Development of Unsteady Aerodynamic and Aeroelastic Reduced-Order Models Using System Identification

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Outline

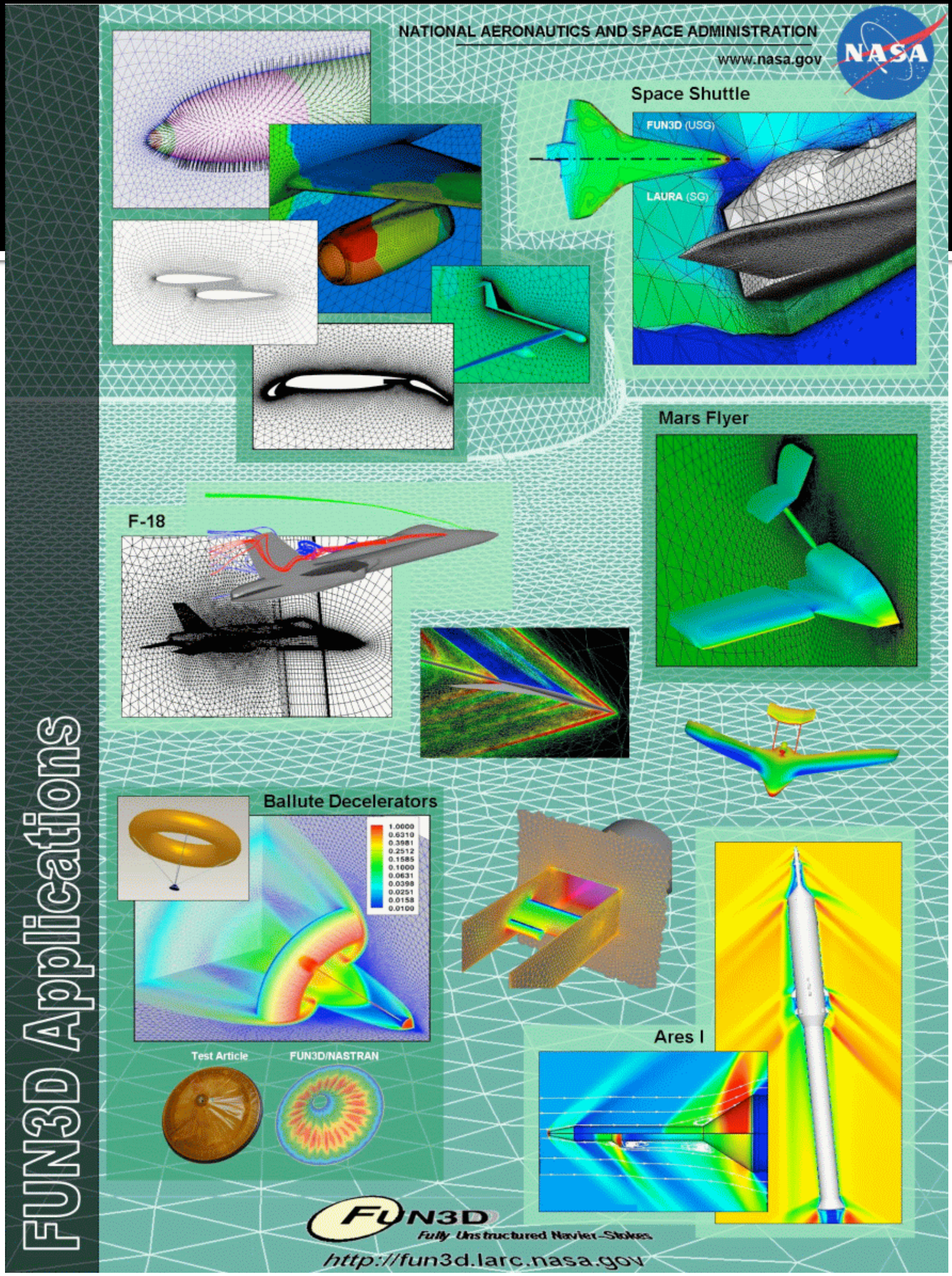
- Introduction
- FUN3D Code
- ROM Development Process
  - Unsteady Aerodynamic and Aeroelastic ROMs
  - Error Minimization
  - Root Locus
- Applications
  - BACT, 2D, Viscous
  - AGARD 445.6 Wing, 3D, Inviscid
- Concluding Remarks

Introduction

- A method for generating ROMs was recently developed based on the simultaneous excitation of modes
- This method was implemented in the CFL3D structured grid flow solver
- This paper presents the implementation of this method in the FUN3D unstructured grid flow solver
- Additionally, wanted to develop additional capabilities: error minimization and aeroelastic root locus plots

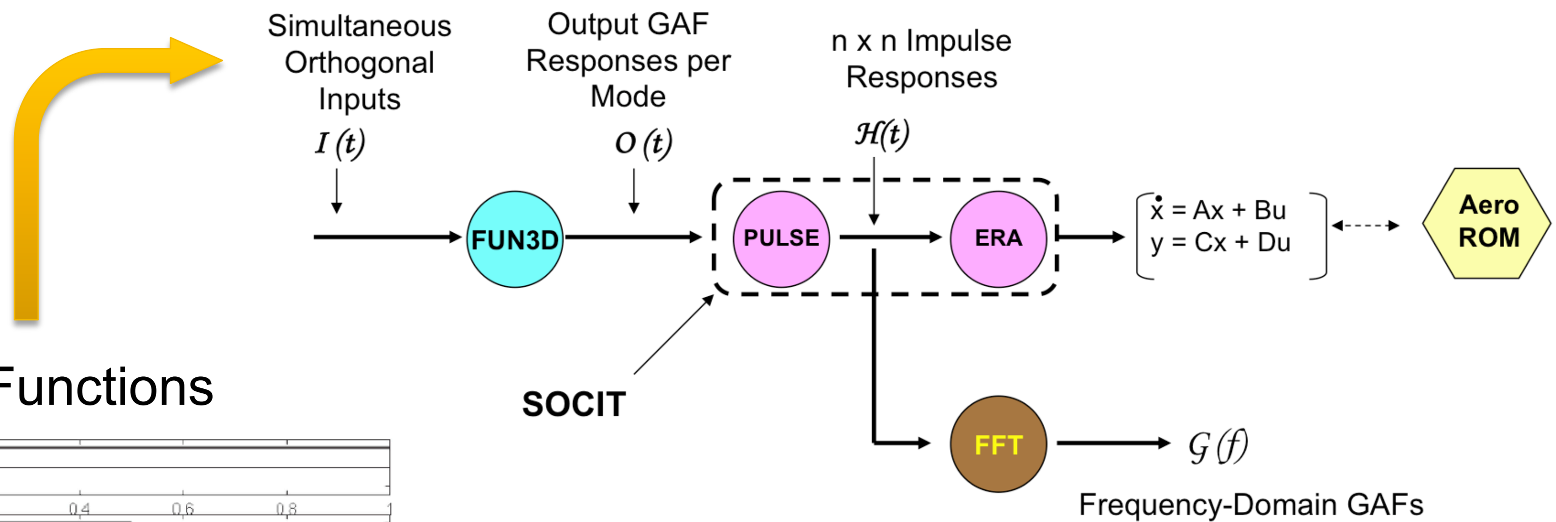
FUN3D Code

- Unstructured-grid flow solver
- Langley-developed code
- Aeroelastic capability
- Multiple turbulence models

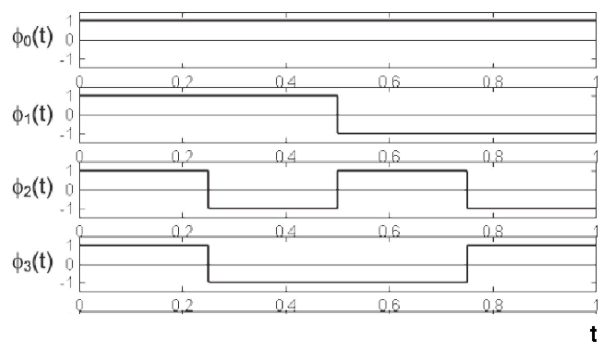


ROM Development Process

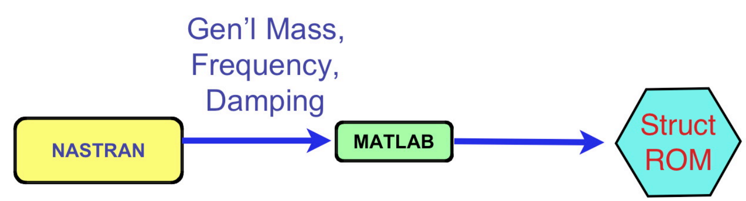
Unsteady Aerodynamic State-Space ROM



Walsh Functions

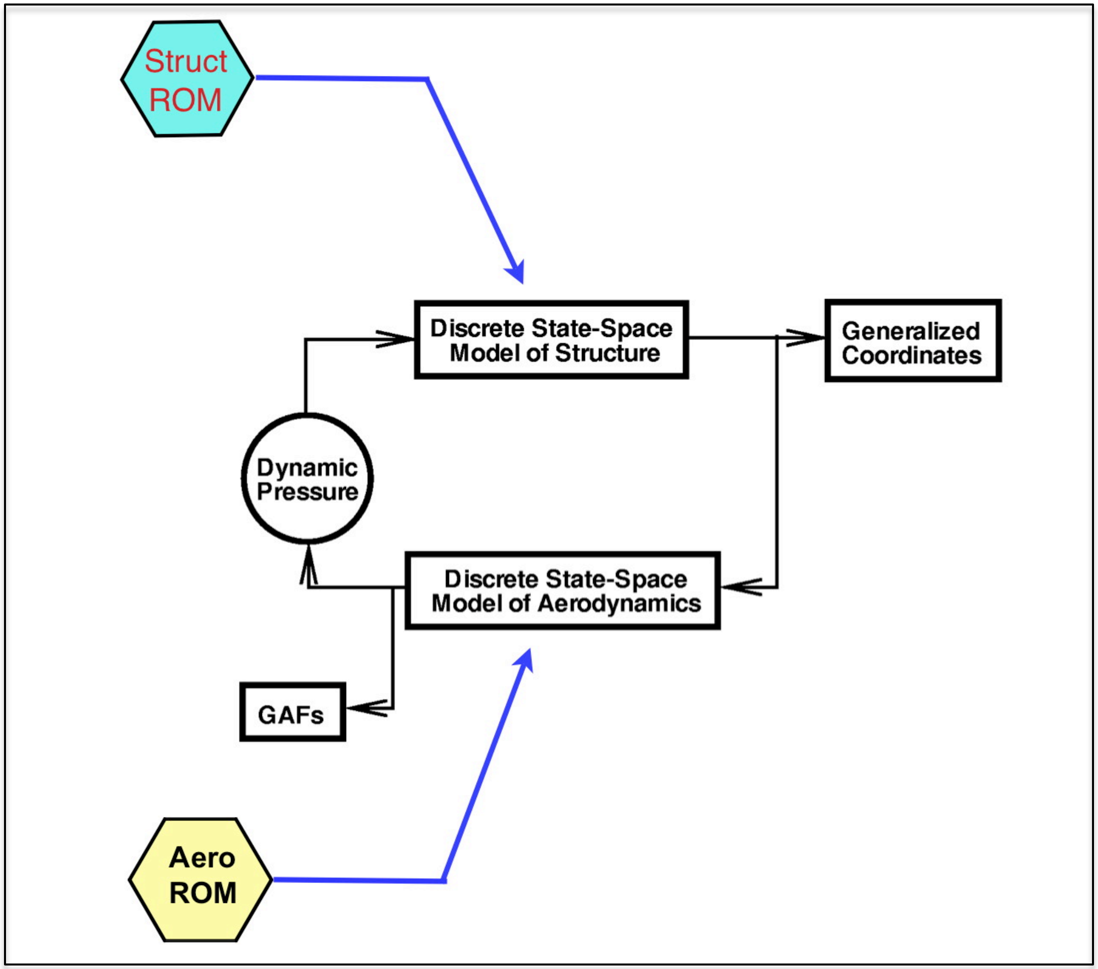


Structural state-space ROM



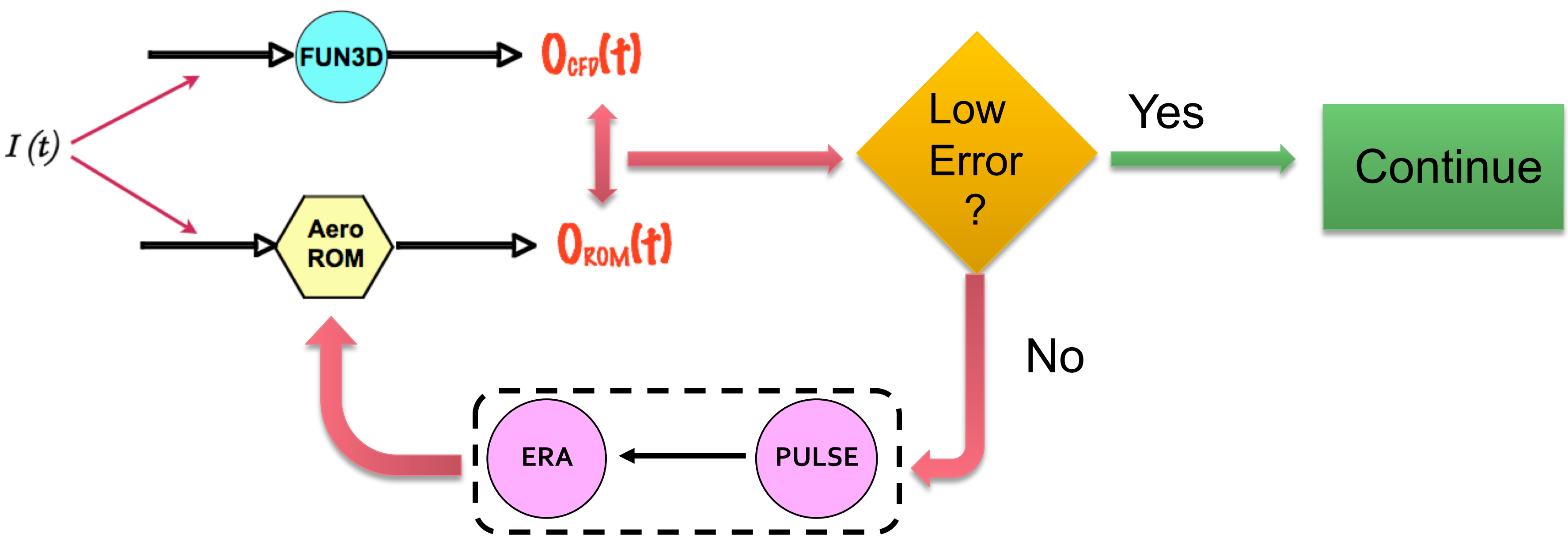
ROM Development Process

Aeroelastic Simulation ROM



ROM Development Process

Error Minimization (Unsteady Aerodynamics)



