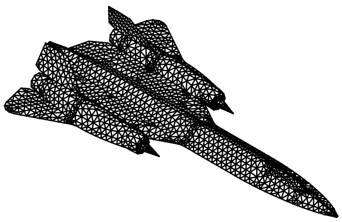
Master's Thesis Defense

Improved System Identification for Aeroservoelastic Predictions



Presented by

Charles Robert O'Neill

School of Mechanical and Aerospace Engineering
Oklahoma State University

Time and Location

10:30 am
2 July 2003
MAE Conference Room
218 Engineering North

Abstract

Modern high performance aerospace vehicles are particularly susceptible to destructive fluid-structure interactions. Accurate and timely aerodynamic predictions are needed for efficient vehicle design and evaluation. System identification offers an efficient and powerful prediction methodology by substituting a trained mathematical system model for the actual aerodynamic system. Coupling the system model with structural and control systems allows for fast and intuitive vehicle analysis. The challenge becomes determining a system model that accurately represents the dominant fluid-flow physics. This thesis investigated linear aerodynamic system identification for aeroservoelastic predictions based on Computational Fluid Dynamics (CFD) flow predictions.

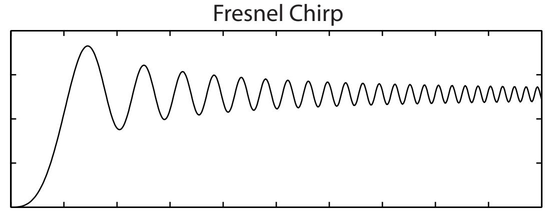
Presentation Preview

System Model

$$y(k) = \sum_{i=1}^{na} \left[A_i\right] y(k-i) + \sum_{i=0}^{nb-1} \left[B_i\right] x(k-i)$$

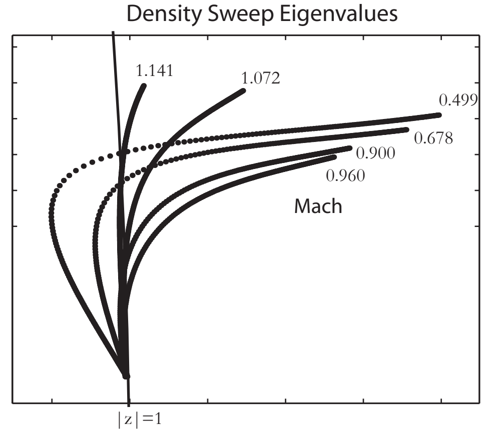
Excitation Signals

Fresnel Chirp



Aeroelastic Sensitivity Studies

Density Sweep Eigenvalues



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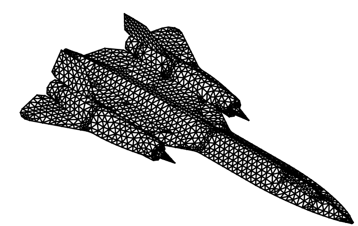

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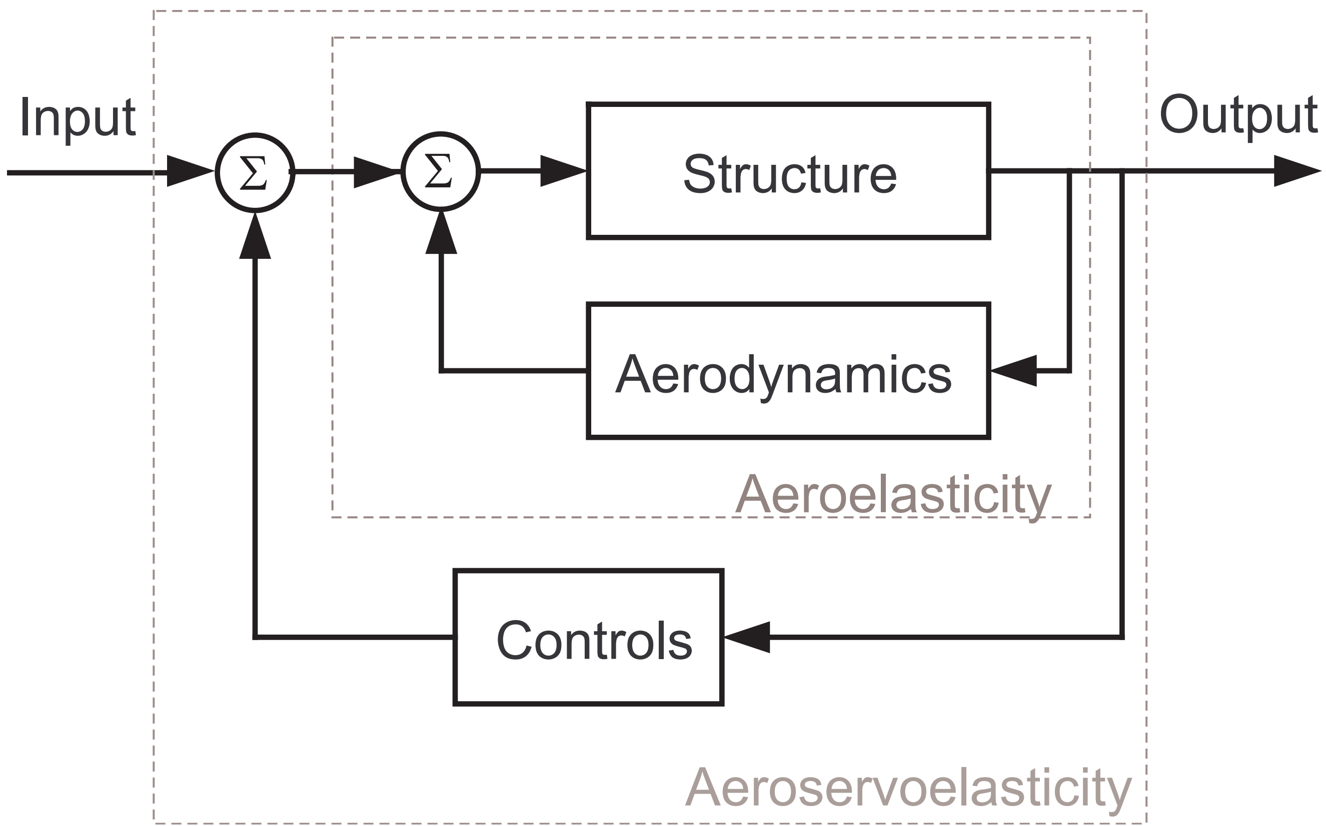
Aeroservoelasticity

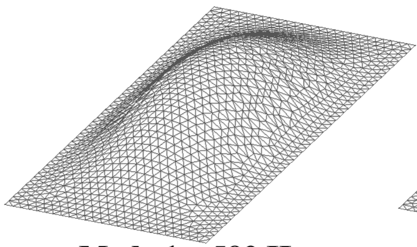
Aeroservoelasticity is a combination of structural, aerodynamics and controls systems.



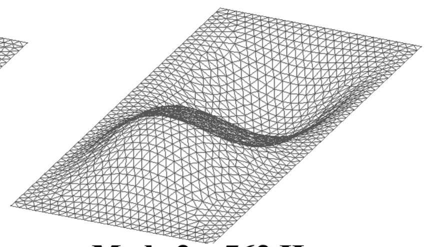
Structural System

The structural system properties are determined through decomposing the overall structure into modeshapes and frequencies.

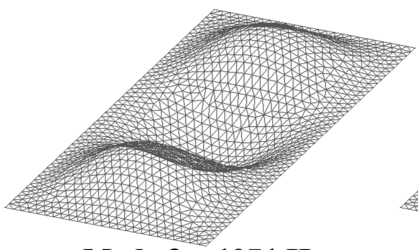
6 mode plate example



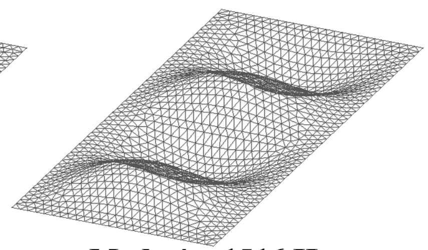
Mode 1: 589 Hz



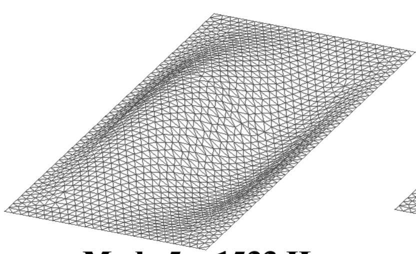
Mode 2: 762 Hz



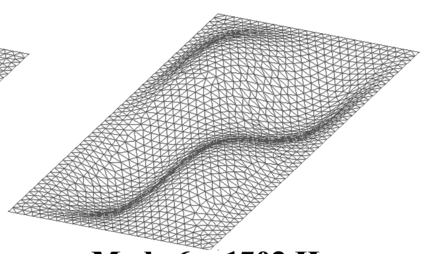
Mode 3: 1071 Hz



Mode 4: 1516 Hz



Mode 5: 1533 Hz



Mode 6: 1702 Hz

Governing Equation

The generic structural governing equation contains mass, damping, stiffness and an external forcing function.

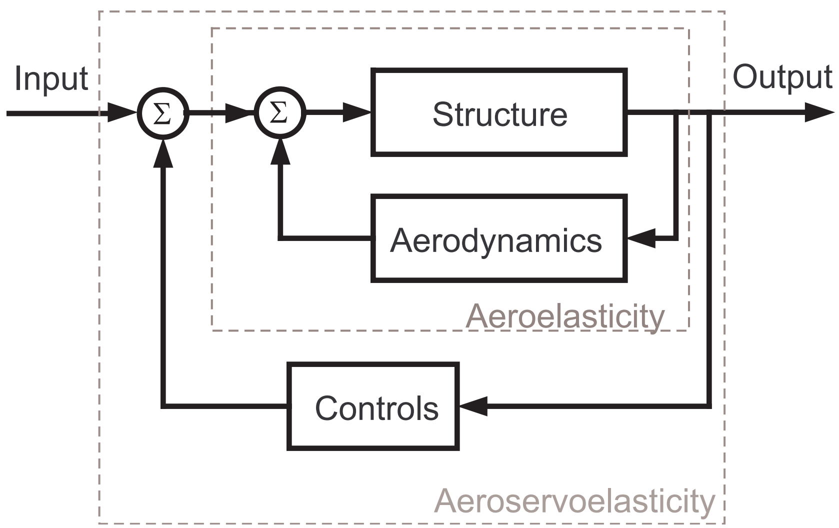
$$[M]\ddot{q} + [C]\dot{q} + [K]q = F$$

The discrete time structural model is the following:

$$x_s(k+1) = [G_s]x_s(k) + [H_s]F(k)$$
$$q(k) = [C_s]x_s(k) + [D_s]F(k)$$

Controls System

The control system properties are determined through the designer's specific system performance criteria. A control system modifies the overall system response.



