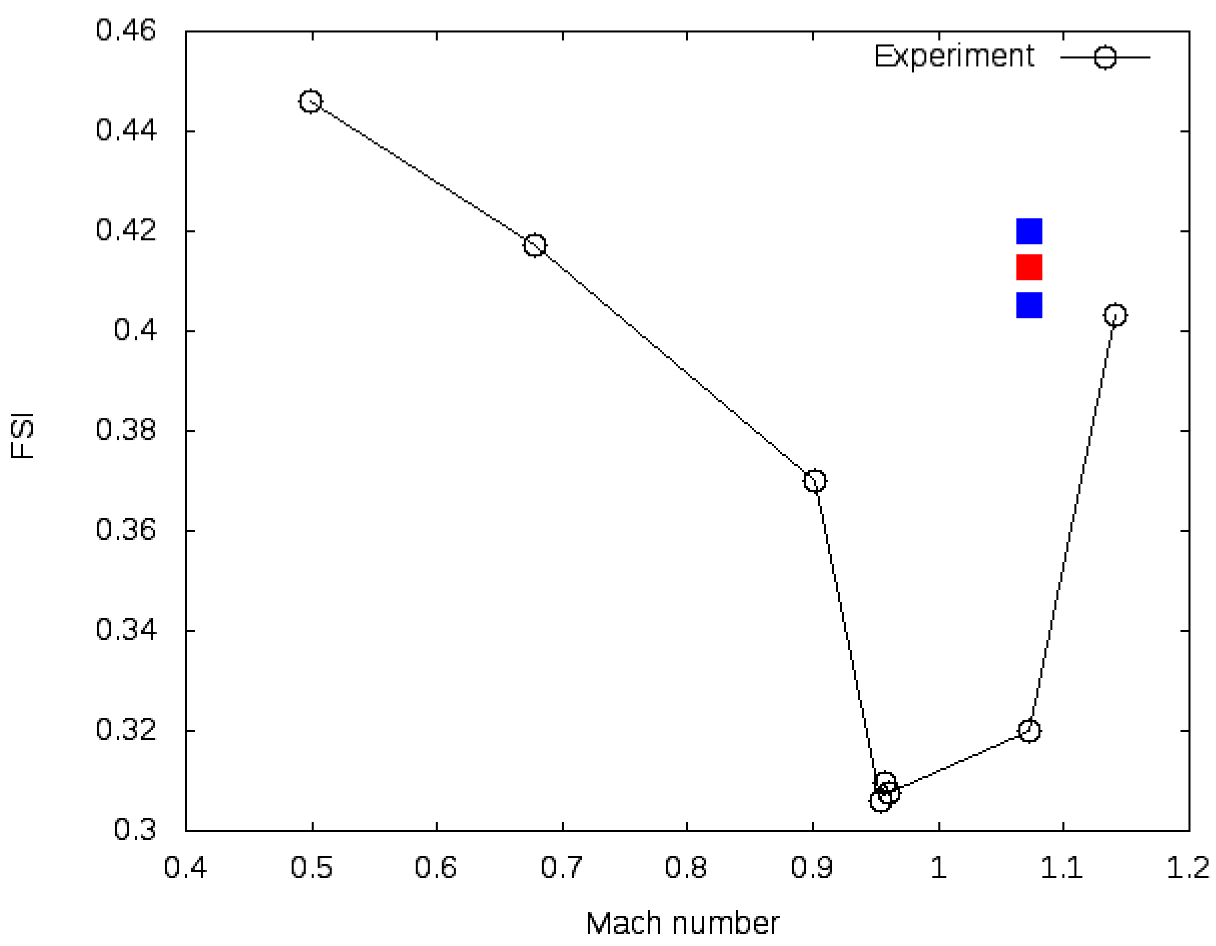
Mach number=1.072, FSI=0.405

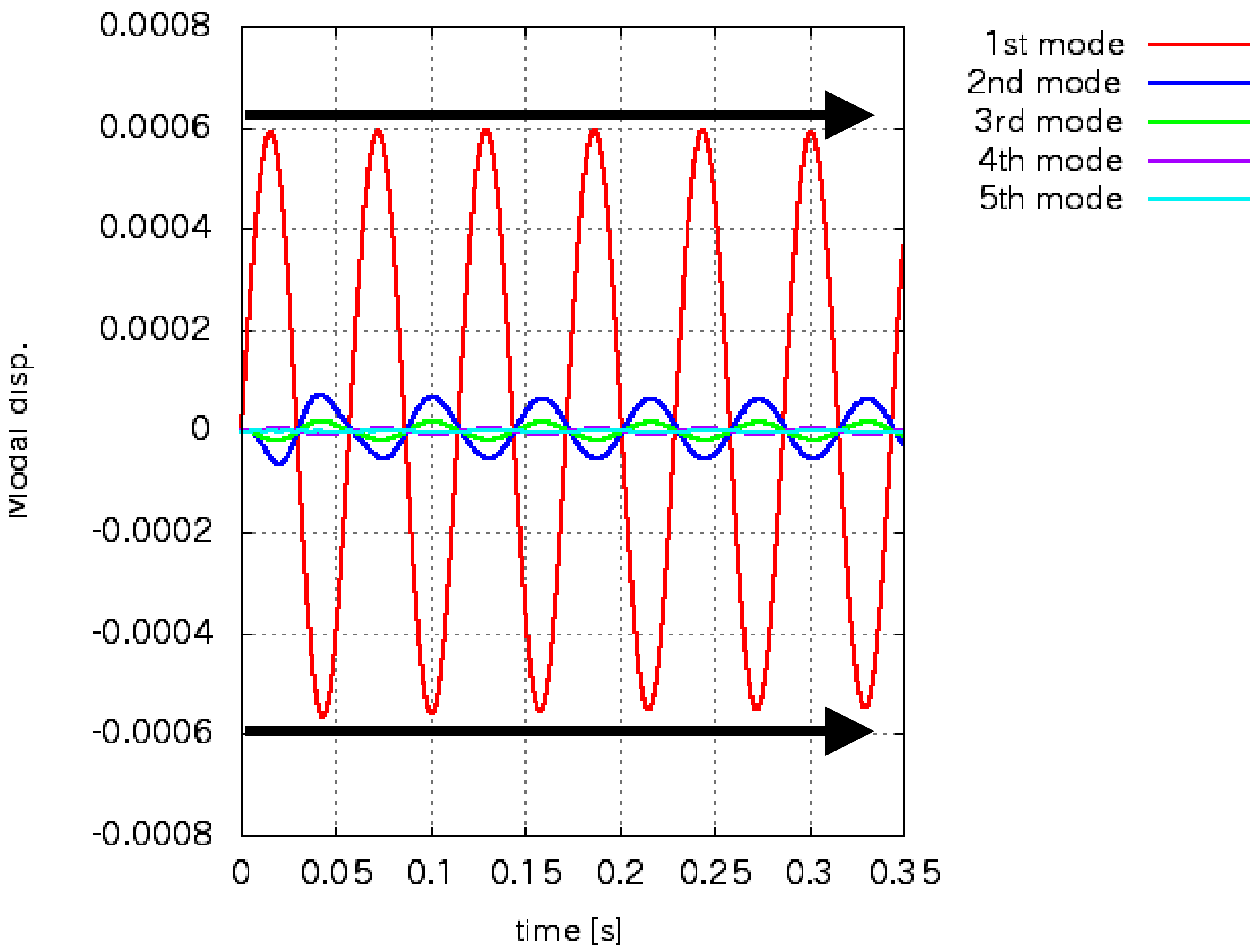