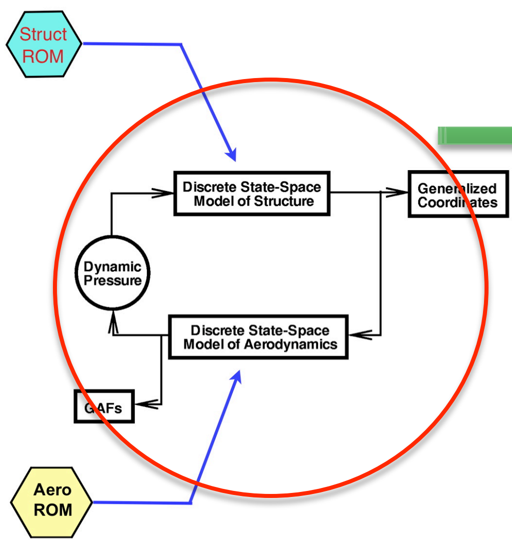
ROM Development Process

Error Minimization Philosophy (Unsteady Aerodynamics)

- Currently, error minimization process applied to the development of the unsteady aerodynamic ROM only, not the aeroelastic simulation ROM.
- What is meant by “Low Error”? A maximum error less than 5%.
- Final accepted “Low Error” is a compromise between the lowest error possible while requiring minimal re-design effort.
- How does the error in the unsteady aerodynamic ROM translate into the error in the aeroelastic simulation ROM?

ROM Development Process

Aeroelastic Root Locus Plot Using Aeroelastic Simulation ROM



Modeled as a closed-loop system with gain (dynamic pressure) in MATLAB

Eigenvalues

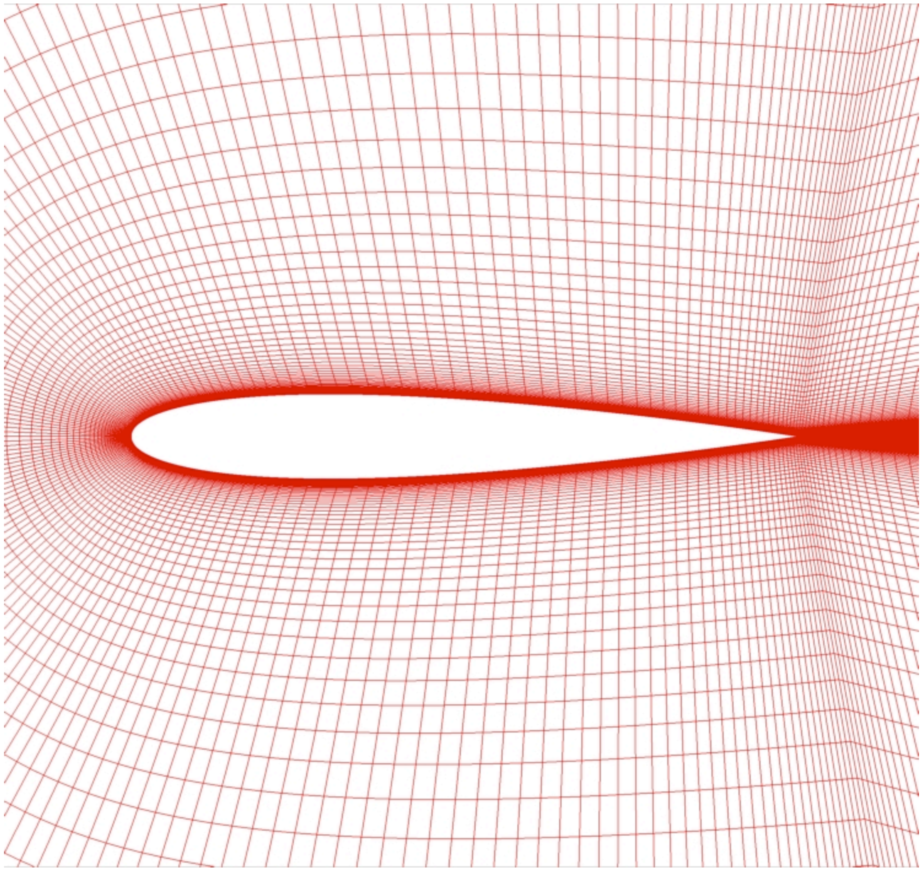
Z-Plane Root Locus

S-Plane Root Locus

Frequency vs Damping Ratio Root Locus

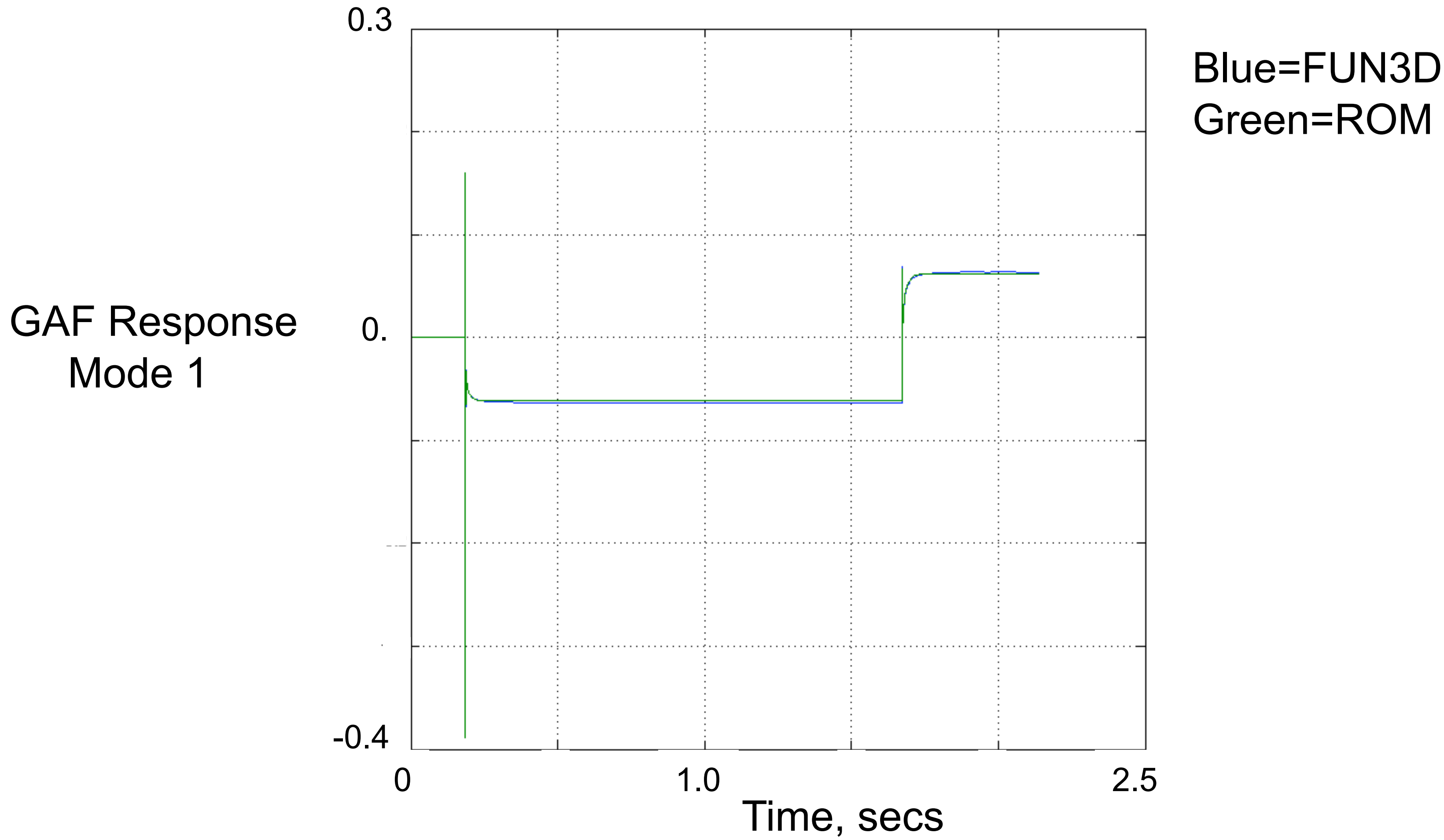
BACT, 2D, Viscous

- Benchmark Active Controls Technology (BACT) wing
- 2D, viscous (SA turbulence model)
- 39,000 hex cells
- Plunge and pitch
- Mach = 0.51