Determining a useful controls model is conceptually straightforward. The exact implementation methodology can vary. A generalized control law follows:

$$\eta = [K]\vec{x}$$

The Problem

Traditional free response analysis of aerospace vehicles with Computational Fluid Dynamics requires significant computing power and does not allow for intuitive or quick analysis and design.

Objective

The objective is to develop an improved system identification methodology for aeroservoelastic predictions. Substituting the trained aerodynamic system model for the actual aerodynamic system will allow for an efficient and powerful prediction methodology.

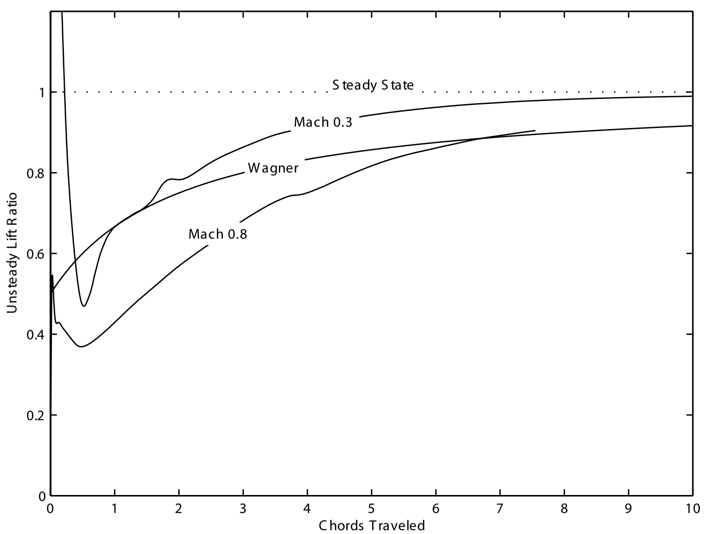
Decompose into 4 areas

Aerodynamic System Model	How to represent the aerodynamic system
Training Method	How to determine the aerodynamic system parameters from raw data
Excitation Signal	How to excite the dominate aerodynamics
Performance Criteria	How to evaluate and select a system model

Unsteady Aerodynamics

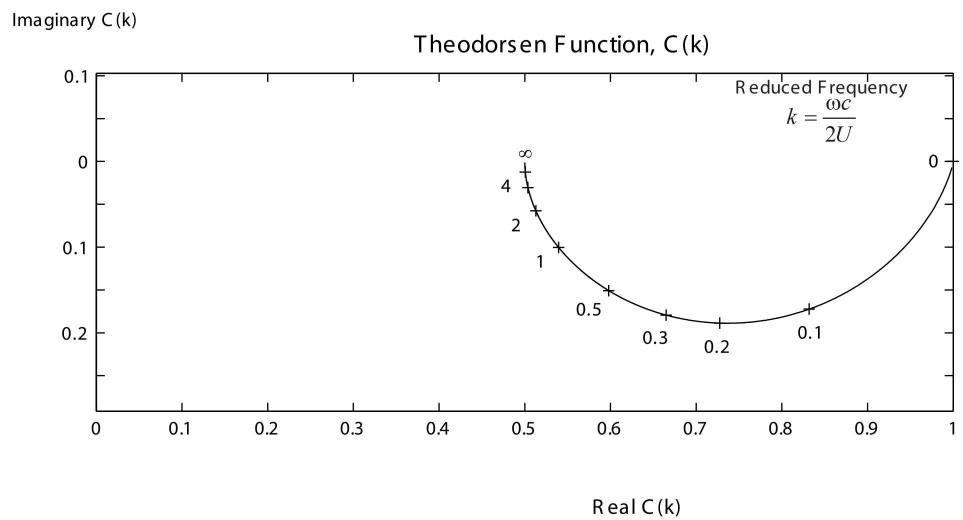
No general closed form solution exists for unsteady aerodynamics. Two classical unsteady aerodynamic expressions result from assuming an incompressible, inviscid flow with simple motions and simple geometry. The Wagner, Theodorsen and wave-equation expressions allow insights into representing unsteady aerodynamic

Wagner Step Input



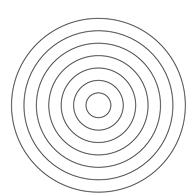
Theodorsen Harmonic Motion

$$L = \pi\rho b^2(\ddot{h} + U\dot{\alpha} - ba\ddot{\alpha}) + 2\pi b\rho U(\dot{h} + U\alpha - ba\dot{\alpha})C(k)$$

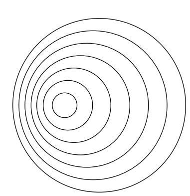


Wave Equation

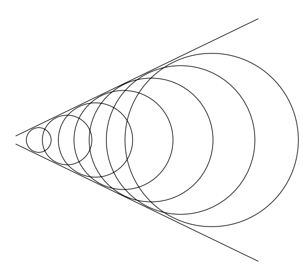
$$\frac{D^2}{Dt^2} = a_0^2\nabla^2$$



No Motion



Subsonic



Supersonic

Aerodynamic Modeling Requirements

Consistent Boundary Conditions

Input-Output Dynamics

Starting and Ending Conditions

Accuracy near system stability point

Captures different time scales

Motion limitations to remain in linear region

Aerodynamic Representations

Using the previous unsteady aerodynamic results and modeling requirements, the following generic aerodynamic function is proposed.

$$f^{(n)} + \ldots + \ddot{f} + \dot{f} + f + f(delays) = x^{(n)} + \ldots + \ddot{x} + \dot{x} + x + x(delays) + C$$

Now, a specific system model needs to be selected. The best candidates were the indicial response model and the ARMA model.

Indicial Response

The indicial response consists of a step response. The system response is determined through convolution. The system parameters are determined by the step response function g(t). Determining g(t) becomes complicated when the boundary conditions are coupled.

$$y(t) = \int_0^t g(t-\tau)u(t)d\tau$$

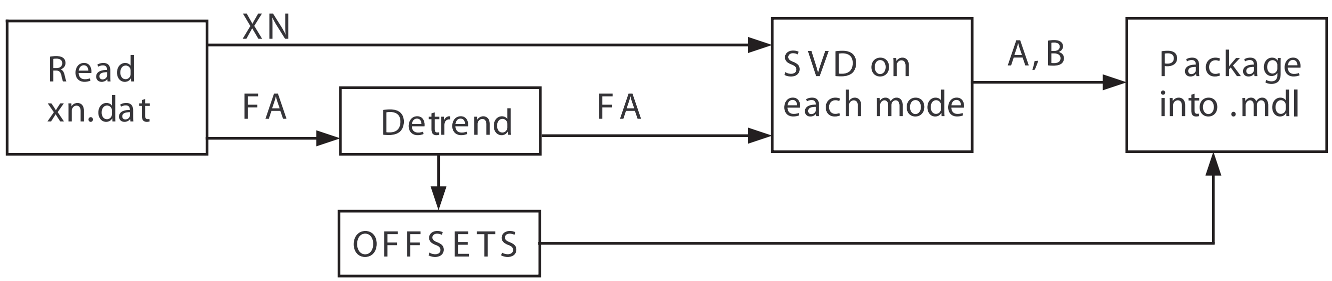
ARMA Model

The Auto Regressive Moving Average (ARMA) model consists of an input-output expression with internal and input responses. Individual coefficients A_i and B_i determine the system parameters. The ARMA model directly corresponds to a discrete-time ODE representation.

$$f(k) = \underbrace{\sum_{i=1}^{na} [A_i] f(k-i)}_{\text{Internal Response}} + \underbrace{\sum_{i=0}^{nb-1} [B_i] q(k-i)}_{\text{Input Response}}$$

Training Methodology

The training method reduces the raw aerodynamic time histories to usable aerodynamic system models.



Expressing the inputs and outputs in the ARMA system form yields:

$$\begin{bmatrix} \overbrace{y(t-1) \;\cdots\; y(t-na)}^{\text{Previous Outputs}} & \overbrace{x_1(t) \;\cdots\; x_{nr}(t) \;\cdots\; x_1(t-nb-1) \;\cdots\; x_{nr}(t-nb-1)}^{\text{Past and Current Inputs}} \\ \vdots & \vdots \quad \cdots \quad \vdots \end{bmatrix} \begin{bmatrix} A_i \\ B_i \end{bmatrix} = \begin{bmatrix} \overbrace{y(t)}^{\text{Current Output}} \\ \vdots \end{bmatrix}$$

This is a linear equation of the form:

$$[A]\vec{x} = \vec{b}$$

Solving for the x vector yields the ARMA model coefficents. Singular value decomposition (SVD) is used to solve this linear least squares algebraic system. SVD is preferred because of its robustness and its abiliity to solve overdetermined systems.

Parallel Training

Parallel training is possible by making noticing the structure of the training data matrix. The columns represent the model order, the rows represent the individual timesteps.

$$\begin{bmatrix} y(0) & x(1) & x(2) \\ y(1) & x(2) & x(3) \\ y(2) & x(3) & x(4) \end{bmatrix} \cdot \begin{bmatrix} A_1 \\ B_1 \\ B_2 \end{bmatrix} = \begin{bmatrix} y(1) \\ y(2) \\ y(3) \end{bmatrix}$$

Catenating additional rows onto the matrix is permitted. The only caveat is to ensure consistency of previous forces and displacements occuring before time zero.

