BSCW High-Angle of Attack Computations Using KESTREL and AEROM

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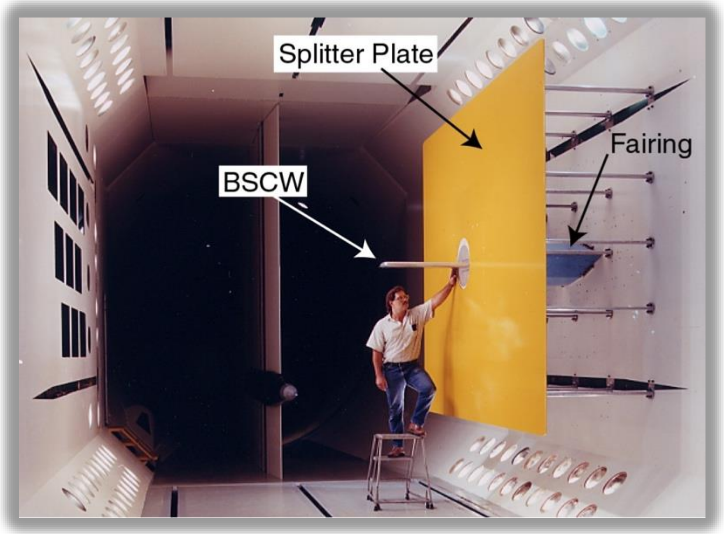
AePW-4 High Angle Working Group Meeting

Outline

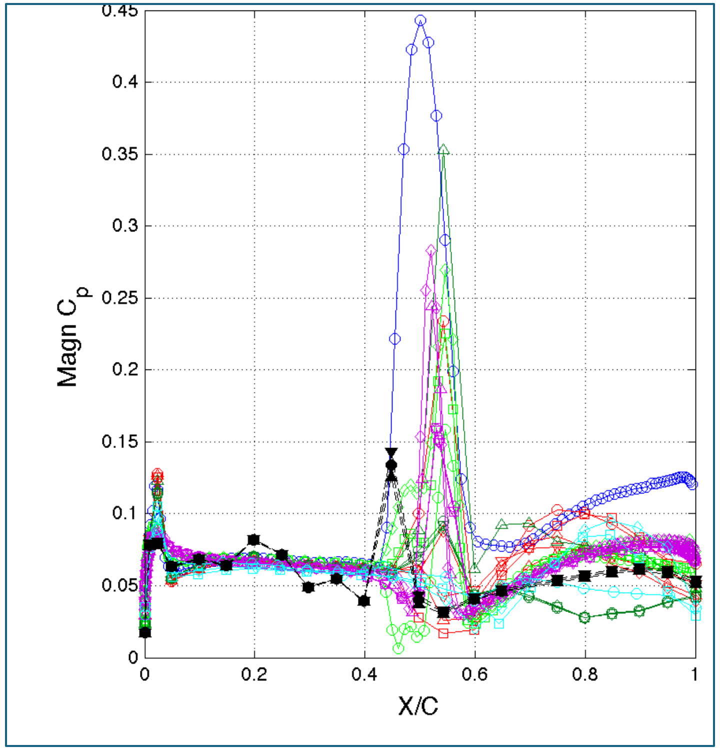
- Benchmark SuperCritical Wing (BSCW), Aeroelastic Prediction Workshop (AePW)
- Background
- AEROM
- Results
  - Alpha=0, 1, 3, and 5 degs (skip alpha=1 deg; similar to alpha=0 deg)
  - Amplitudes = 0.04, 0.01, 0.08, and 0.001 (modal)
  - Comparison of full solution GAFs vs ROM GAFs (error quantification)
  - Root locus
  - Comparison of full solution transients vs ROM transients (at a specified Q)

Benchmark Supercritical Wing (BSCW)