Computed results of neutral response

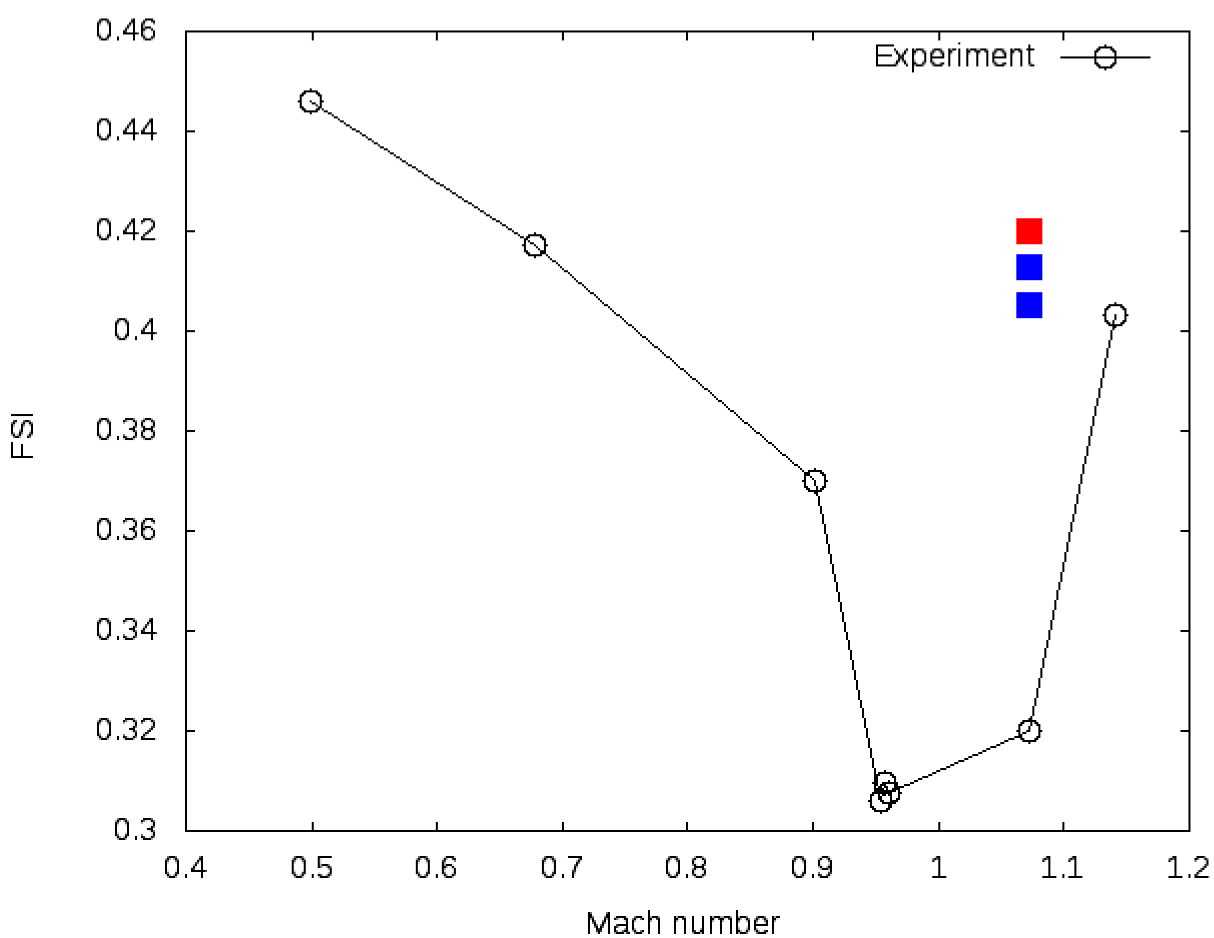
Mach number=1.072, FSI=0.413