Advantages:

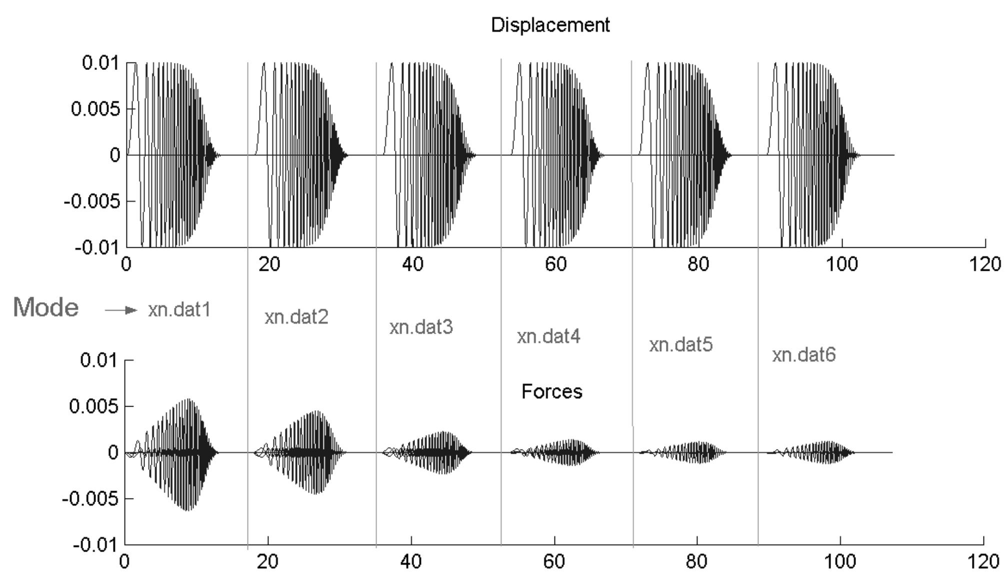
Eliminates long-lag contamination

Eliminates modal dispersion

Distributed computing

Excitation tailoring

Less sensitive to errors than serial training



Disadvantages:

Extra bookwork

Must join all signals for model evaluations

Excitation Signals

For the aerodynamic identification process to capture a useful model, the dominant aerodynamics must be excited. The excitation is directly related to the input signal. The following criteria were identified as important to successful input signal design. The criteria are based on physics, performance and system model characteristics.

Criteria

The excitation must be consistent with the unsteady aerodynamic representation.

Static offset forces must be calculated

Excite the dominant unsteady aerodynamics while being kept in the "linear" aerodynamic range

Input and output dynamics must be excited

Excite the system within a useful frequency range

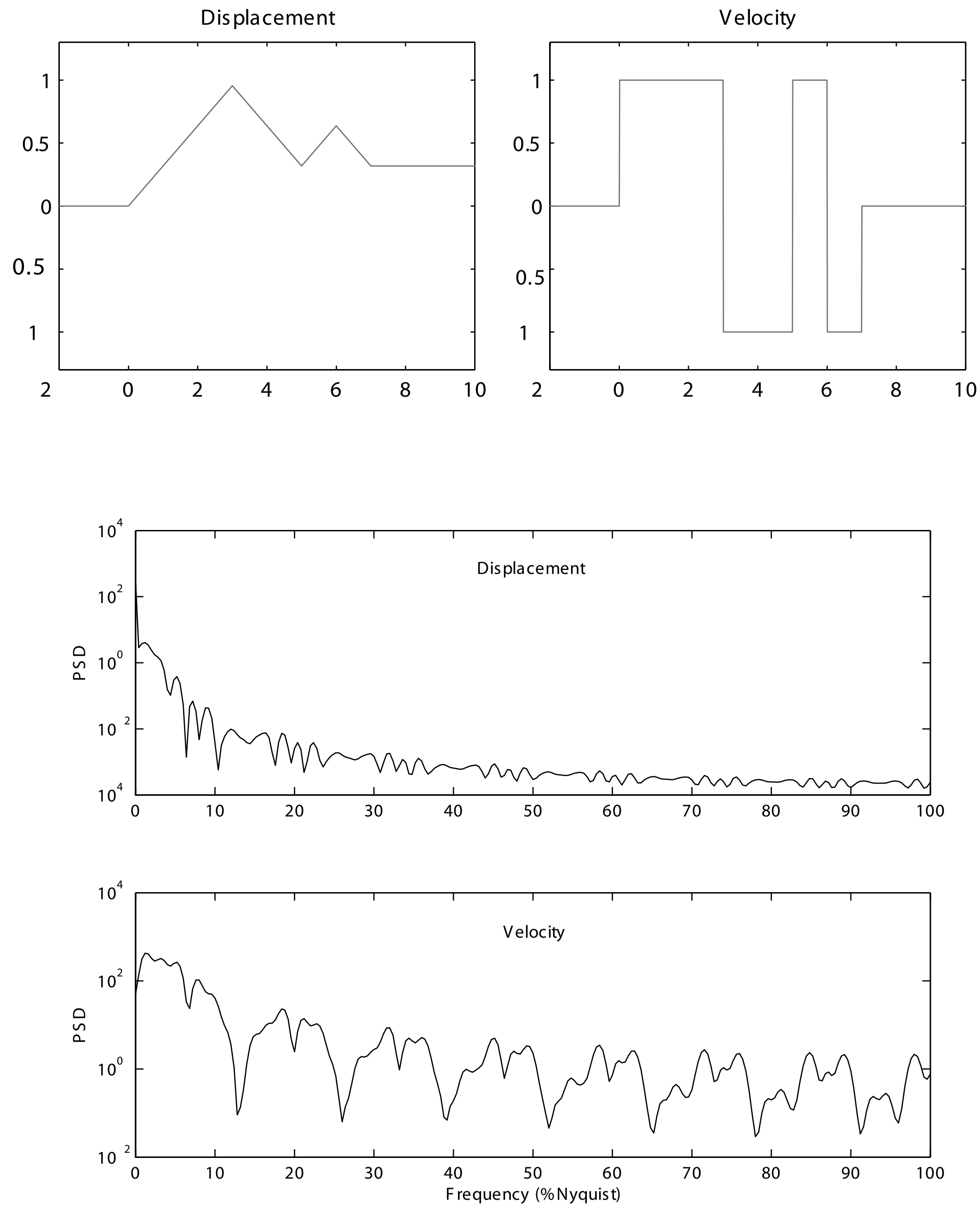
Multistep

Advantages:

Easy to implement
Simple functional form
Broad PSD
Common flight-test signal

Disadvantages:

Inconsistent Boundary Conditions
Non intuitive excitation length
Holes in PSD



Chirp

Linear Frequency Sweep

$$d(t) = \sin(\omega t^2)$$

$$v(t) = 2\omega t \cos(\omega t^2)$$

Advantages:

Consistent with functional requirements

Flat PSD

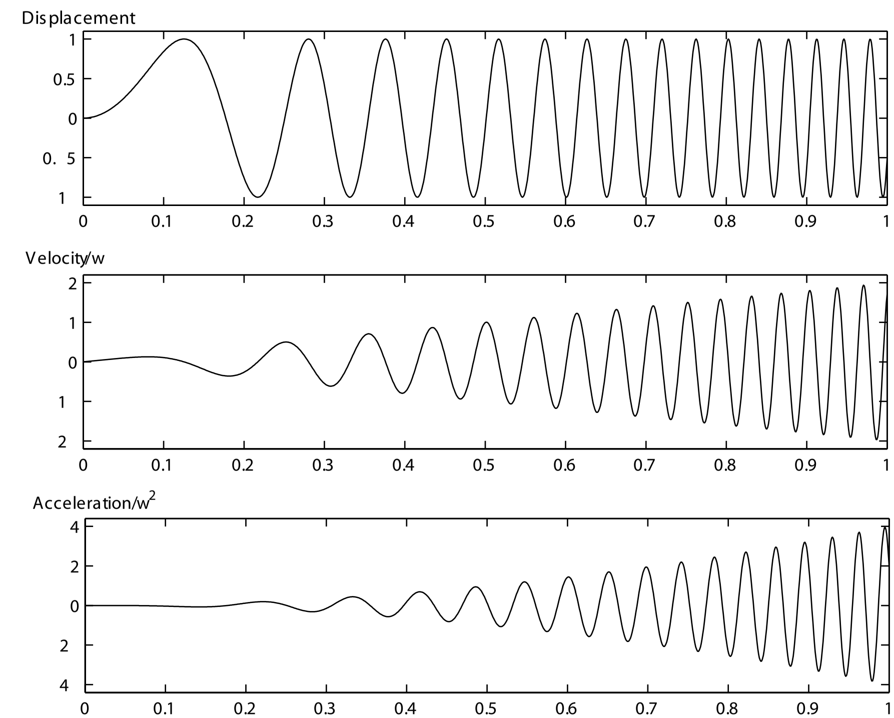
Intuitive excitation length

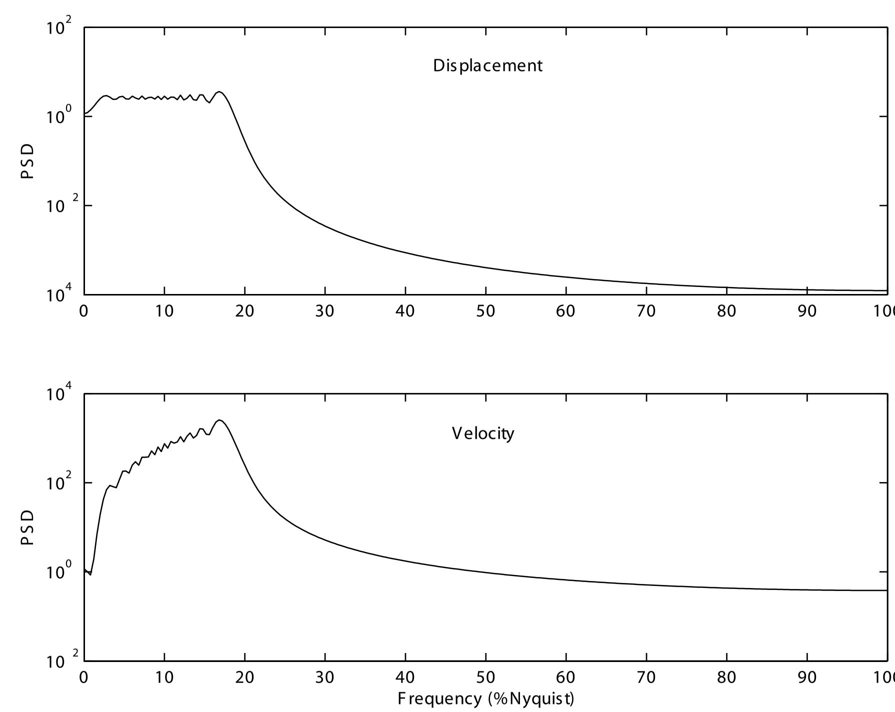
Disadvantages:

Poor low frequency performance

Only captures analytic response

Can overexcite the system





DC Chirp

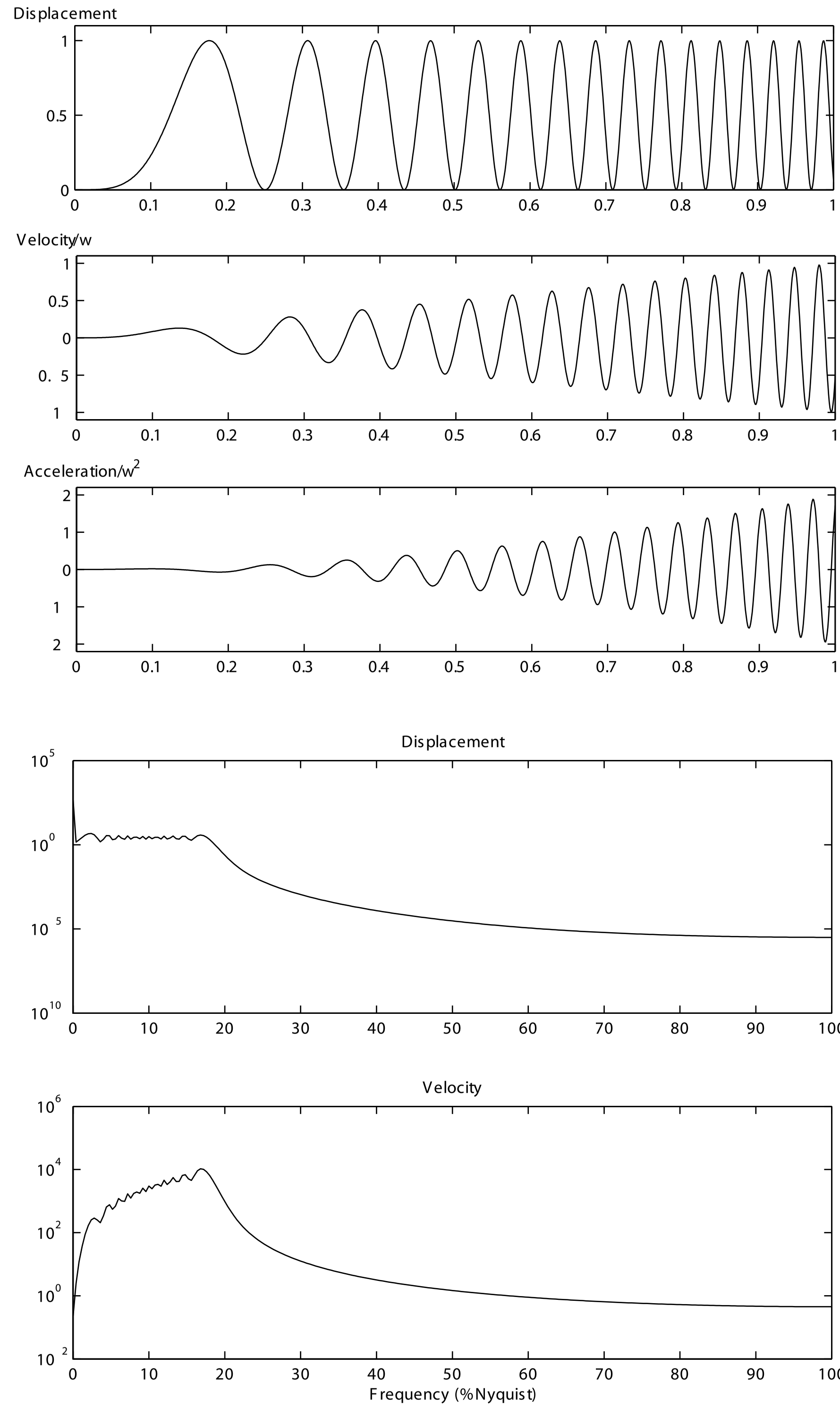
Linear Frequency Sweep with a DC Offset

$$d(t) = -\frac{1}{2}\cos(\omega t^2) + \frac{1}{2}$$

$$v(t) = \omega t \sin(\omega t^2)$$

Advantages:
Same advantages as the chirp
Improved low frequency excitation

Disadvantages:
Peak factor is twice the chirp's



Fresnel Chirp

The Fresnel chirp is the integral of the sine function. The Fresnel form is commonly seen in optics.

$$d(t) = S(t) = \int \sin(\omega t^2)$$

$$v(t) = \sin(\omega t^2)$$

Advantages:

Flat PSD for velocity

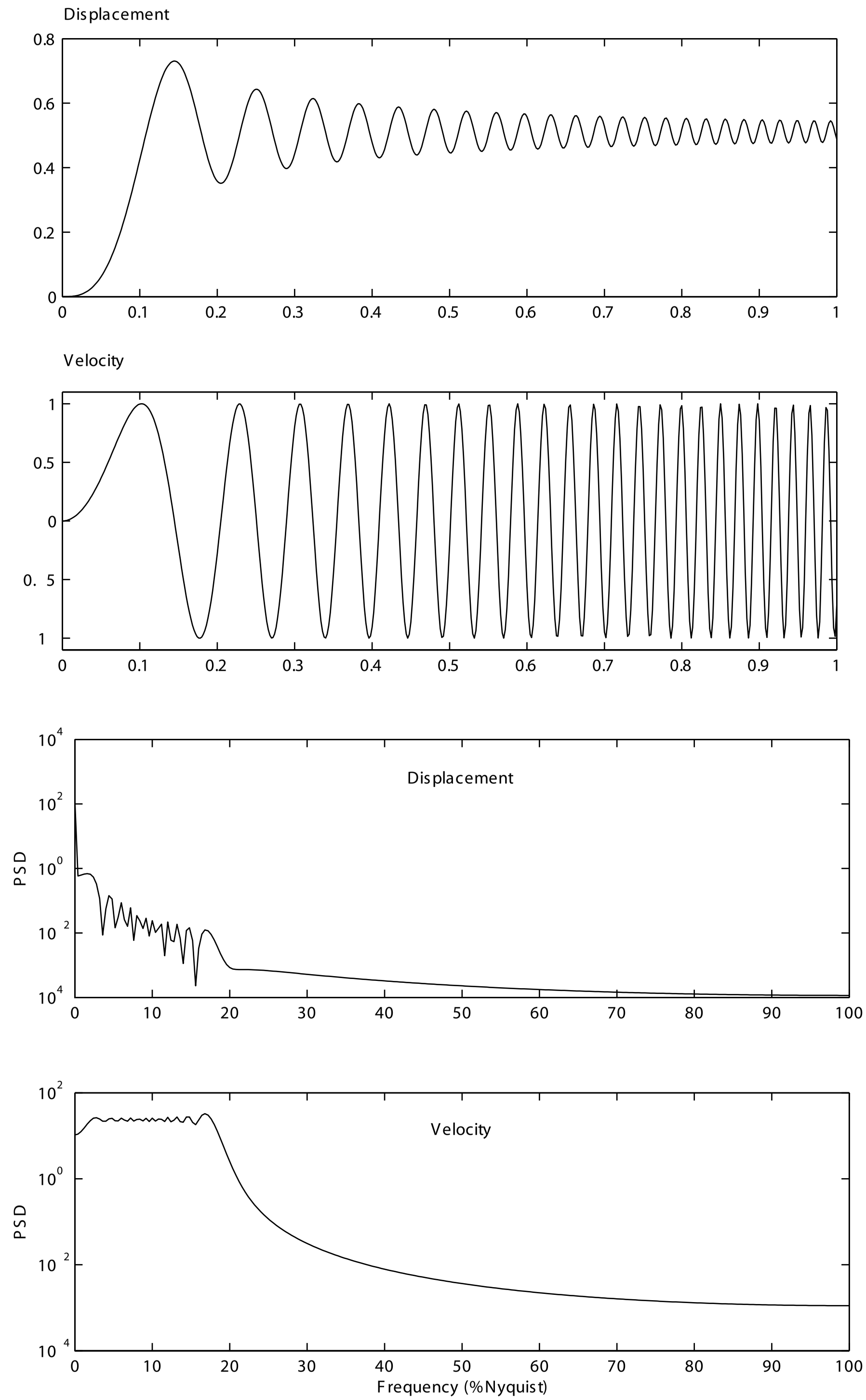
DC offset component

Disadvantages:

No closed form solution

Displacement PSD has holes

Offset Fresnel is impractical



Schroeder Sweep

The Schroeder form is based on a sum of cosine terms with a specified phasing. The form is analytic in time but not smooth in frequency.

$$d(t) = \sum_{k=1}^{N} \sqrt{\frac{1}{2N}} \cos(\frac{2\pi kt}{T} - \frac{\pi k^2}{N})$$

$$v(t) = \sum_{k=1}^{N} \frac{-2\pi k}{T} \sqrt{\frac{1}{2N}} \sin(\frac{2\pi kt}{T} - \frac{\pi k^2}{N})$$

Advantages:

Flat PSD

Optimal peak factor

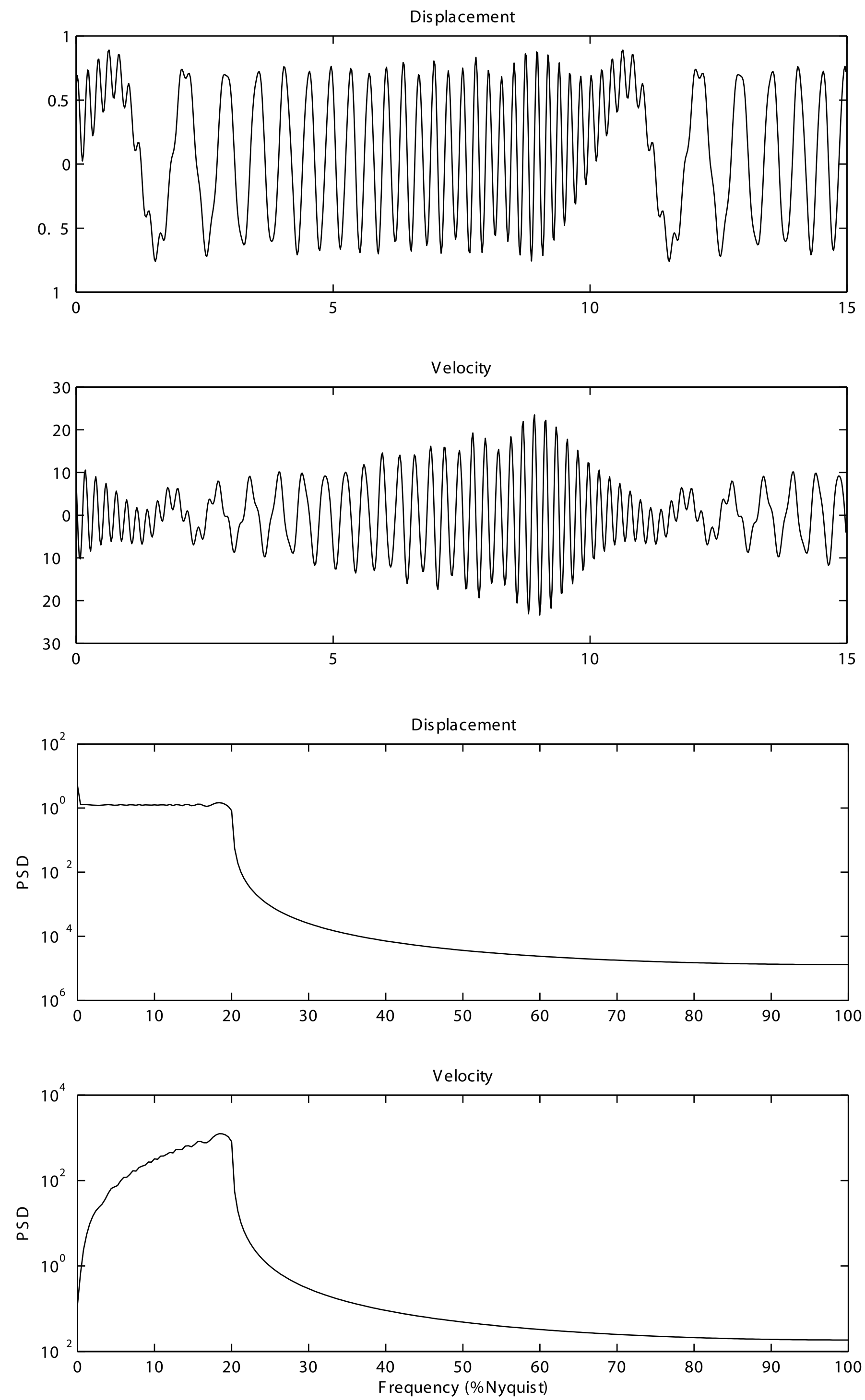
Desirable low frequency response

Harmonic signal allows an arbitrary excitation length

Disadvantages:

Does not start from rest

Sensitivities to excitation method



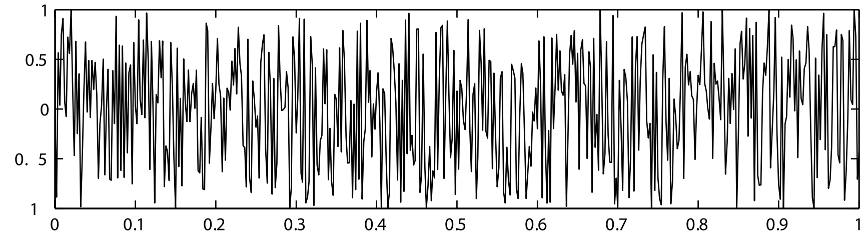
Noise

An often proposed solution is to use
a noise input signal.

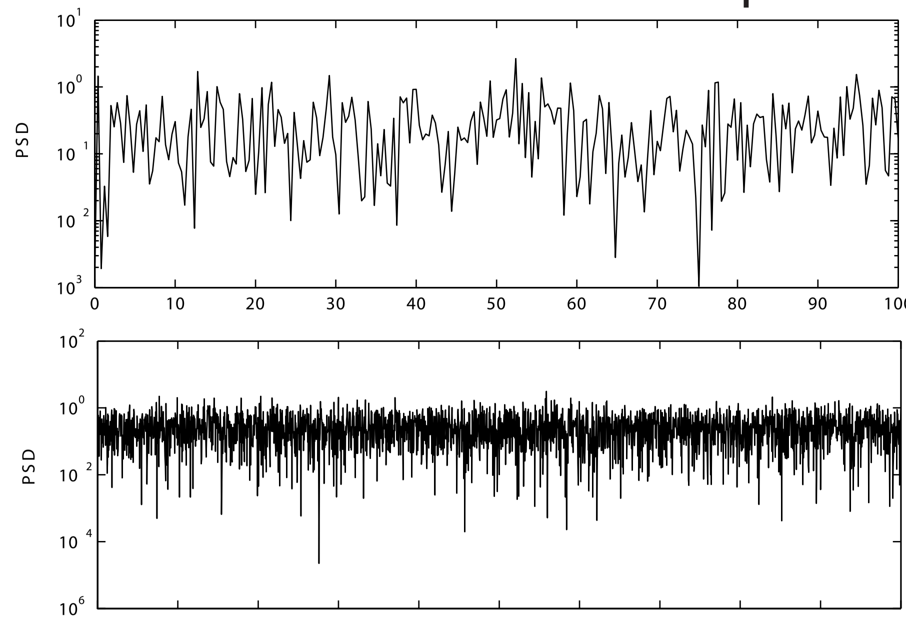
Advantages:
Flat PSD
No limit on excitation length
Excites entire flow dynamics

Disadvantages:
Flat PSD only occurs in the limit
Non intuitive excitation length
Non deterministic causes BC problems
Equal power means "sharp" changes

Motion

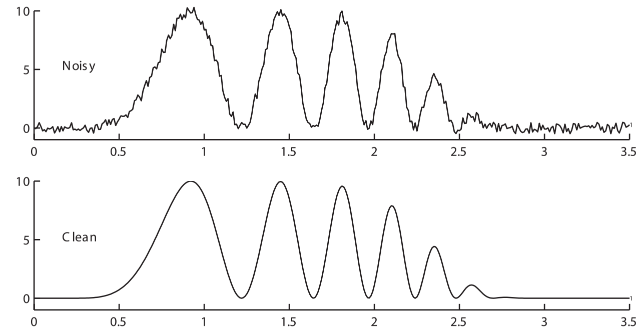


PSD for 500 and 5000 data points

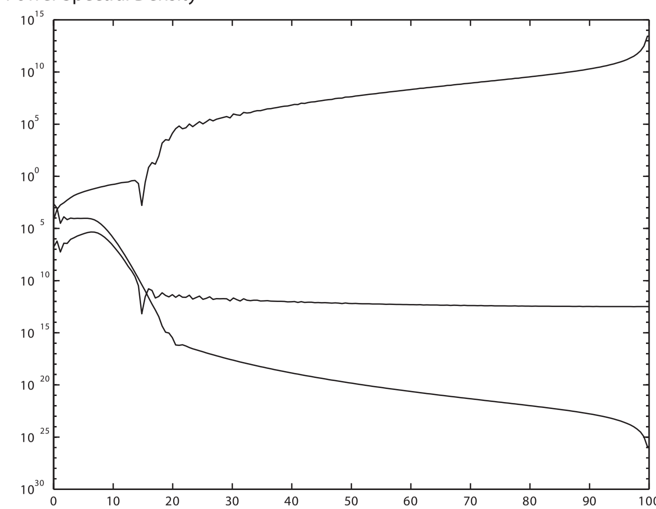


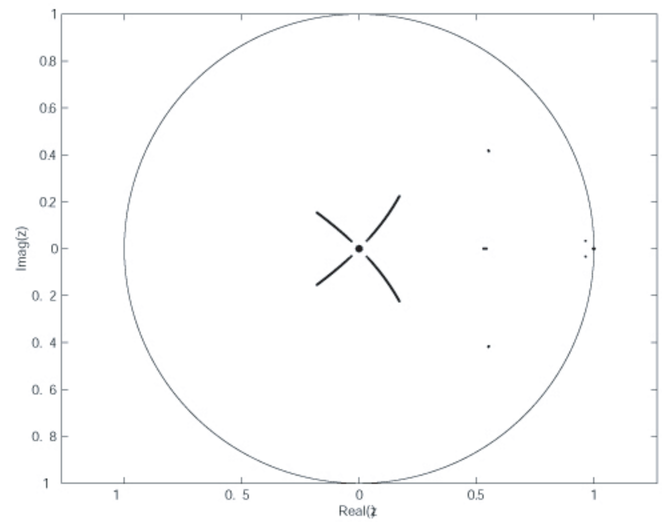
Artificial Noise

Contrary to intuition, adding noise to an existing signal is often desired for better high frequency modeling.

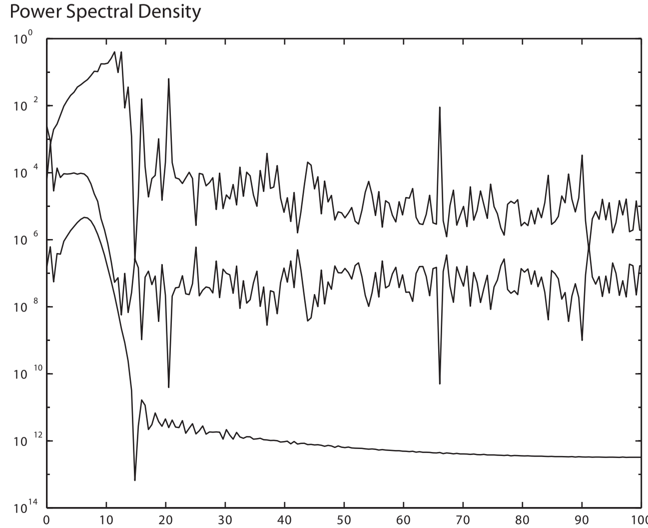


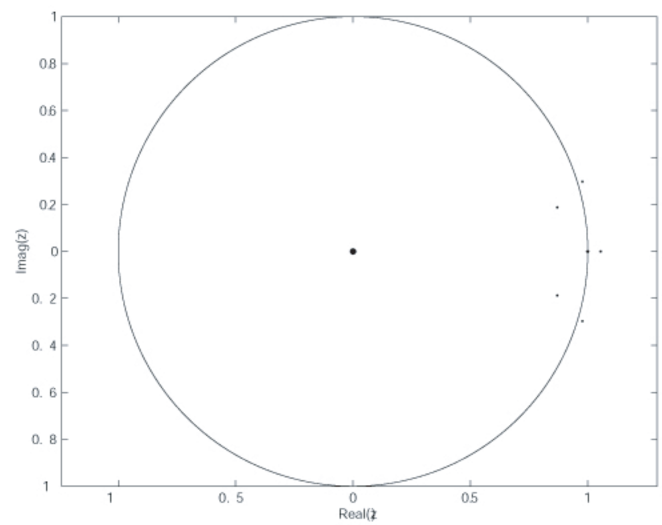
Clean Signal





Noisy Signal





Motion Specification

Strict Specification

For strict motion specification, the motion boundary conditions at each timestep are determined from a numerical or analytical expression.