- Chosen as a challenging test case, flow-wise, but simple geometry
  - Strong shock with suspected shock-induced separated flow
- Some preliminary assessments from AePW
  - Computational methods had difficulty producing converged solutions due to flow field complexity
  - **Complex flow field also observed in experimental data; Largest magnitude of dynamic behavior appears to represent shock oscillations**
  - **CFD solutions vary widely, even for static solution;**

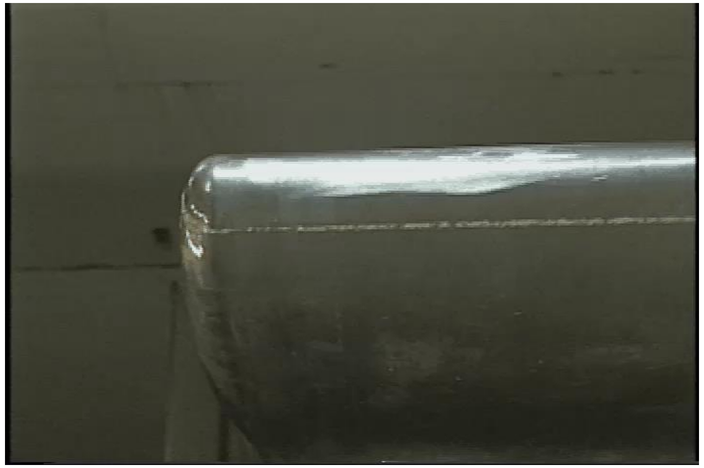


M=0.85, Re_c=4.49 million, test medium: R-134a, α = 5°, θ = 1°, freq 1 & 10 Hz



<u>Likely plan of action:</u>

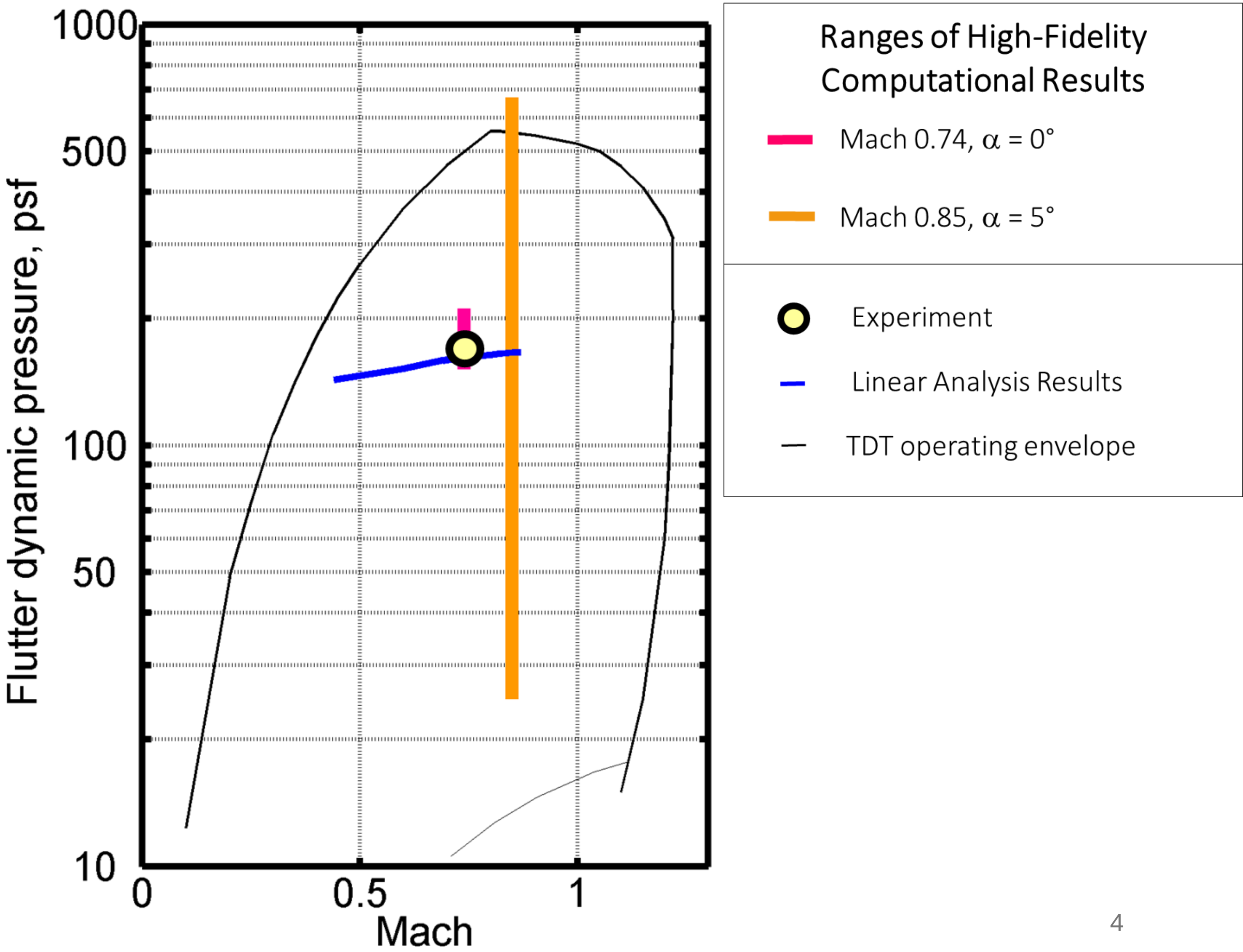
- Form technical working group of BSCW analysts
- Extensive study of available experimental data; characterize different flow phenomena
- Benchmark against more benign cases- lower Mach number, lower angle of attack
- Analyze the static (unforced) problem using time-accurate evaluation methods
- Study of time convergence criteria