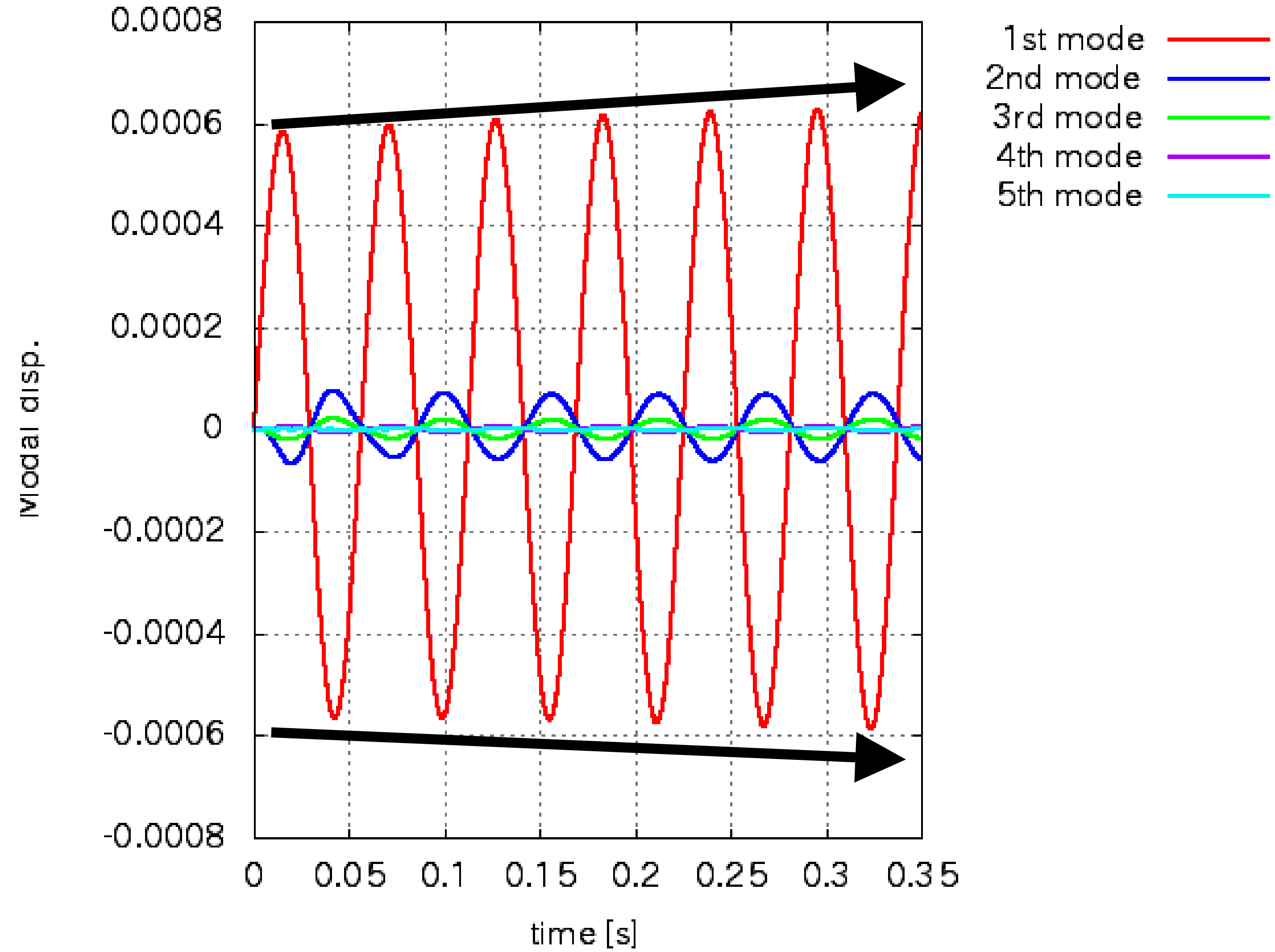




Computed results of diverging response

Mach number=1.072, FSI=0.420





Flutter Speed Index

Parameters of Flutter Speed Index

- b_s : 0.279 [m]
- ω_a : 239.8 [1/s]
- μ : 259.7
- V_∞ [m/s]