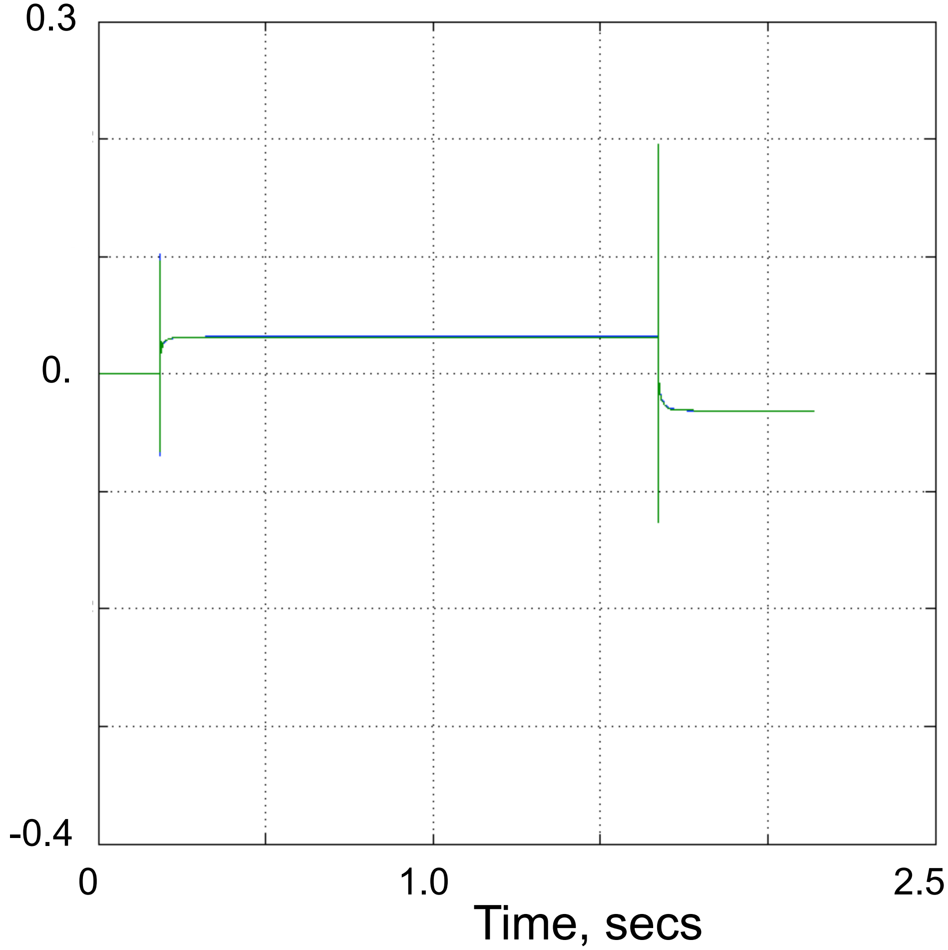
BACT, 2D, Viscous

- Error Minimization



BACT, 2D, Viscous

- Error Minimization



GAF Response
Mode 2

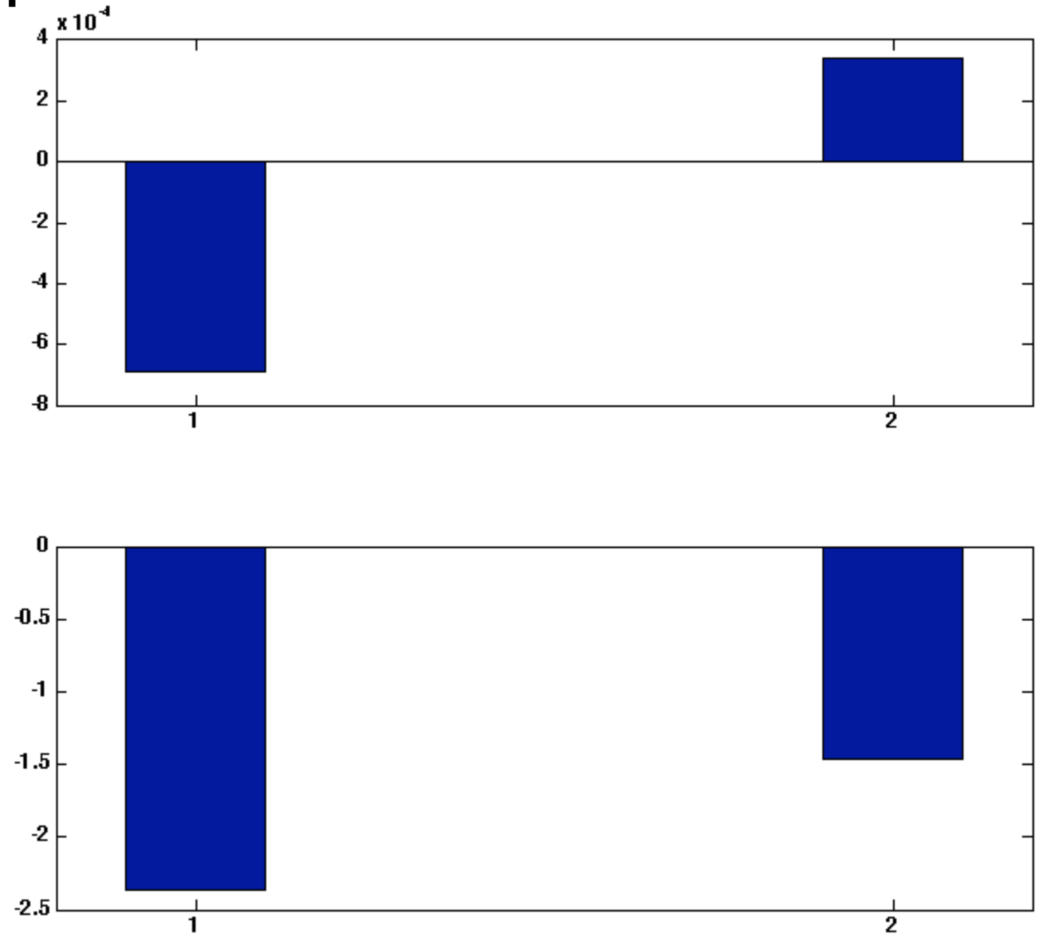
Blue=FUN3D
Green=ROM

BACT, 2D, Viscous

- Error Minimization

Mean Error

Maximum % Error

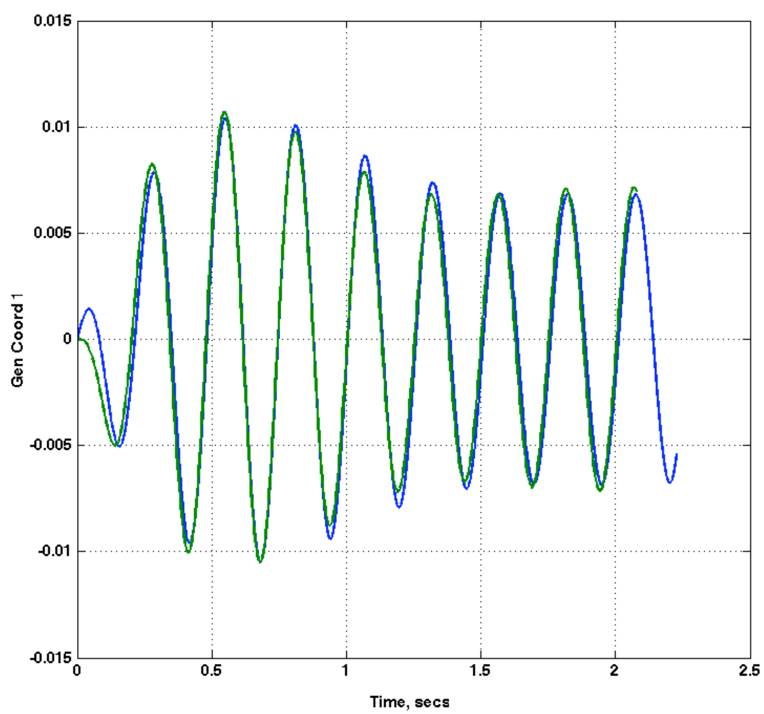


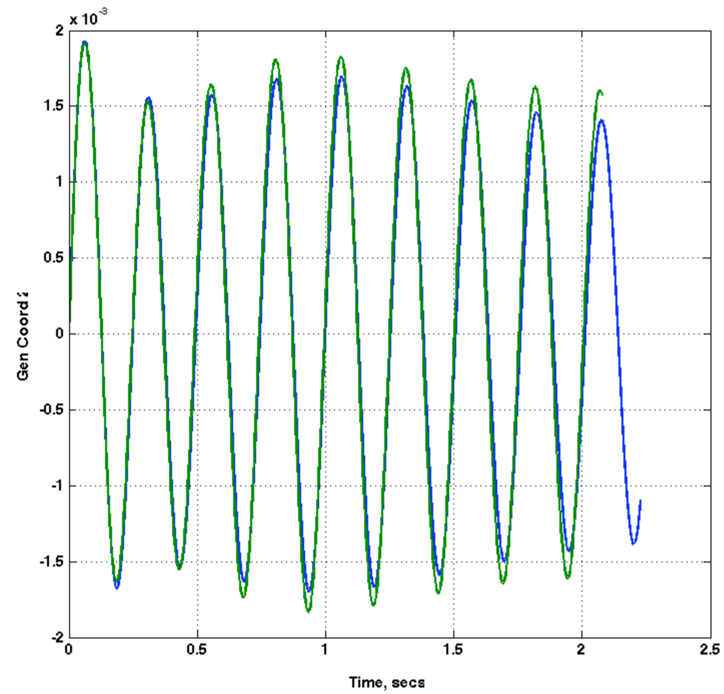
Generalized Coordinate

BACT, 2D, Viscous

- Aeroelastic Responses, ROM and FUN3D, Q=140 psf

Blue=ROM
Green=FUN3D



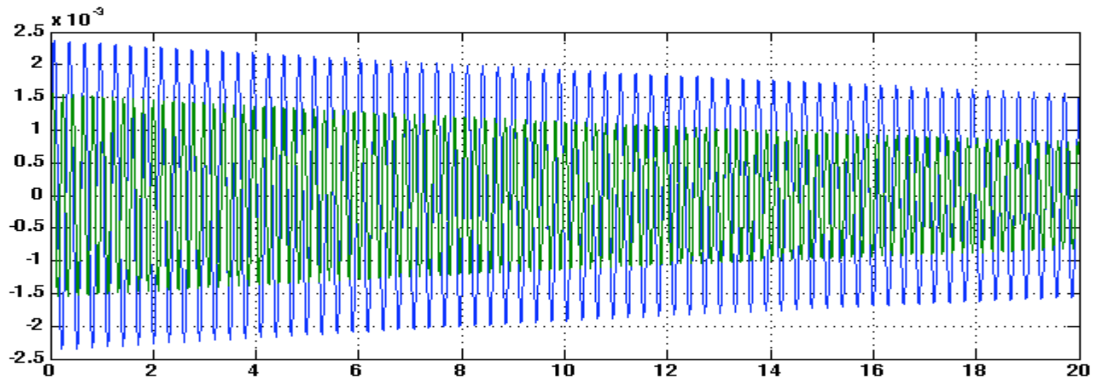


BACT, 2D, Viscous

- Aeroelastic Responses, ROM, Q=0 psf

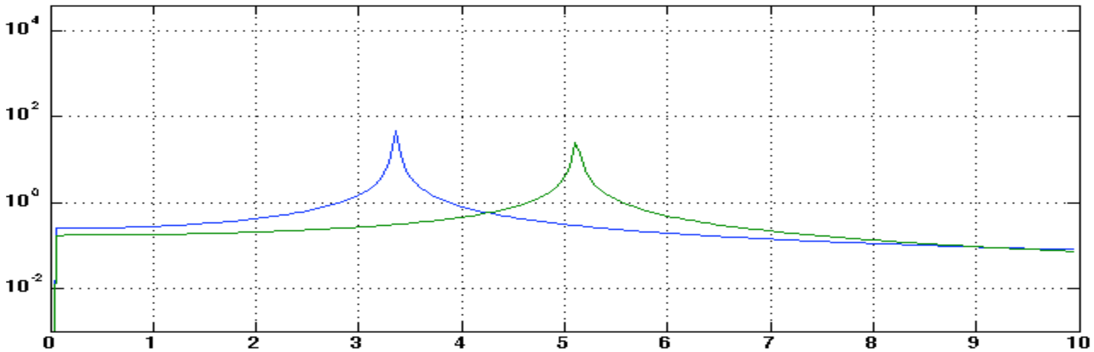
Blue=GC 1
Green=GC 2

Generalized Coordinate



Time

Magnitude



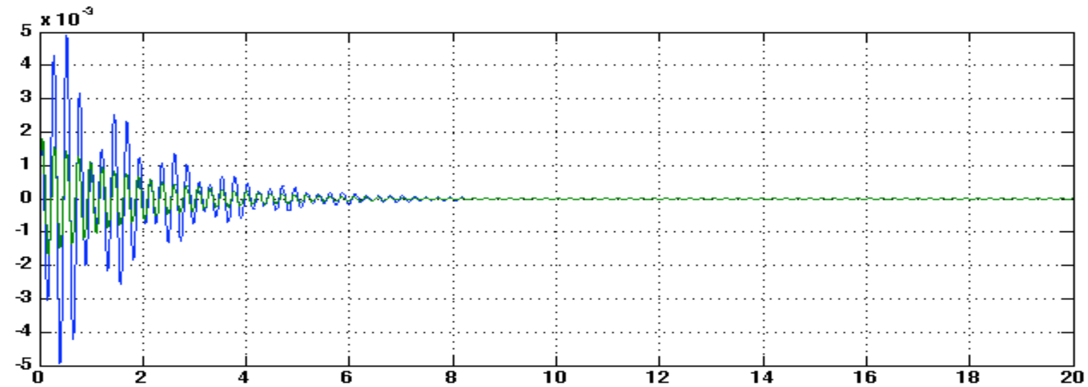
Frequency, Hz

BACT, 2D, Viscous

- Aeroelastic Responses, ROM, Q=100 psf

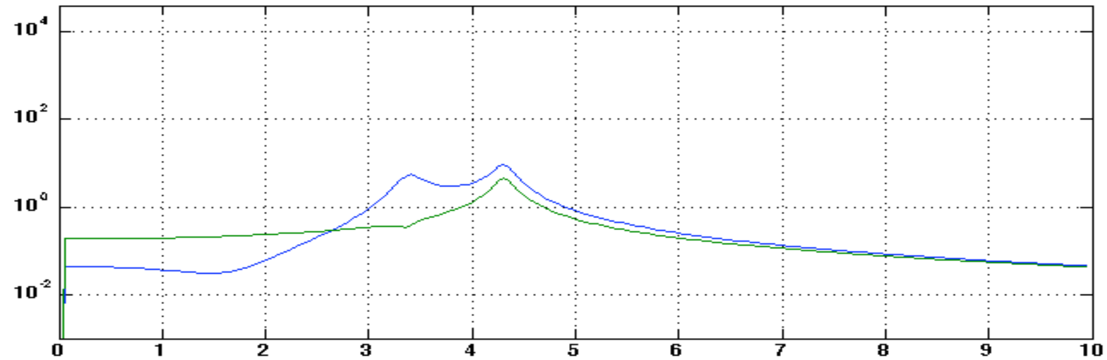