Advantages:

"Perfect" signals

Easy implentation

Disadvantages:

Not consistent in a discrete time sense

State Space Specification

For state space motion specification, the boundary conditions are updated simultaneously though the motion state vector. This exactly duplicates the actual discrete time CFD motion form.

Advantages:

Simultaneous BC updates

Input signals are filtered through a "structure" with mass.

Disadvantages:

Requires selecting a "structural mass"

Undersirable stopping conditions lead to motions that are nonlinear.

Model Evaluation

An evaluation methodology is needed to compare and select the "best" aerodynamic system model. Visual inspection is doomed; the evaluation must be based on a numerical measurement.

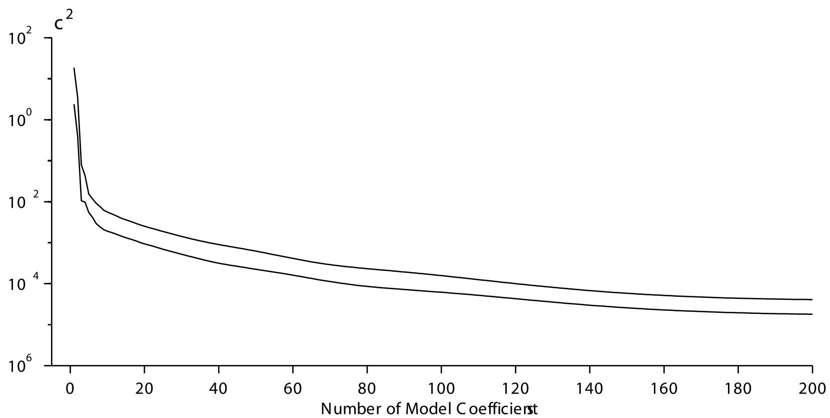
Evaluation based on Model Errors

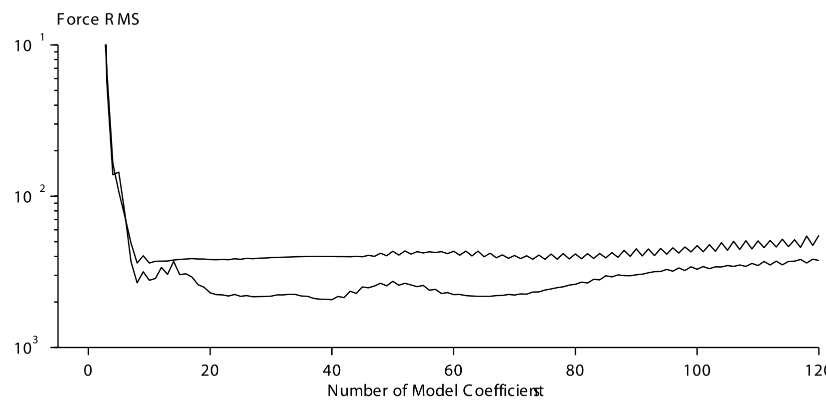
$$\chi^2 = \frac{||A \cdot \hat{x} - b||^2}{nstp}$$

Indicates the matrix solution quality

$$RMS = \sqrt{\frac{1}{N}\sum_{k=0}^{N}(y(k) - \hat{y}(k))^2}$$

Indicates the model prediction quality





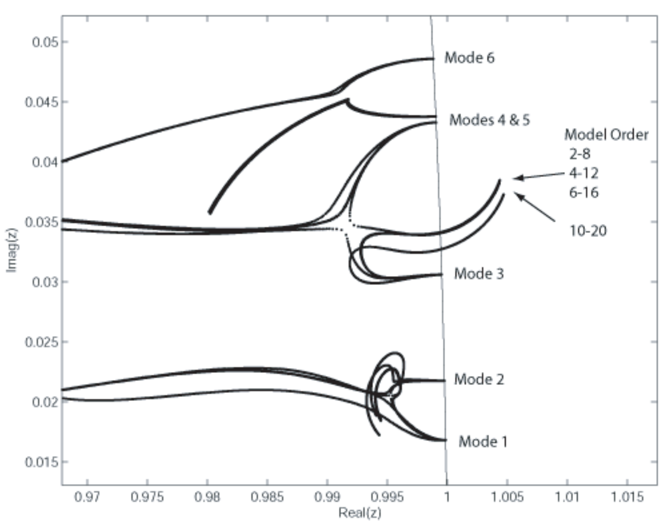
Model Evaluation

Evaluation based on Aeroelastic Stability

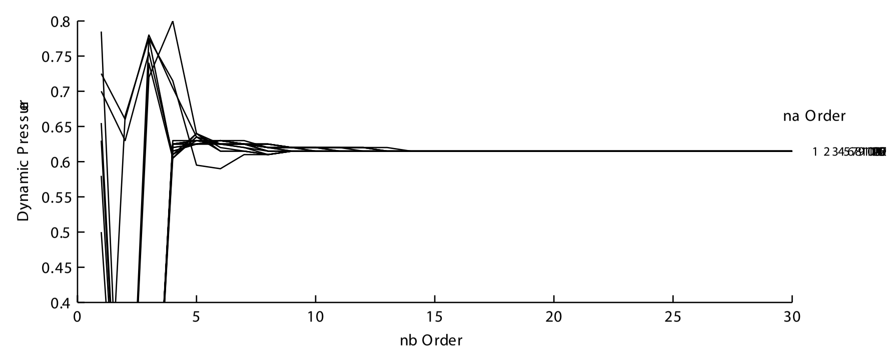
Using the model for coupled aerostructural predictions exercises the model's prediction characteristics in a realistic and intuitive manner. This evaluatation is based on system eigenvalue predictions. The coupled aeroelastic plant matrix is:

$$\begin{bmatrix} G_s + q_\infty H_s D_a C_s & q_\infty H_s C_a \\ H_a C_s & G_a \end{bmatrix}$$

Eigenvalue Form



Stability Boundary Form



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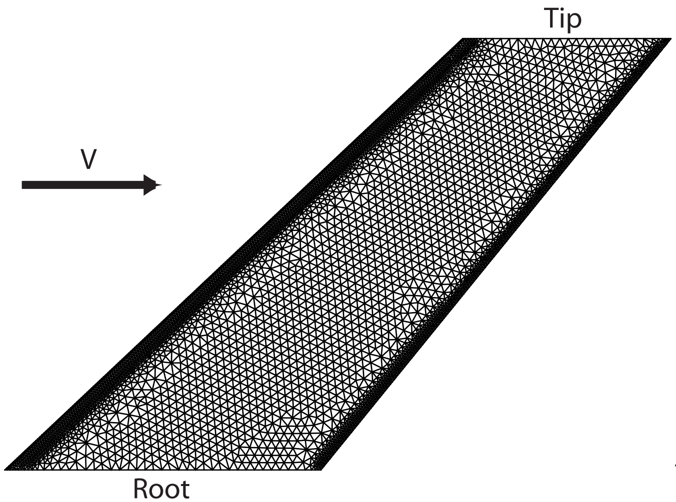
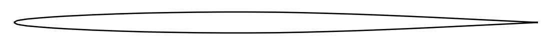
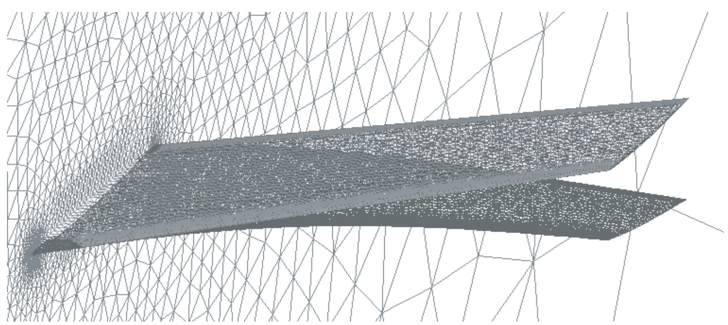


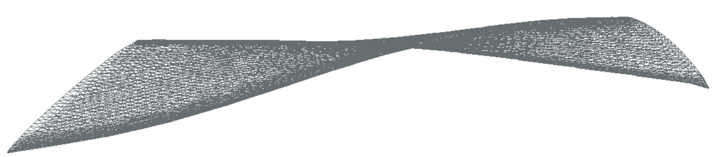
45 degree sweep
Aspect Ratio 2
60% taper ratio
NACA 65A004



Two Mode Structural Model



First Bending Mode
9.6 Hertz



First Torsional Mode
38.2 Hertz

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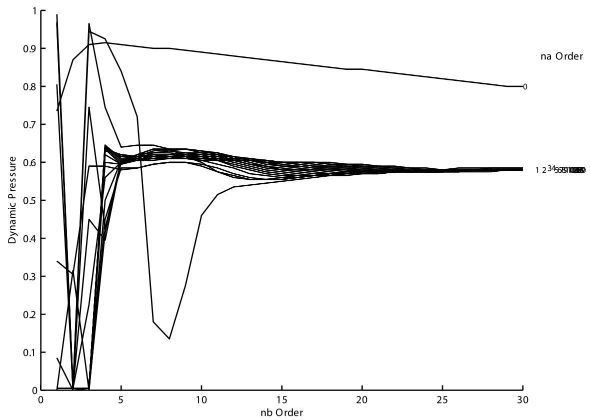
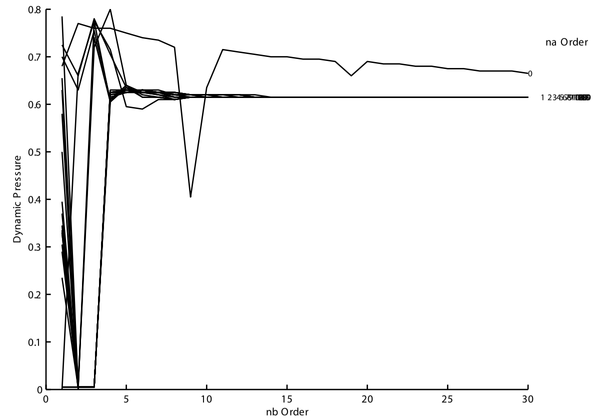
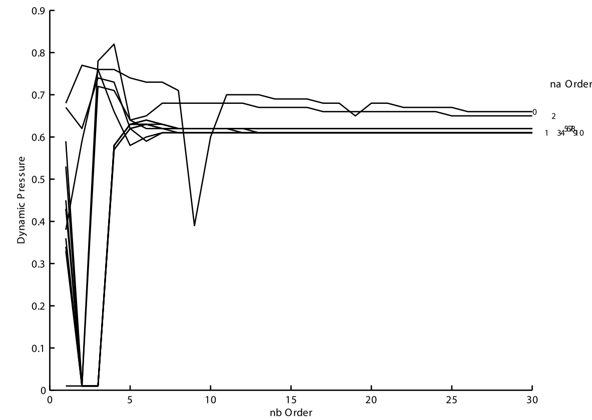
Chirp