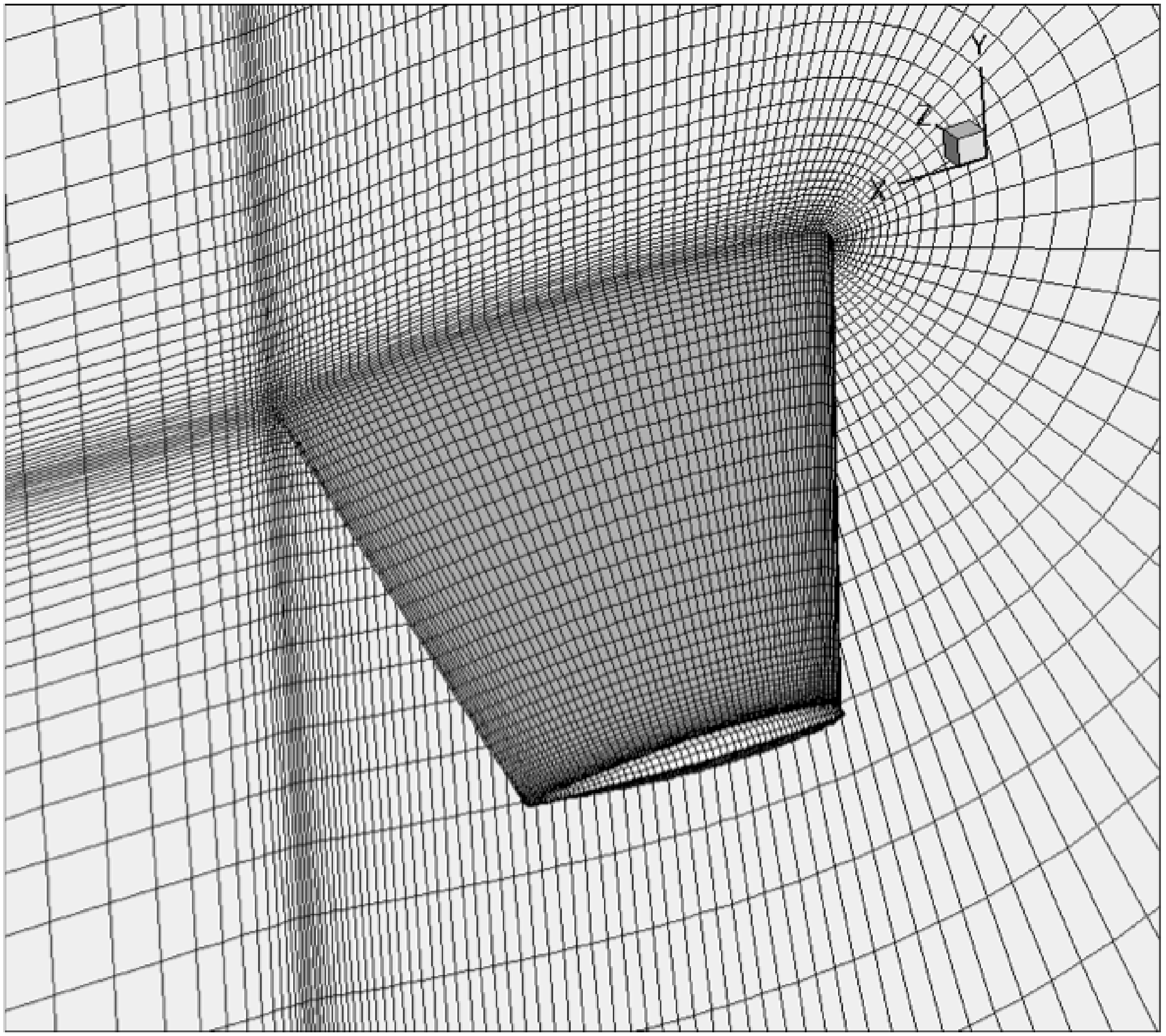
$$\text{Flutter Speed Index (FSI)} = \frac{V_\infty}{b_s \omega_a \sqrt{\mu}}$$

	Mach number of 0.678	Mach number of 0.901	Mach number of 0.96	Mach number of 1.072
Damping response	233.7	281.9	312.0	436.8
Neutral response	235.4	287.0	319.2	444.9
Diverging response	238.3	290.8	326.4	452.4