Blue=GC 1
Green=GC 2

Generalized Coordinate



Time

Magnitude



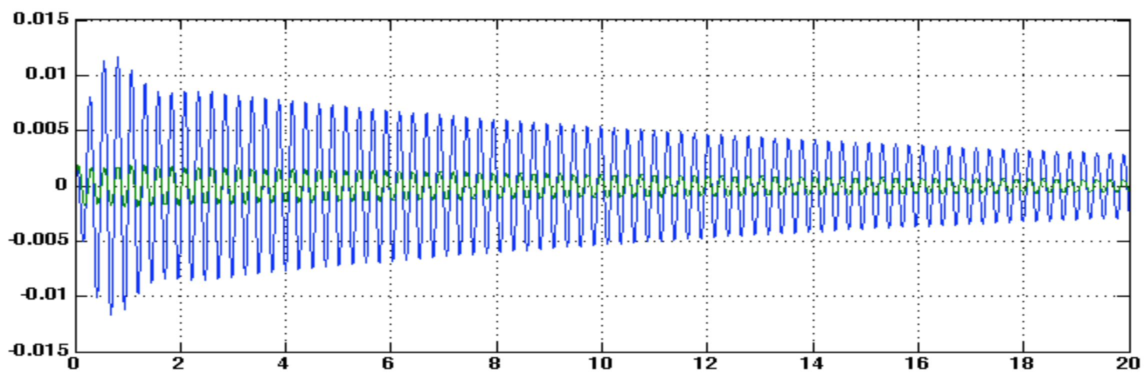
Frequency, Hz

BACT, 2D, Viscous

- Aeroelastic Responses, ROM, Q=140 psf

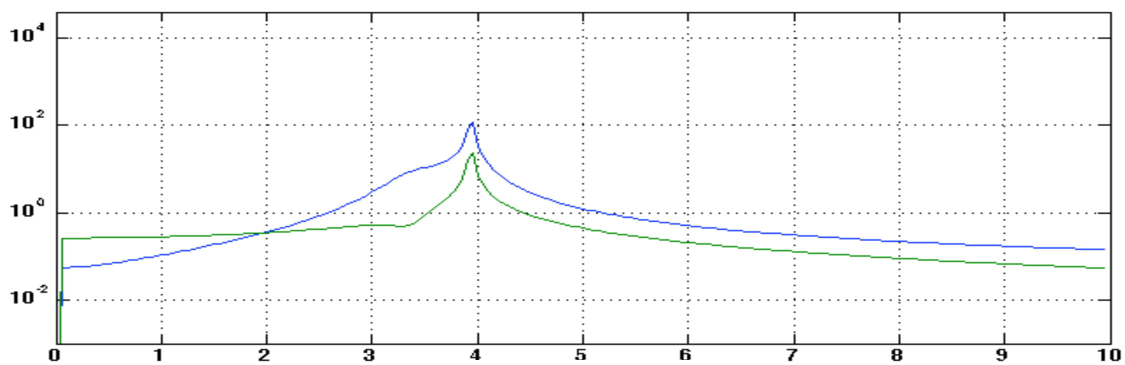
Blue=GC 1
Green=GC 2

Generalized Coordinate



Time

Magnitude



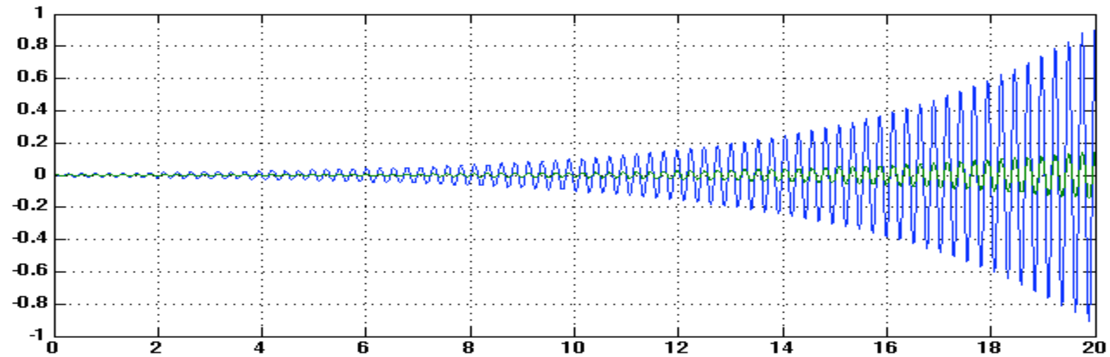
Frequency, Hz

BACT, 2D, Viscous

- Aeroelastic Responses, ROM, Q=150 psf

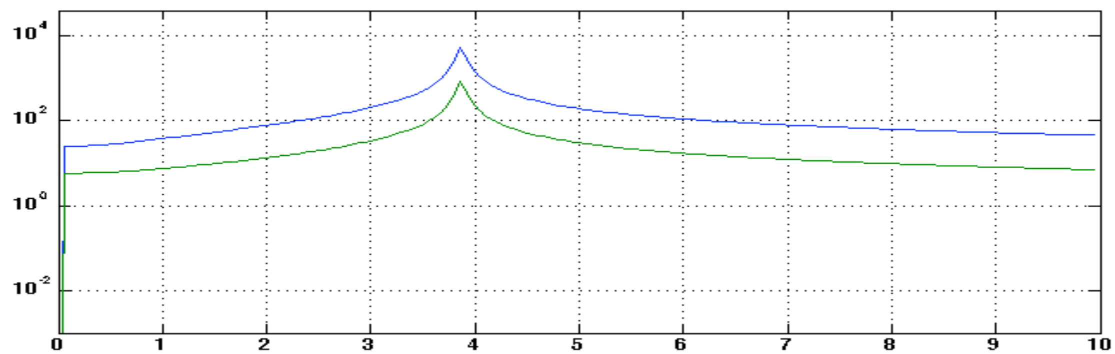
Blue=GC 1
Green=GC 2

Generalized Coordinate



Time

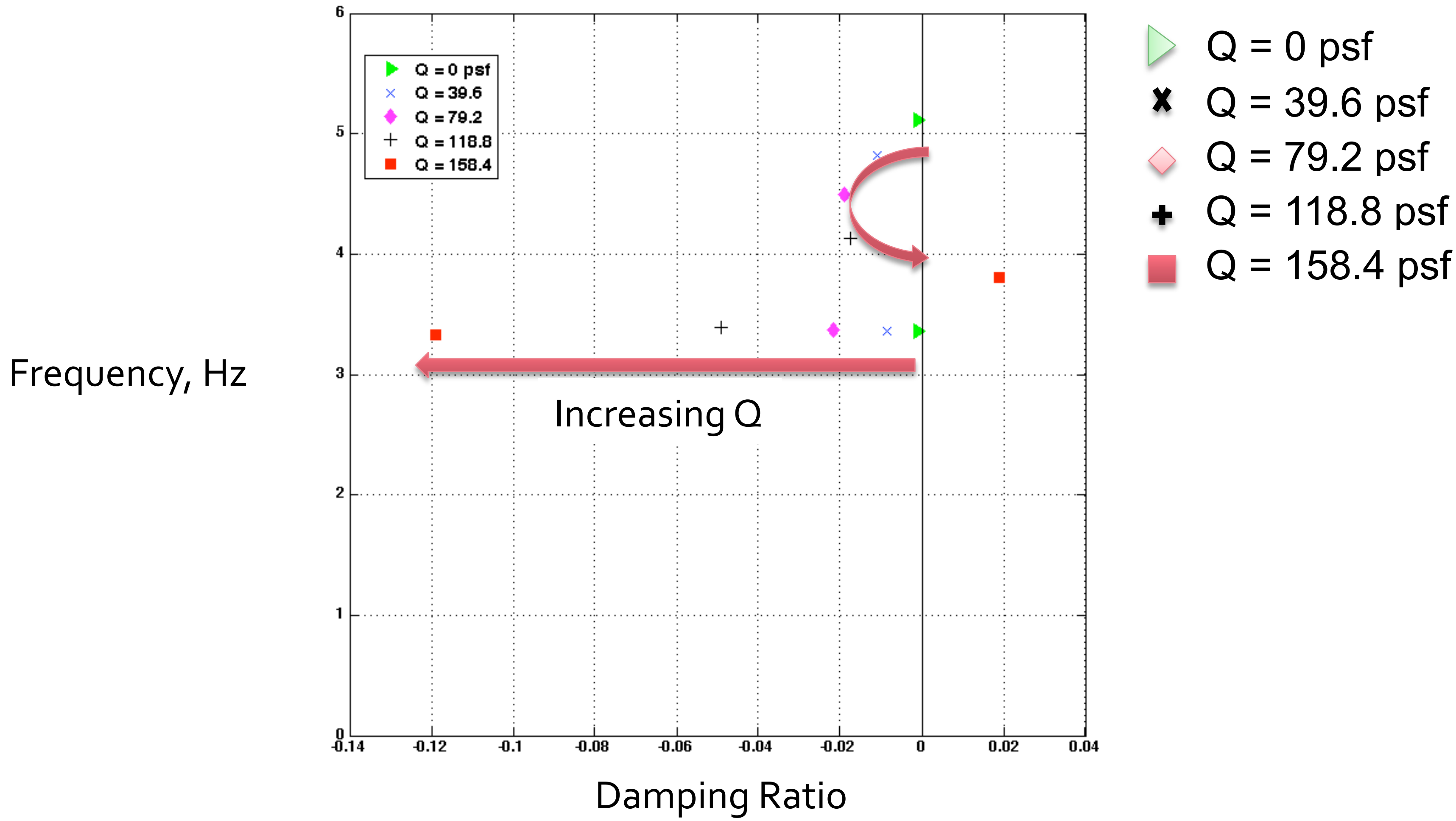
Magnitude



Frequency, Hz

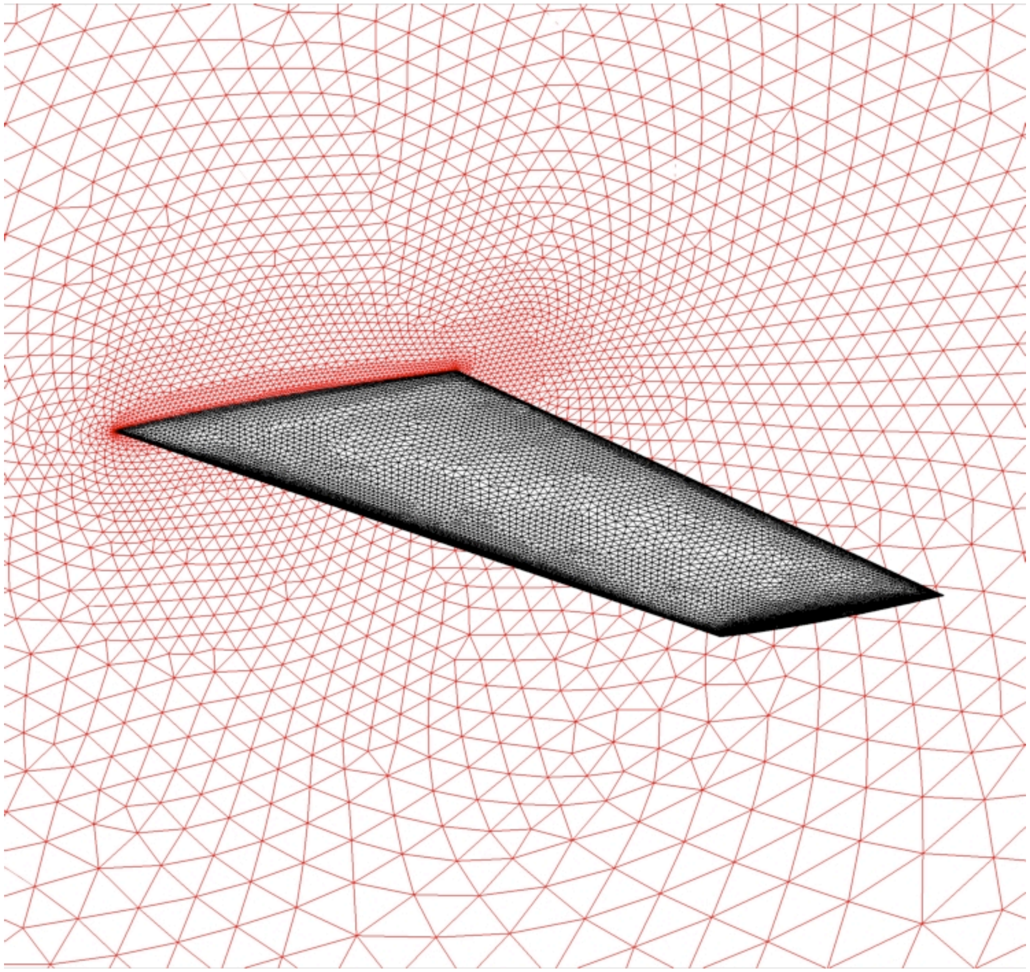
BACT, 2D, Viscous

- Aeroelastic Root Locus, ROM



AGARD 445.6 Wing, 3D, Inviscid

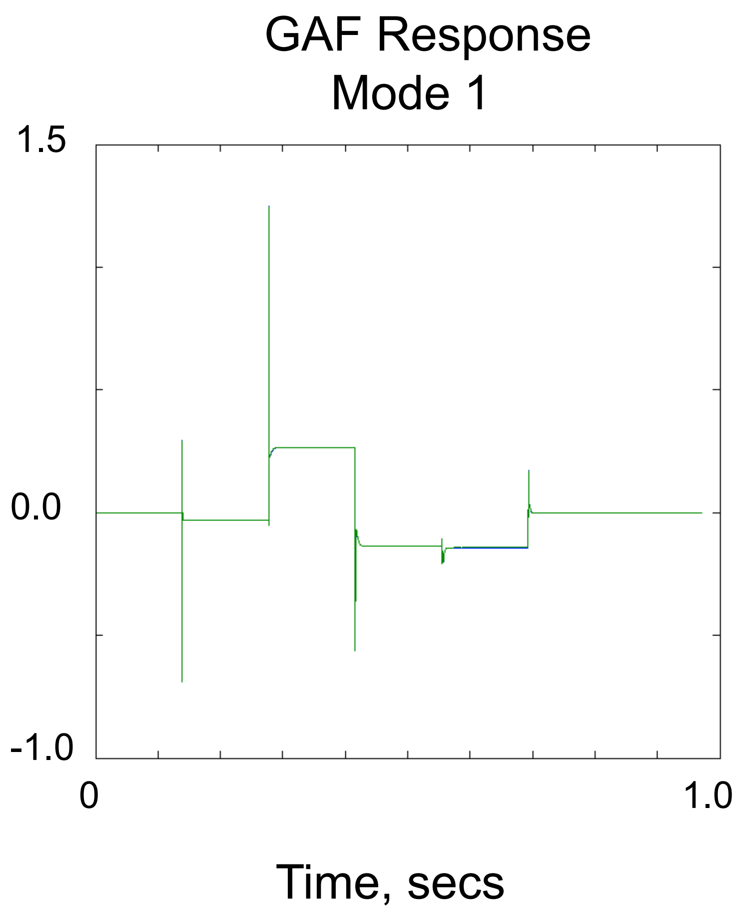
- Typical aeroelastic testcase
- 3D, inviscid
- 2.23M tetrahedra
- Four modes
- Mach = 0.90