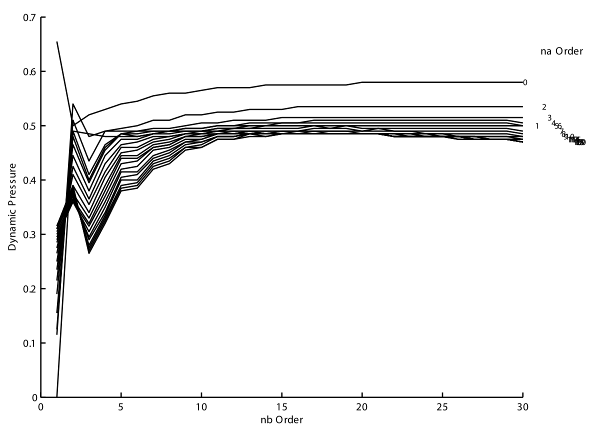
DC Chirp



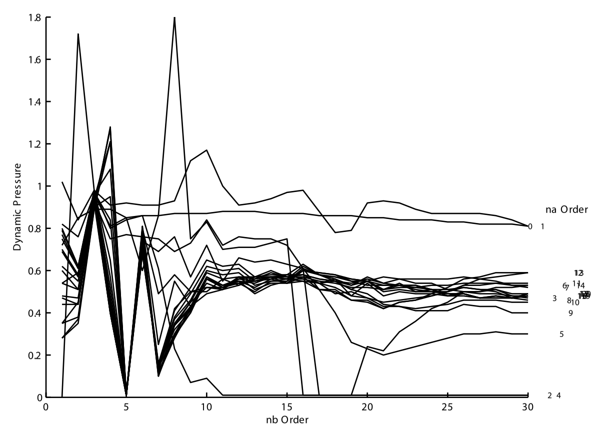
DC Chirp Large Amplitude



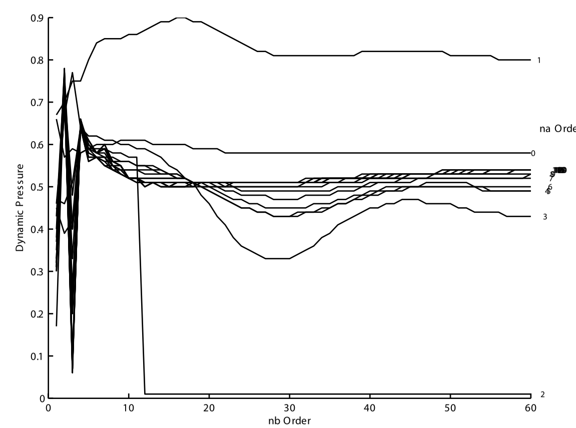
Multistep



Schroeder



Fresnel with State Space Specification



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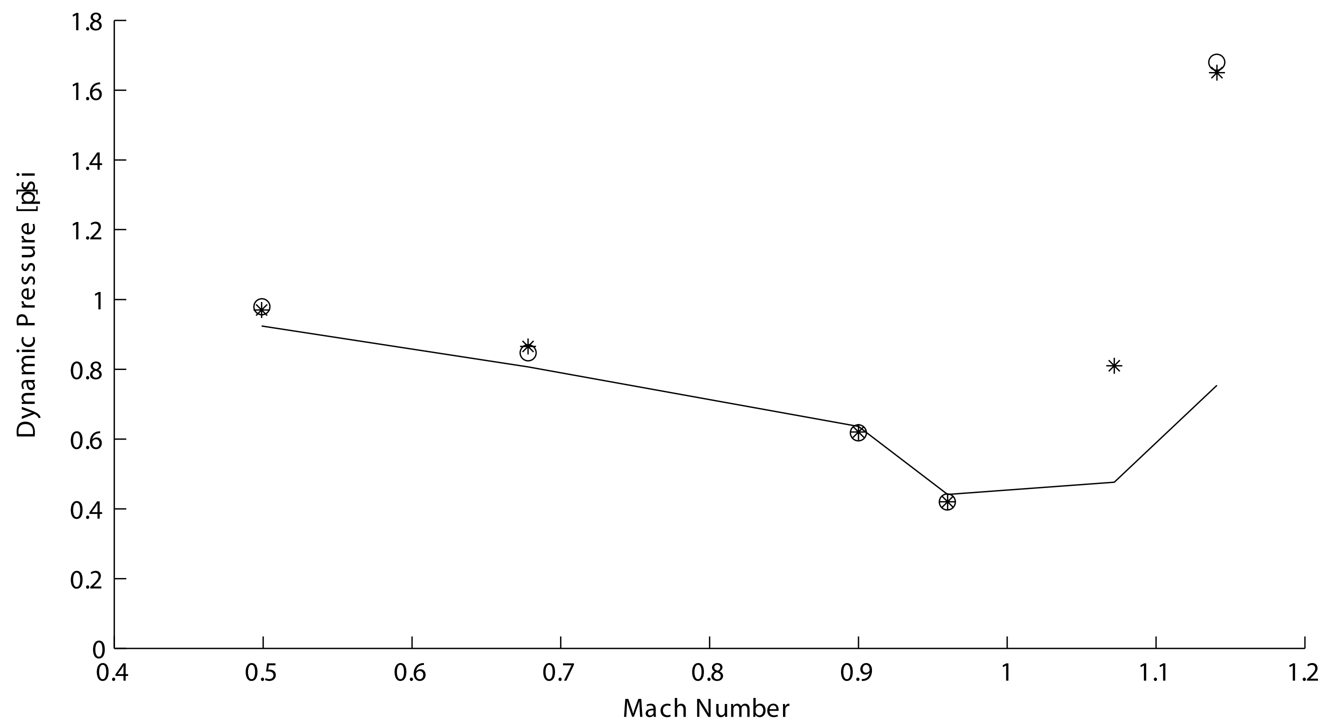
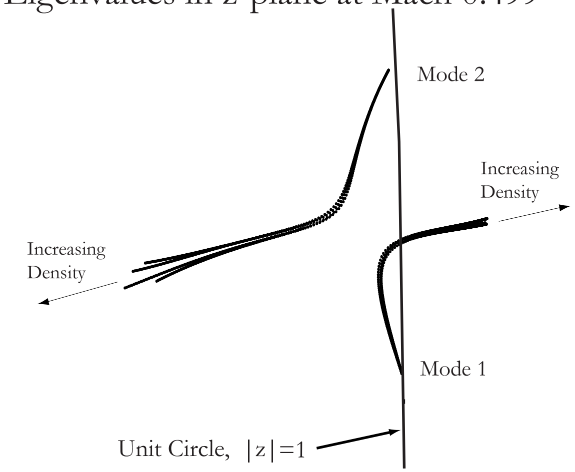
Stability Boundary