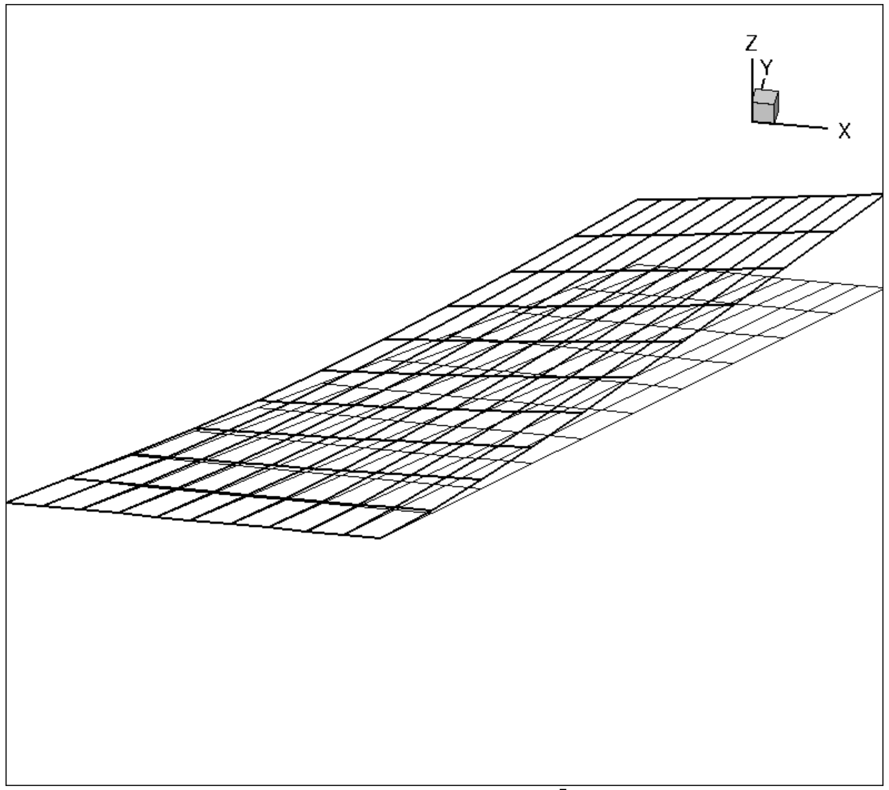
Computational grid for ONERA-M6 wing

ONERA-M6 wing

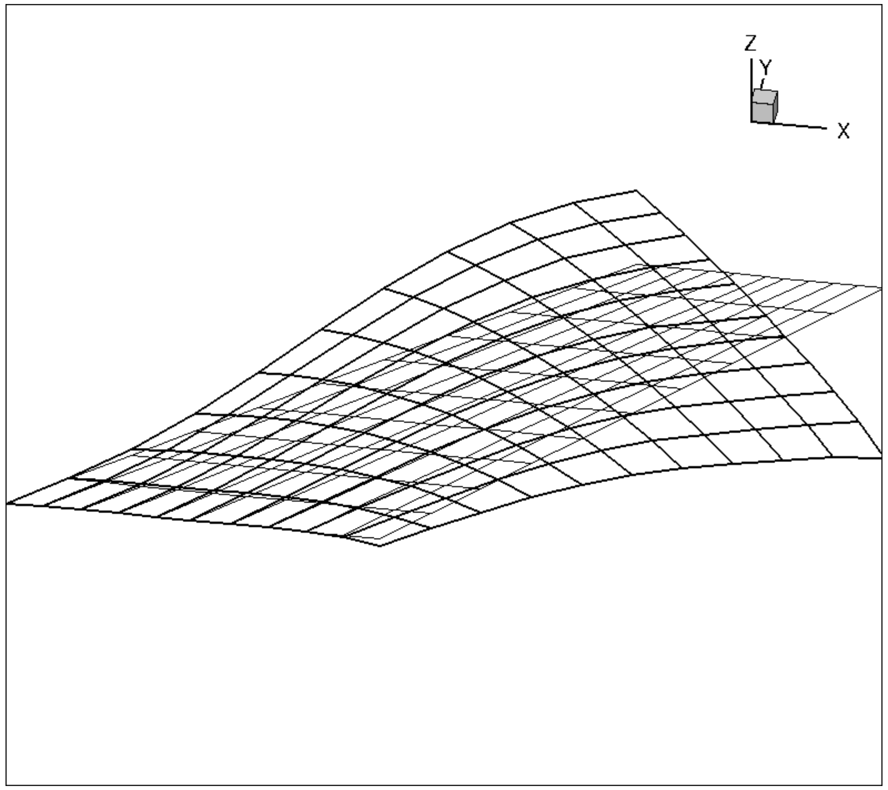
- Number of grid points
  : 197 × 50 × 82
- Computational domain
  : 30 root chord lengths
- Minimum grid spacing
  : 5×10^{-3} root chord length