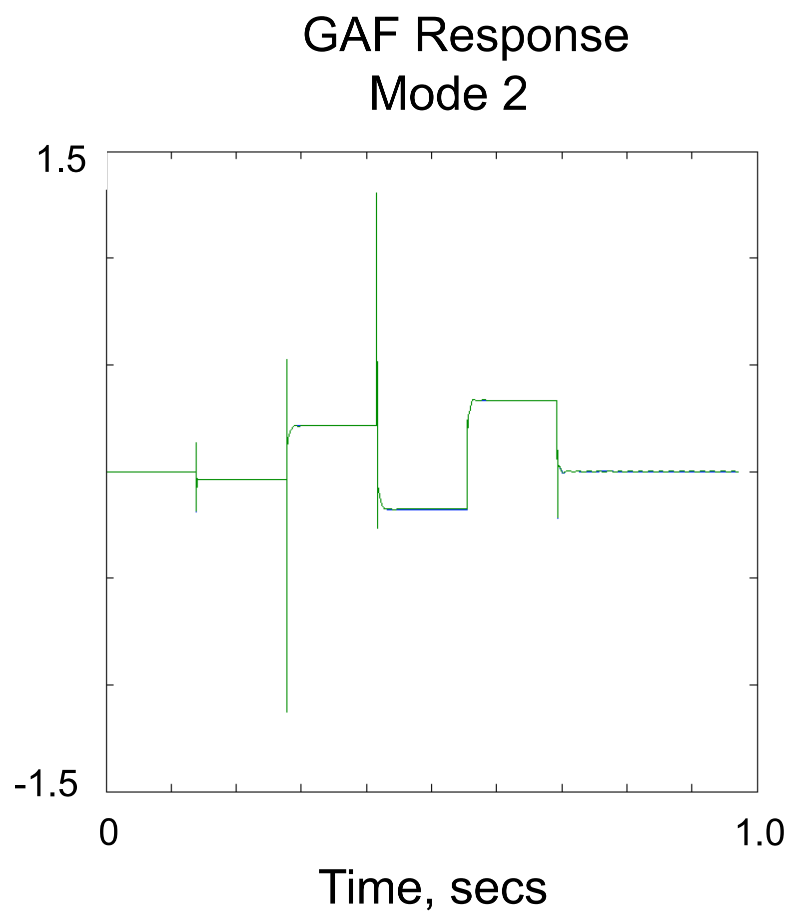


AGARD 445.6 Wing, 3D, Inviscid

- Error Minimization

Blue=FUN3D
Green=ROM

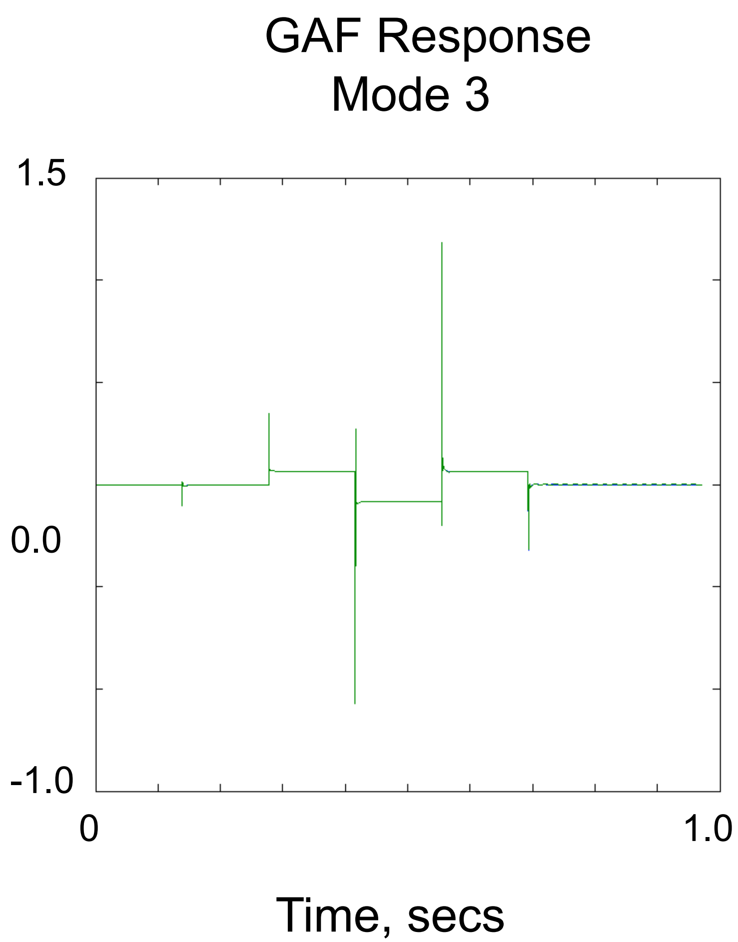


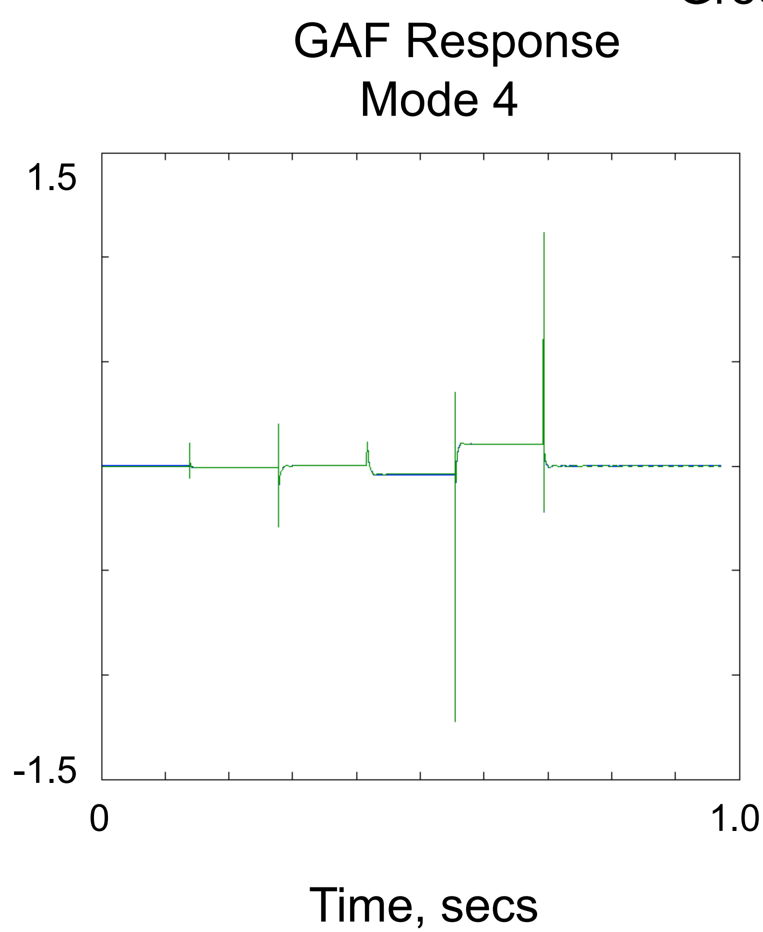


AGARD 445.6 Wing, 3D, Inviscid

- Error Minimization

Blue=FUN3D
Green=ROM

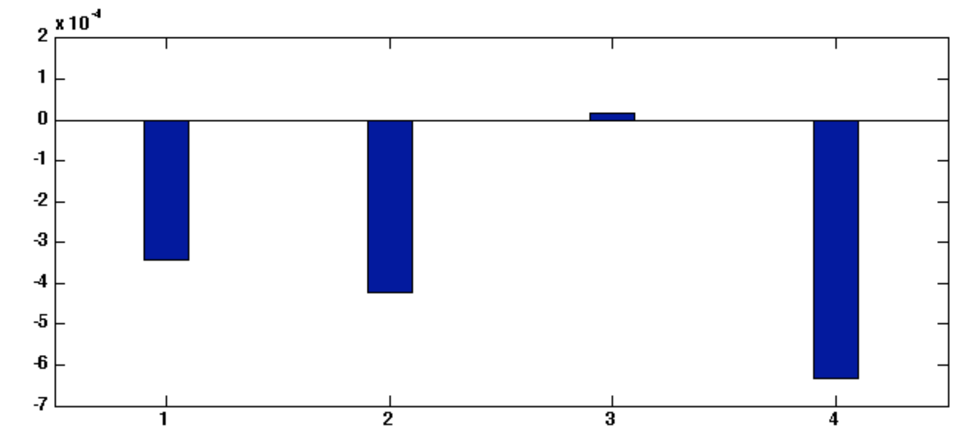




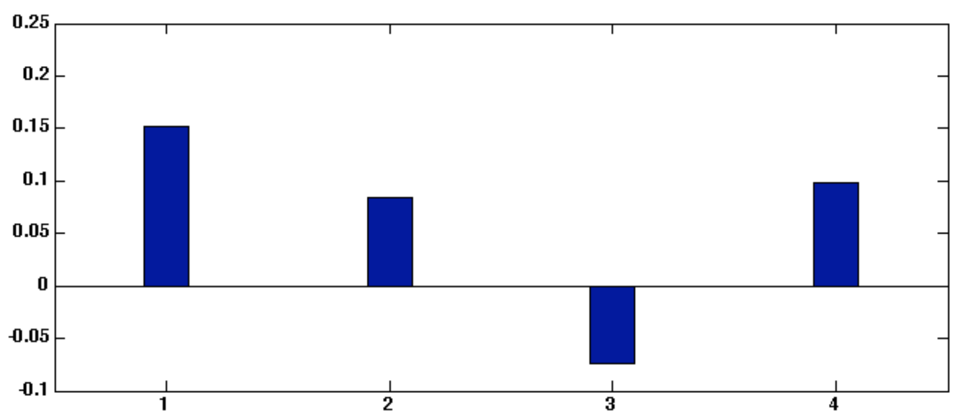
AGARD 445.6 Wing, 3D, Inviscid

- Error Minimization

Mean Error



Maximum % Error



Generalized Coordinate

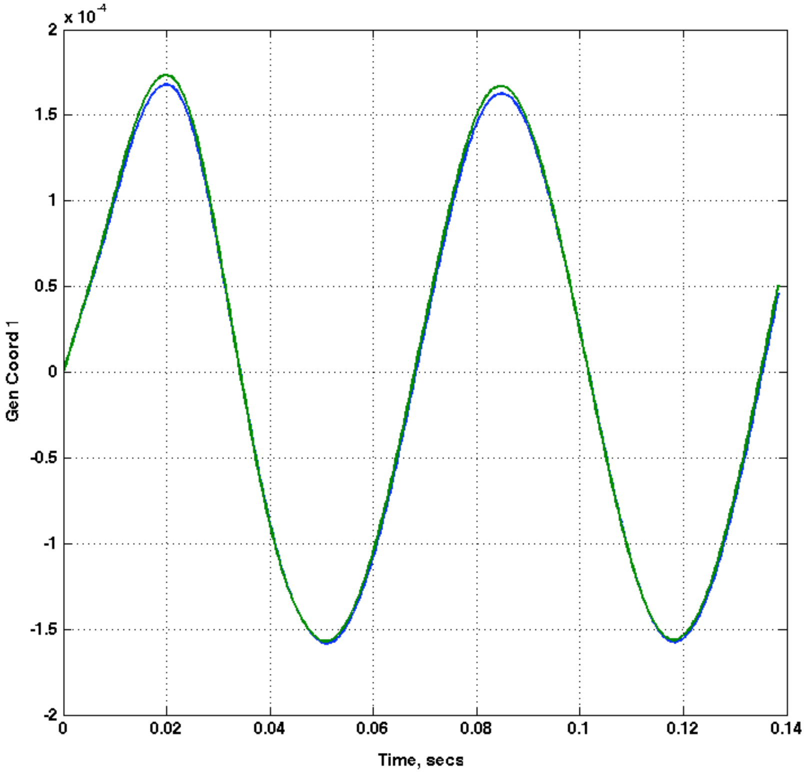
AGARD 445.6 Wing, 3D, Inviscid

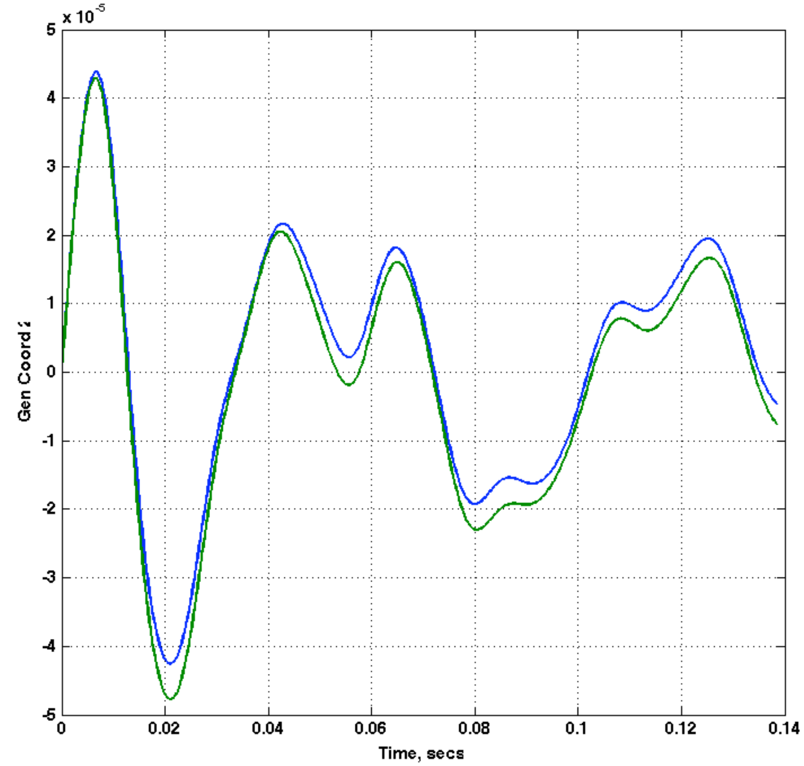
- Aeroelastic Responses, ROM and FUN3D, Q=75 psf