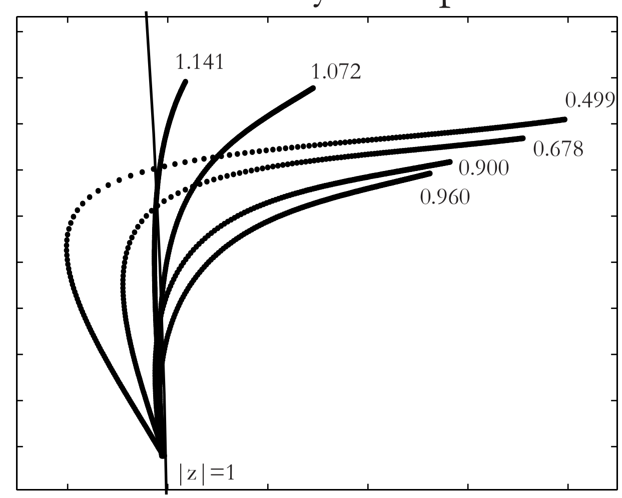
AGARD 445.6 Sensitivity Studies

Model Sensitivity Study

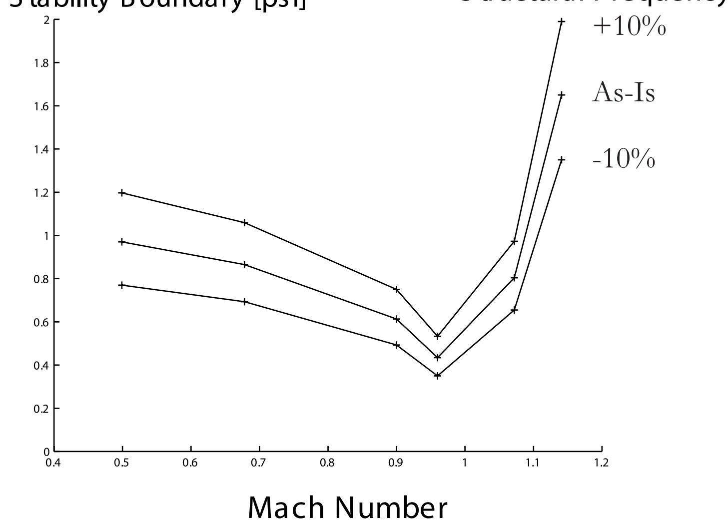
Eigenvalues in z-plane at Mach 0.499



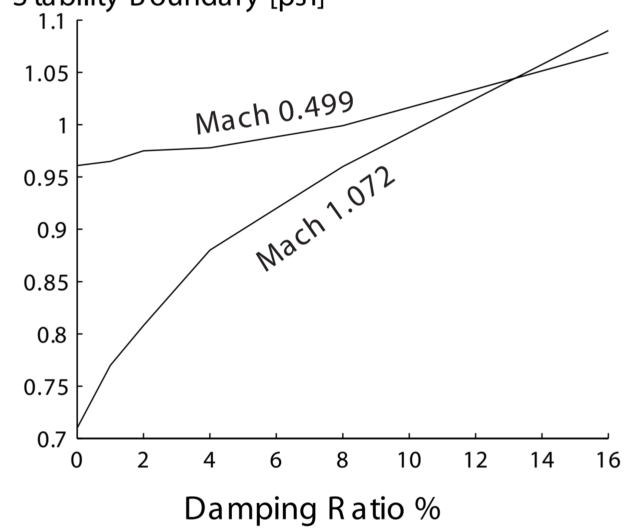
Density Sweep



Stuctural Frequency Study

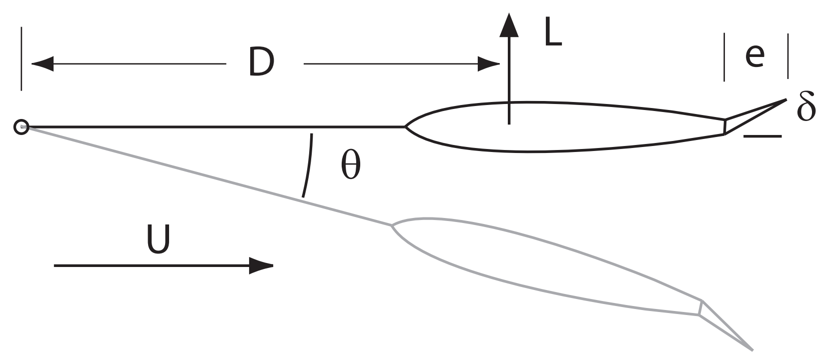


Stuctural Damping Study

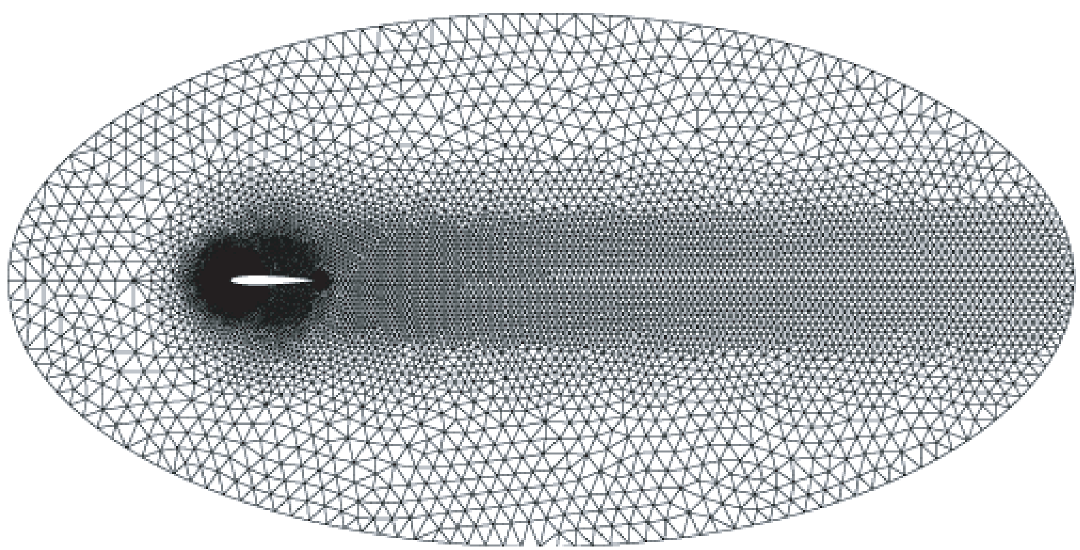


Wing/Flap Control

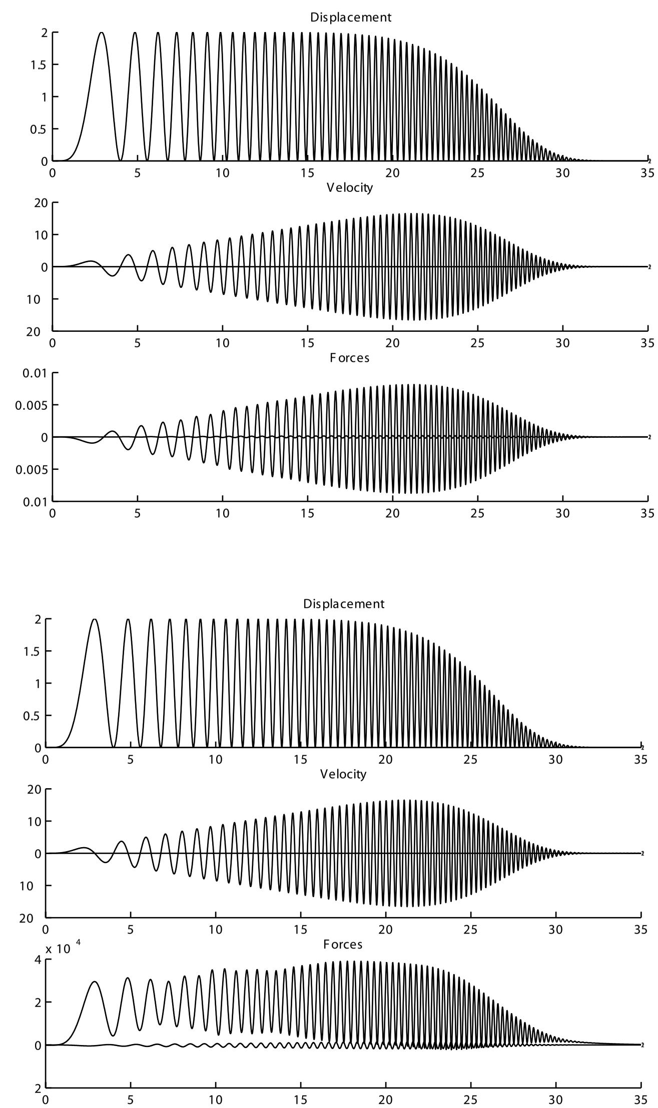
Schematic



CFD Grid

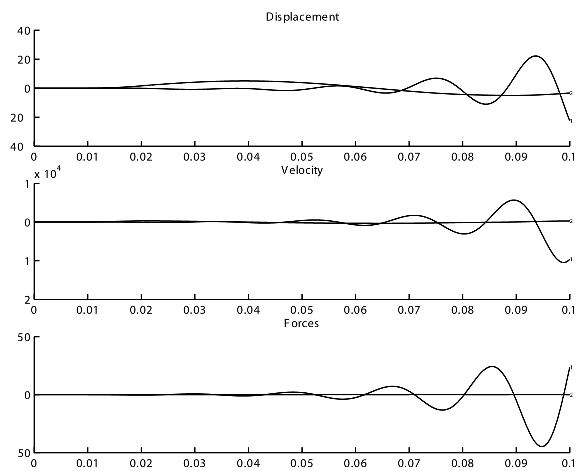


Training Signals

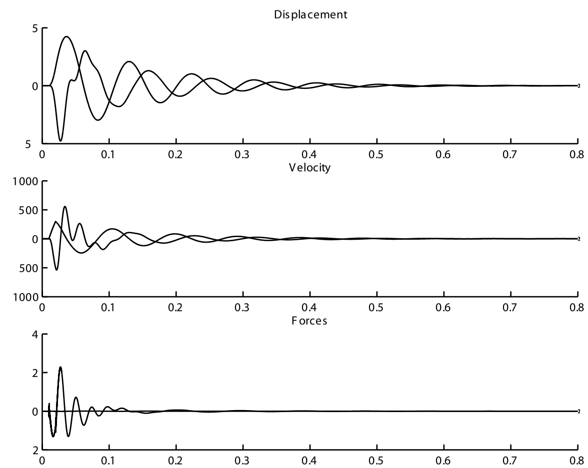


Wing/Flap Control

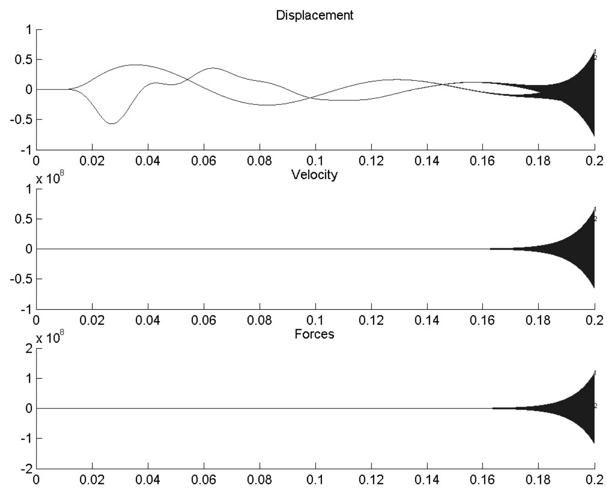
Open Loop



Closed Loop
k={3.5, 0, -0.01, -0.04}

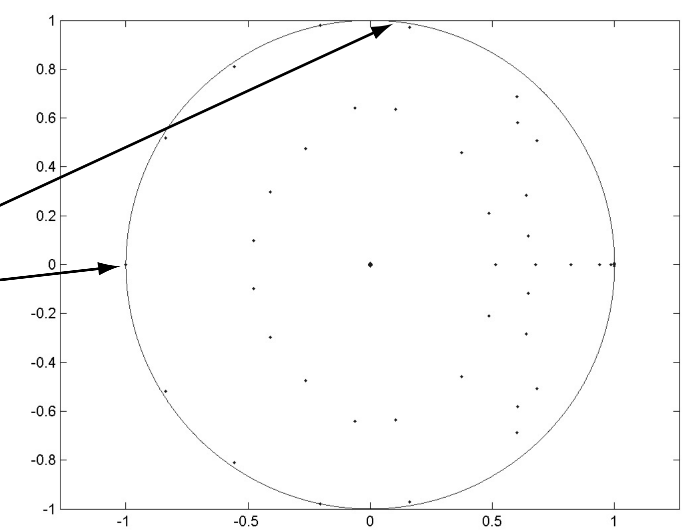


Closed Loop
k={3.5, 0, -0.01, -0.05}



Closed Loop Eigenvalues
k={3.5, 0, -0.01, -0.05}

Eigenvalues near the
unit circle are causing
a non-physical instability.



Conclusions

Improvements were made in the system identification routine.

A comparison of classical unsteady aerodynamic solutions was performed. The ARMA form remains the preferred system representation.

A parallel training method was developed. Parallel training allows for decoupled excitation and yields better system models.

An excitation signal survey was conducted. The DC-Chirp gave the most consistent results. High frequency limitations of the current signals were identified and evaluated.

Model quality "Evaluation criteria" were tested. The coupled stability prediction evaluation appears to give the best "model quality" indication.