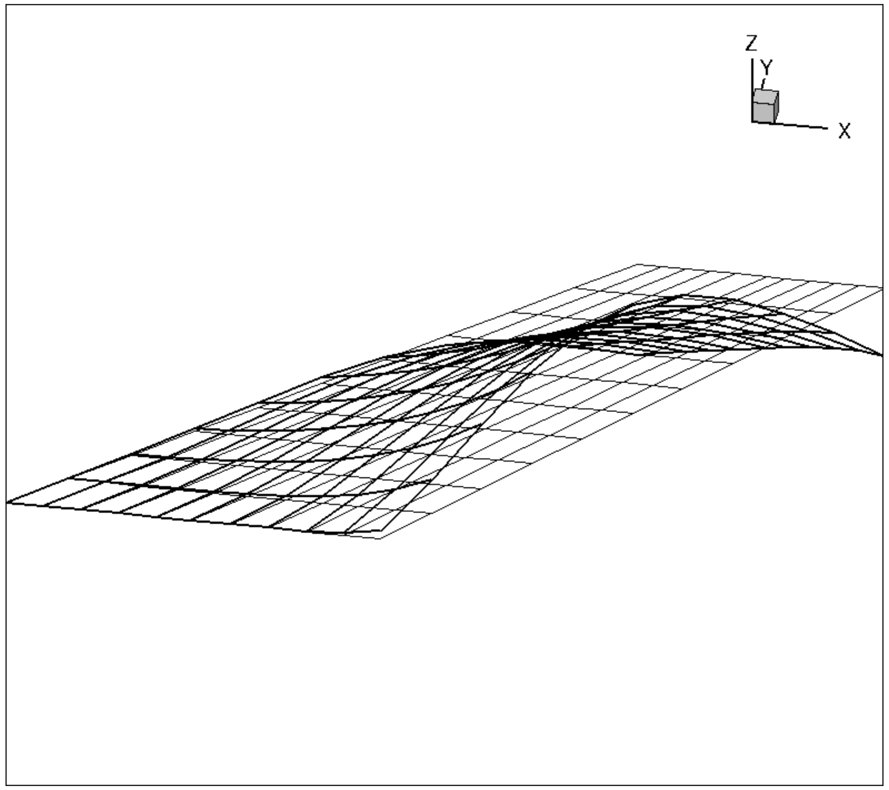
Modal shapes of AGARD wing 445.6



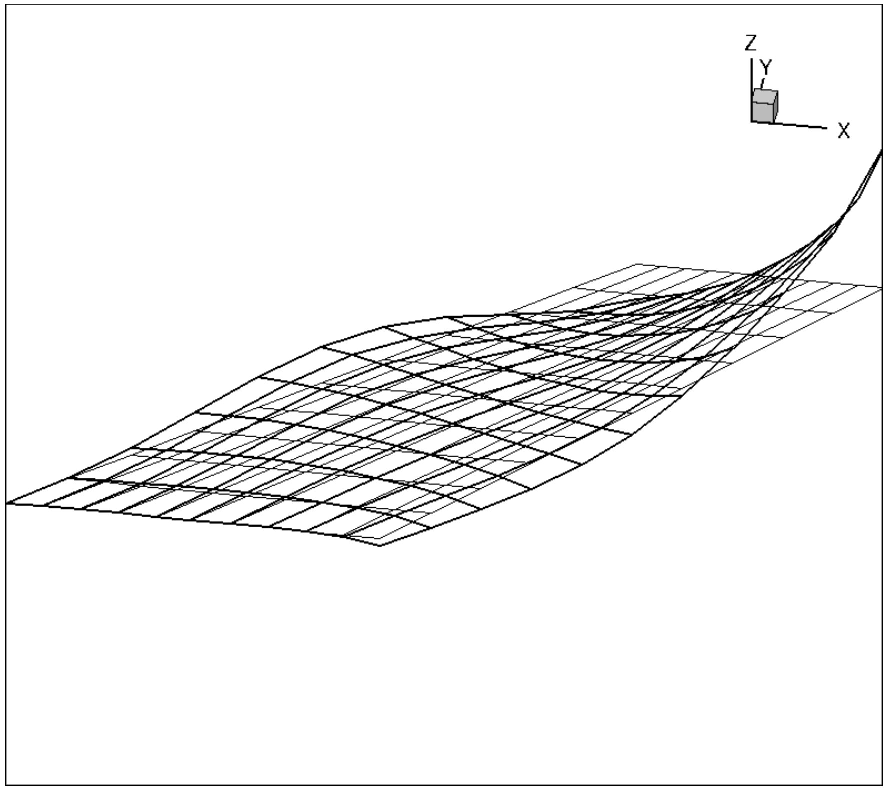
1st mode



2nd mode



3rd mode



4th mode

Parameters of the model

Parameters of the weakened model 3

- Share modulus : 0.41 [GPa]
- Young's modulus : 3.24 [GPa]
- Poisson's ration : 0.31

Mode	1st mode (bending)	2nd mode (torsion)	3rd mode (bending)	4th mode (torsion)	5th mode (bending)
Frequency of report by Yates [Hz]	9.6	38.2	48.3	91.5	118.1
Frequency of experimental data [Hz]	9.6	38.1	50.7	98.5	