Generalized Coordinate 1

Blue=ROM
Green=FUN3D

Generalized Coordinate 2





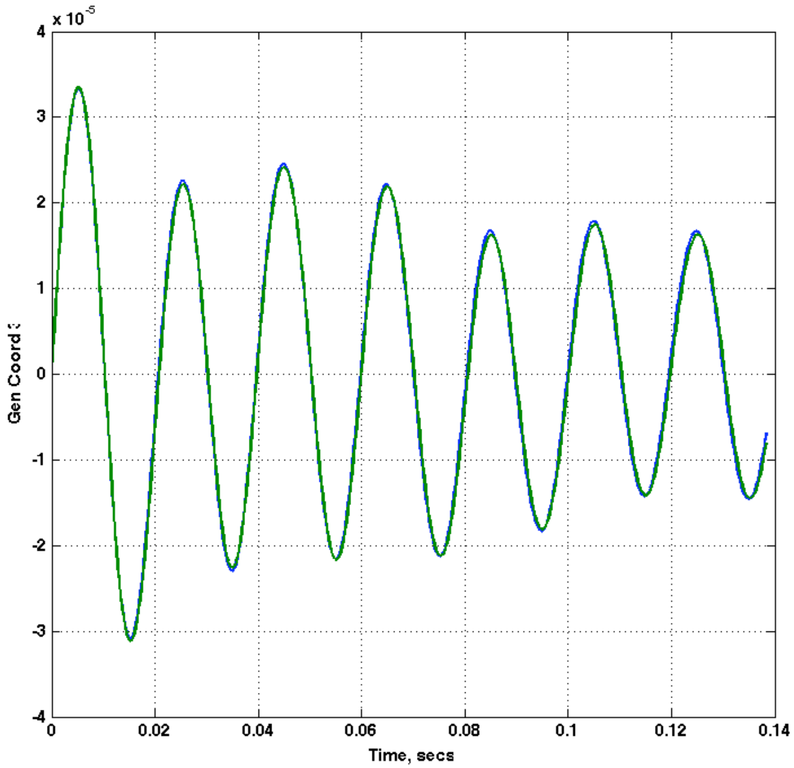
AGARD 445.6 Wing, 3D, Inviscid

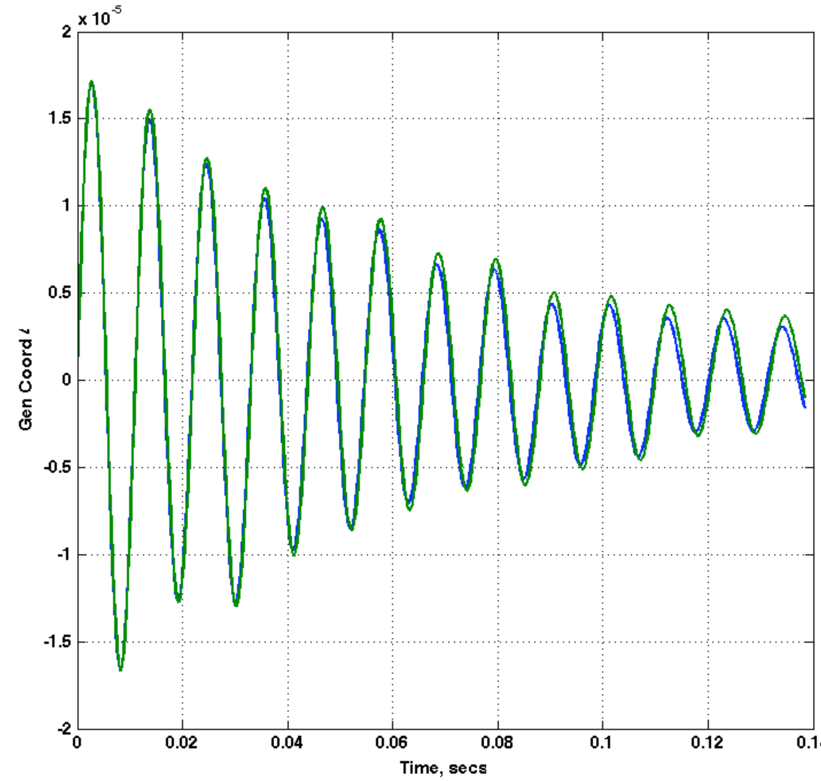
- Aeroelastic Responses, ROM and FUN3D, Q=75 psf

Generalized Coordinate 3

Blue=ROM
Green=FUN3D

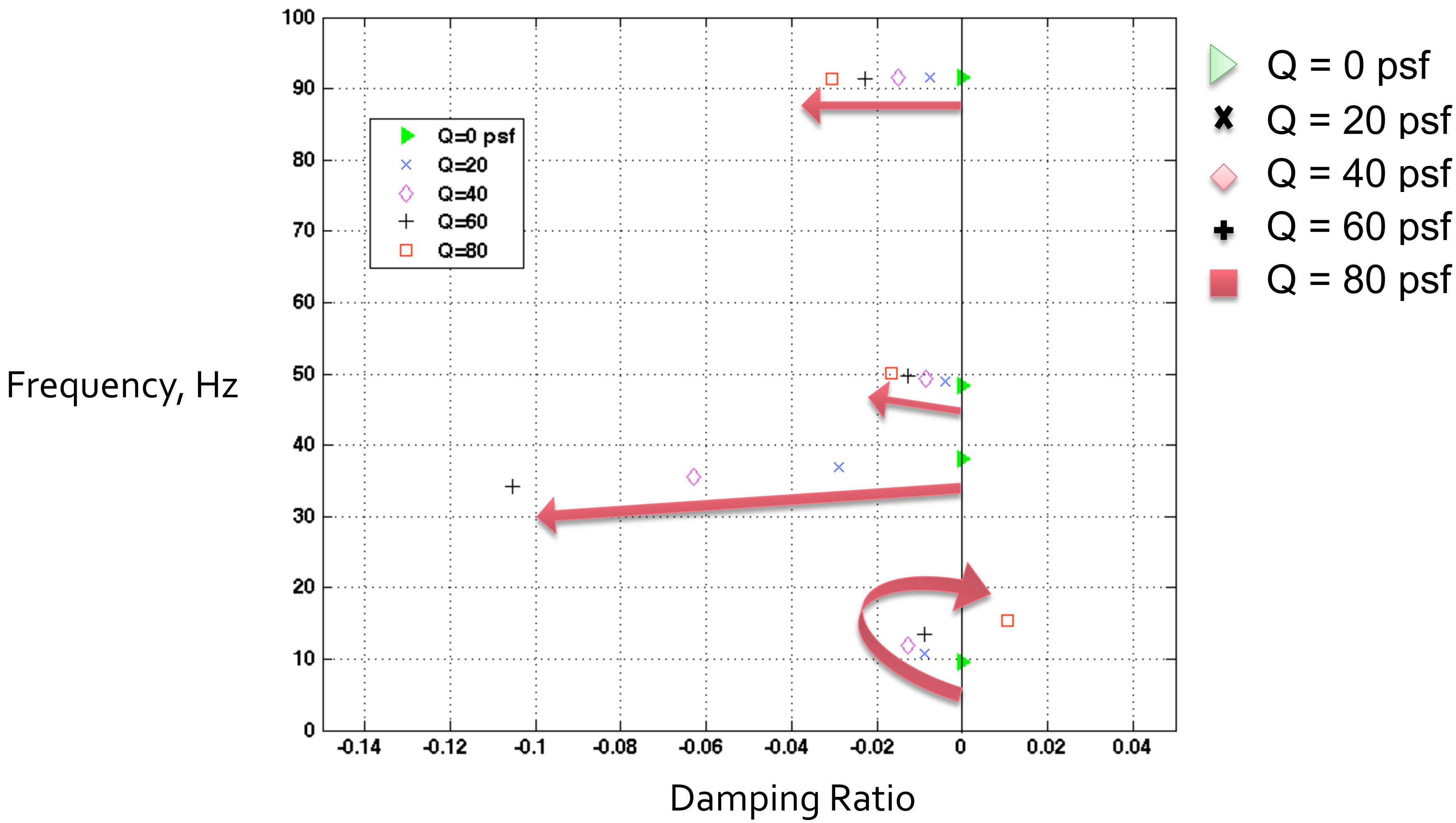
Generalized Coordinate 4



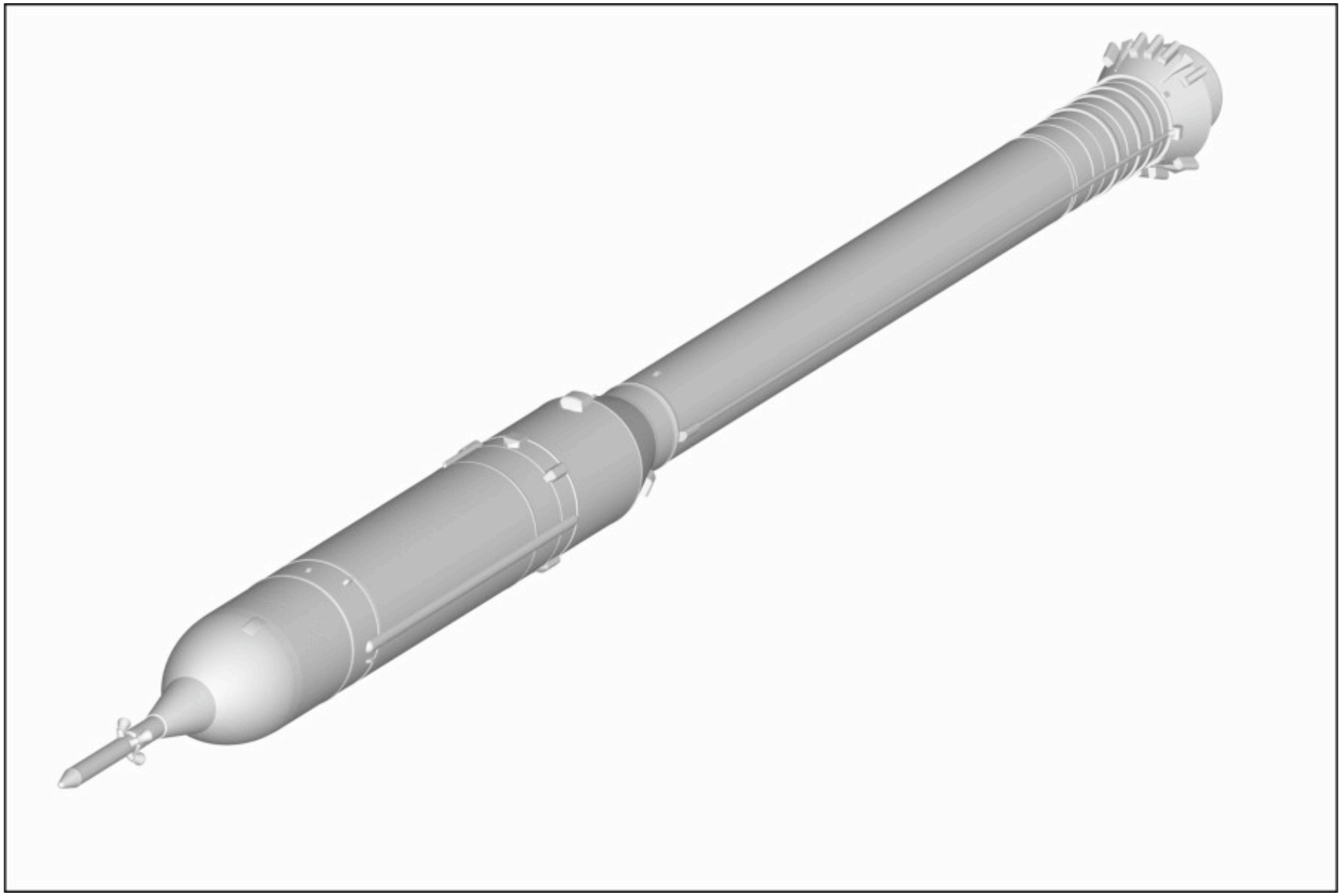


AGARD 445.6 Wing, 3D, Inviscid

- Aeroelastic Root Locus, ROM

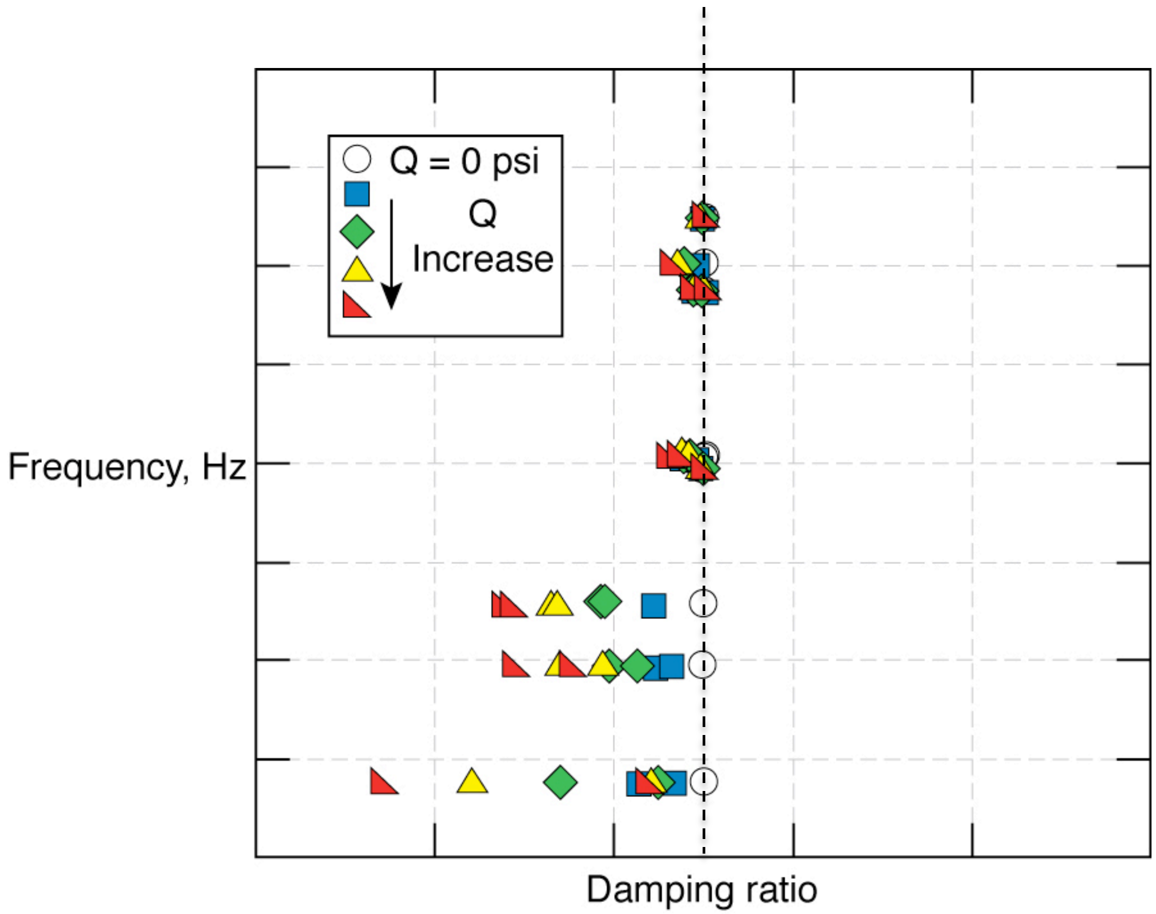


Ares I-X, I Launch Vehicles

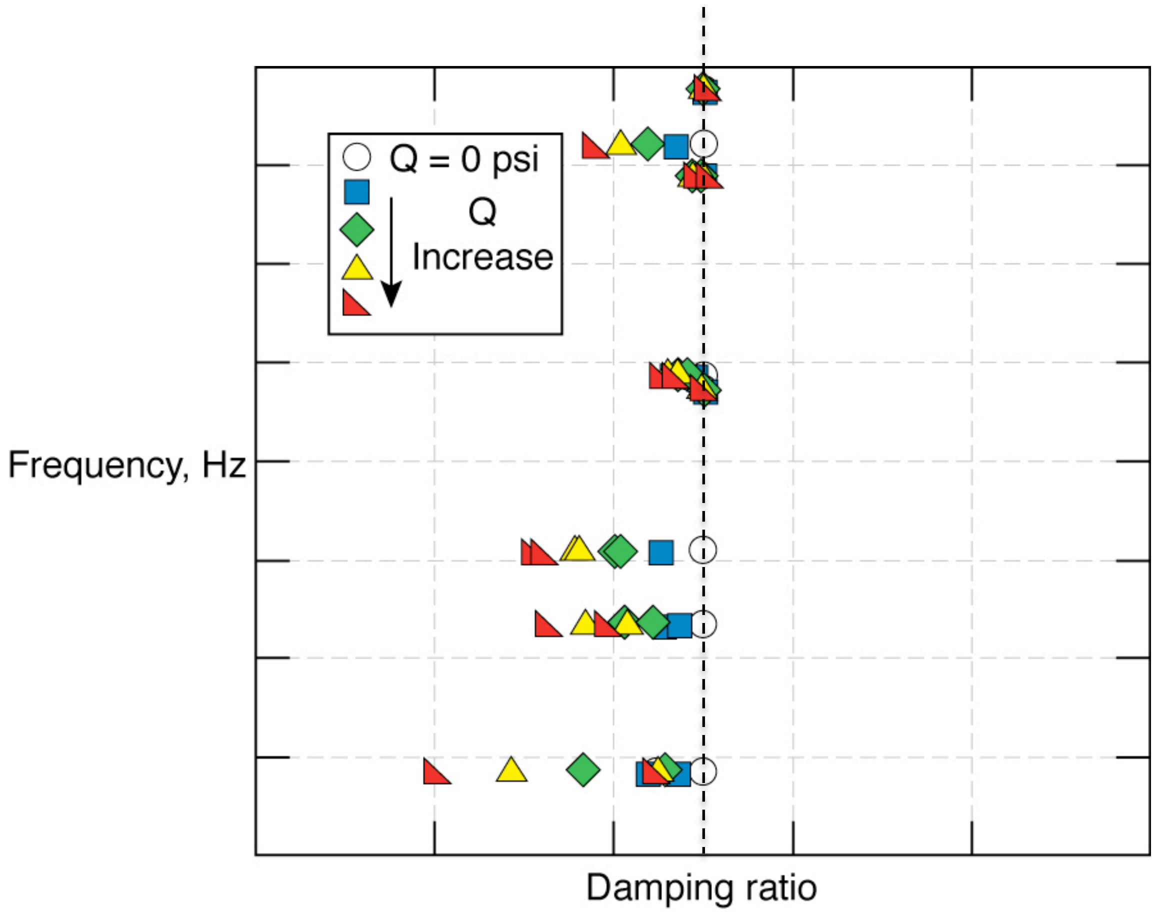


Results : Ares I-X

M=0.95, Baseline Modal Frequencies

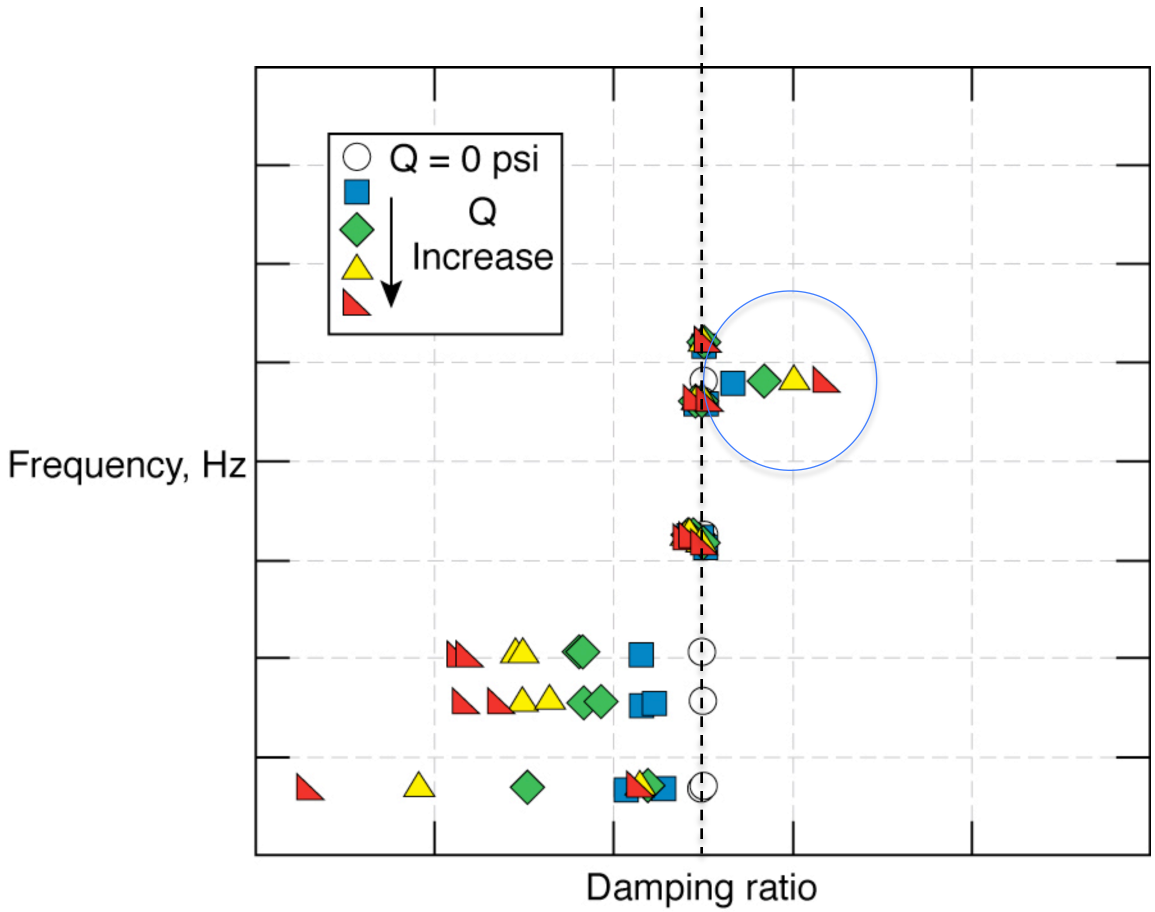


Results : Ares I-X
M=0.95, Increased Modal Frequencies



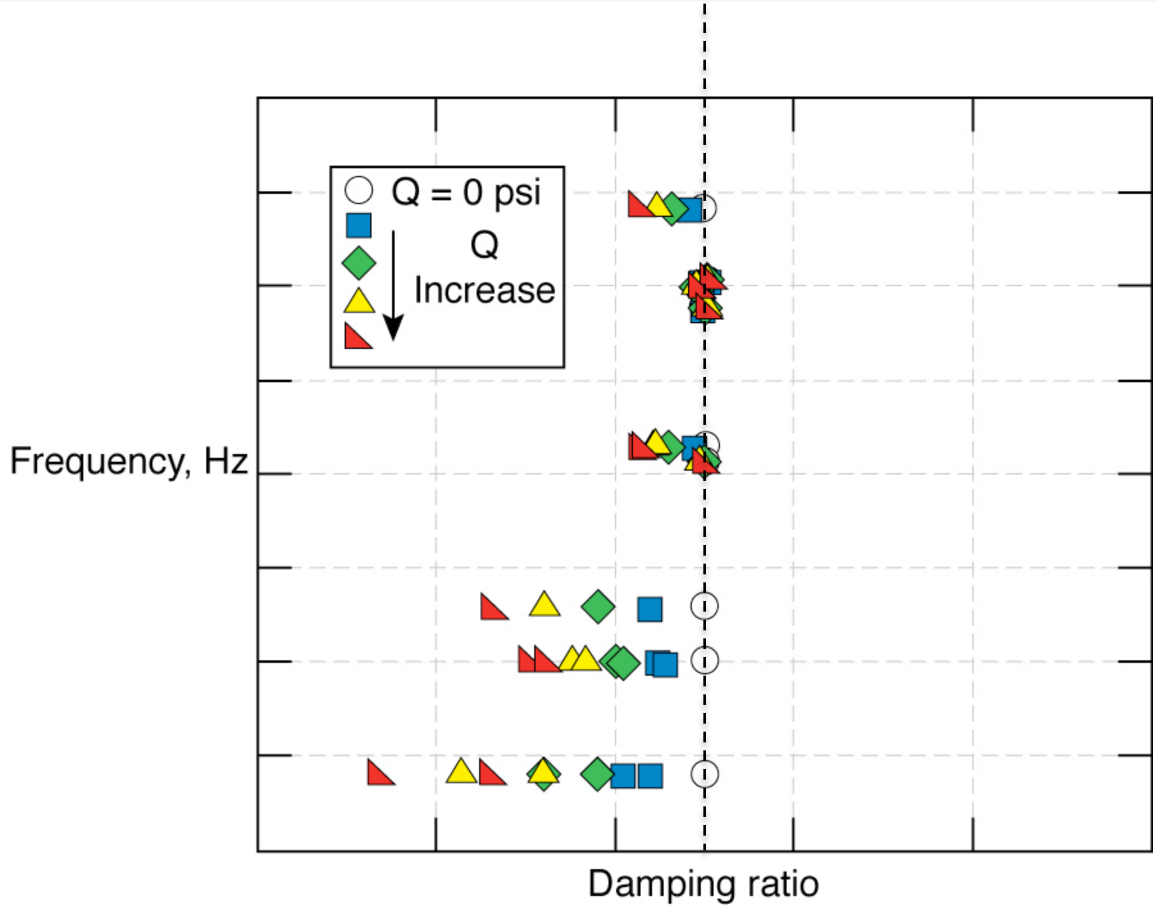
Results : Ares I-X

M=0.95, Decreased Modal Frequencies



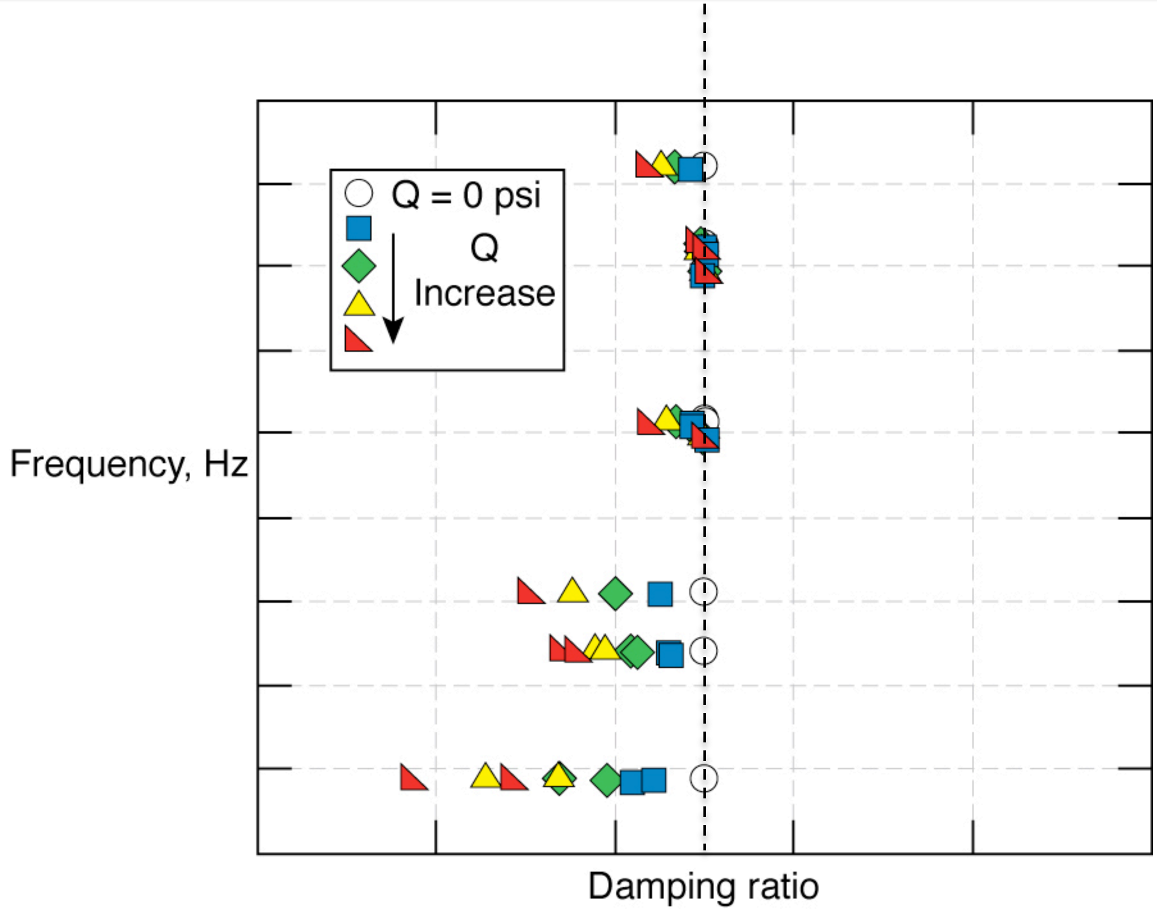
Results : Ares I-X

M=1.44, Baseline Modal Frequencies



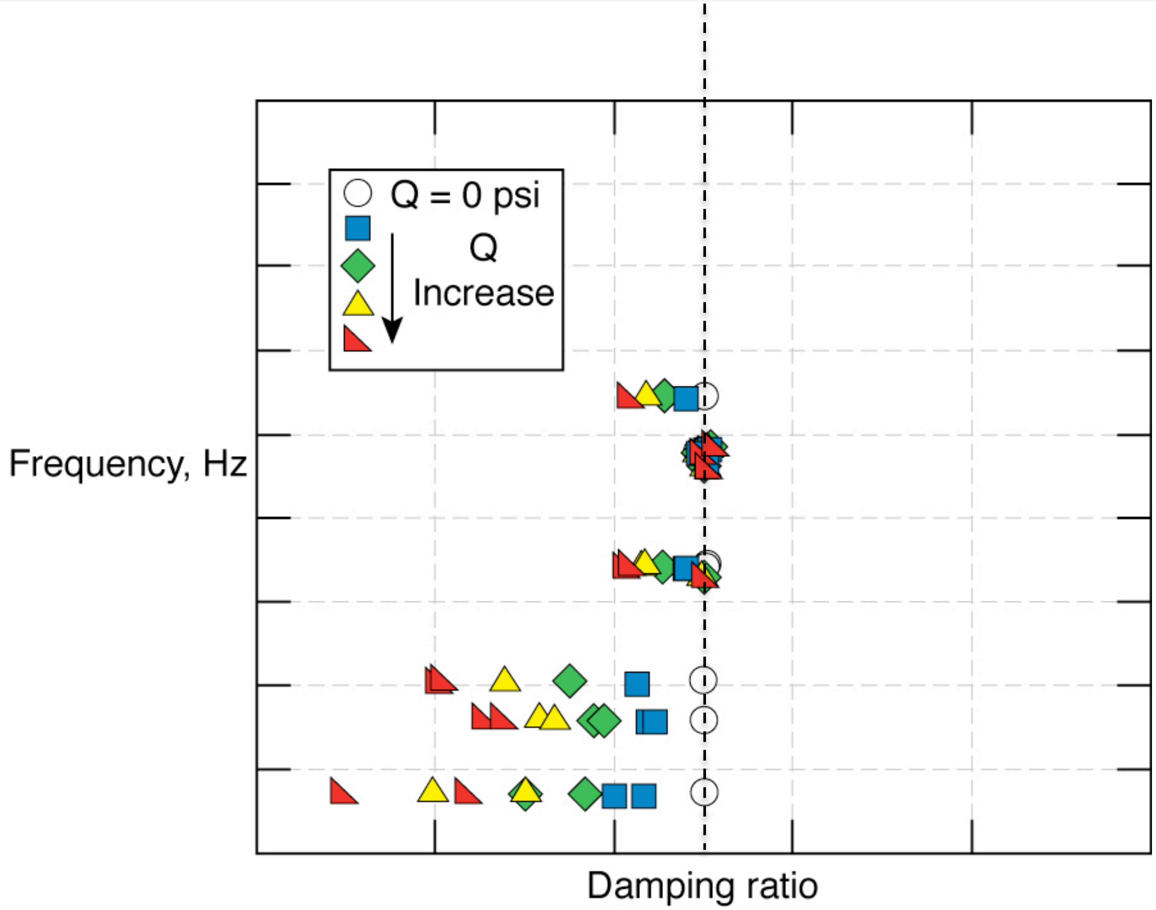
Results : Ares I-X

M=1.44, Increased Modal Frequencies



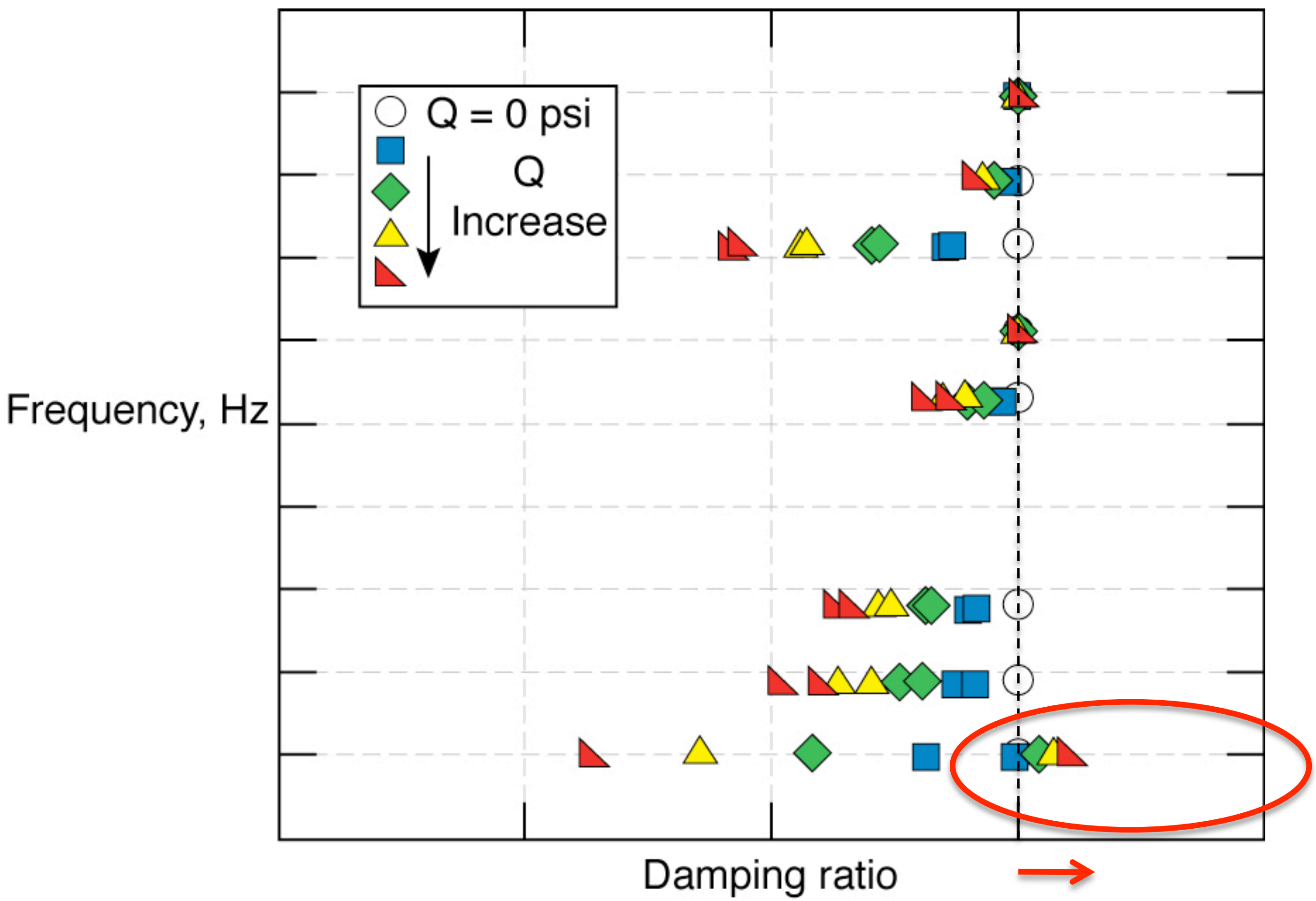
Results : Ares I-X

M=1.44, Decreased Modal Frequencies



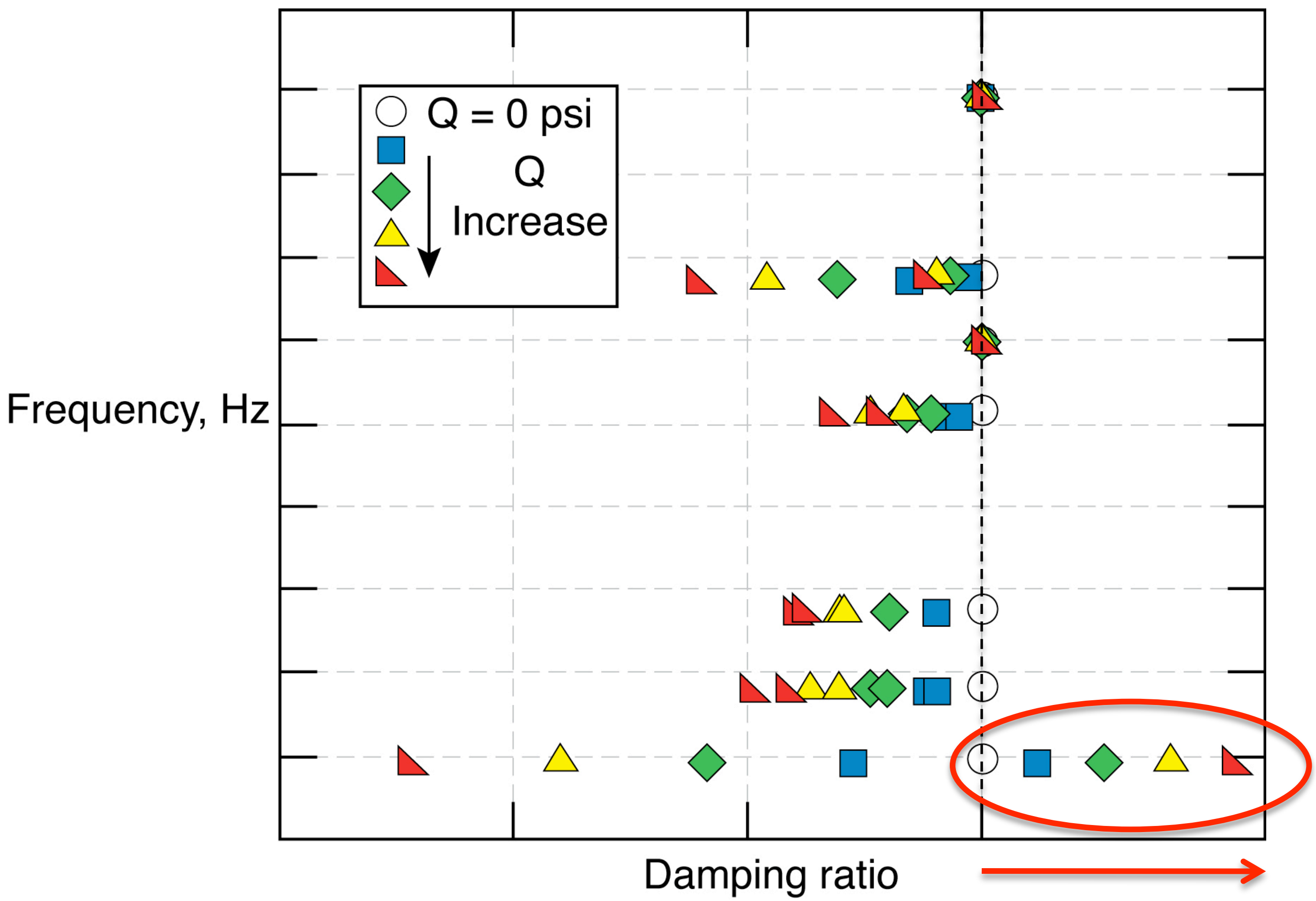
Results : Ares I

M=1.00, Baseline Vehicle



Results : Ares I

M=1.00, Thrust Oscillation Isolator (TOI) Vehicle



Concluding Remarks

- Recent ROM developments have been successfully implemented into FUN3D unstructured flow solver
- An error minimization method was developed to quantify and reduce the error associated with ROM development
- A method for directly generating the aeroelastic root locus plot using the aeroelastic simulation ROM was developed and successfully demonstrated
- Results were presented for the BACT, 2D, viscous case and the AGARD 445.6, 3D, inviscid case and for the Ares launch vehicle

Concluding Remarks

- Process for developing and applying unsteady aerodynamic, structural dynamic, and aeroelastic simulation ROMs presented along with error quantification procedure
- Generation of FUN3D responses per Mach number for ROM generation computed in days
- ROM procedure enables efficient computation of aeroelastic response due to parametric variations of structural parameters (modal frequencies); would require separate (and costly) FUN3D solutions per variation
- Aeroelastic simulations at a given Mach number per dynamic pressure using FUN3D computed in days
- Aeroelastic simulations at a given Mach number per dynamic pressure using ROMs computed in seconds

Concluding Remarks

- ROM root locus plots indicate significant level of reduced aeroelastic stability at M=0.5 for the Ares I-X vehicle
- ROM root locus plots indicate some level of reduced aeroelastic stability at M=0.95 for the Ares I-X vehicle
- ROM root locus plots indicate no reduction in aeroelastic stability at M=1.44 for the Ares I-X vehicle
- ROM root locus plots indicate some reduction in aeroelastic stability at M=1.00 for the Ares I vehicle
- ROM root locus plots indicate significant reduction in aeroelastic stability at M=1.00 for the Ares I vehicle with the Thrust Oscillation Isolator (TOI) variation