From AePW-1 Debrief

AePW-2 Summary of Results

- At Mach 0.74, $\alpha = 0°$
  - Small variation in computational results
  - Match the experimental results well
  - Match the linear results well
- At Mach 0.85, $\alpha = 5°$
  - Significant variation in predictions
  - No experimental data for comparison

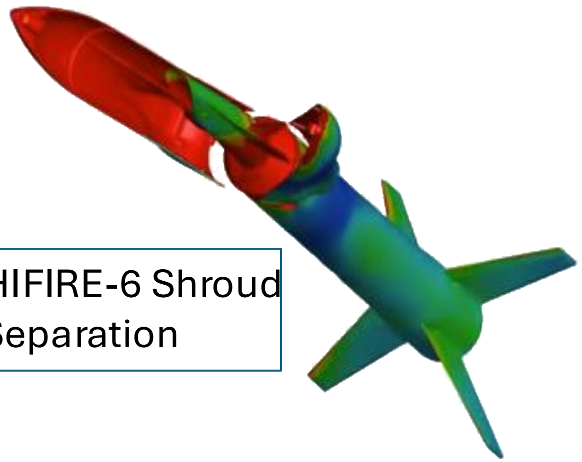


Background

- Application of KESTREL and KESTREL/AEROM to BSCW wing
- At M=0.74, alpha=0 deg, KESTREL, KESTREL/AEROM, FUN3D, and FUN3D/AEROM all compare nearly exactly with data
- At M=0.85, alpha=5 deg, large flow separation/unsteadiness; very challenging problem
- Large variance from one code to another at this condition; differences between KESTREL and FUN3D
- Goal of this analysis: evaluate application of AEROM using KESTREL at M=0.80 and alpha=0, 1, 3, and 5 deg (similar unsteadiness to M=0.85) using multiple amplitude excitations (Walsh functions)
- Follow-up with investigation of code-to-code comparisons

Kestrel

- Fixed-wing product in CREATE-Air Vehicles
- High-fidelity simulation tool
  - Full spectrum of flight conditions and missions
    - Incompressible to hypersonic
    - Cruise, maneuvering, take-off/landing, refueling, store carriage and release, precision air-drop, test facility modeling, and more…
  - Full spectrum of aircraft/weapons types
    - Fighter, bomber, tanker, cargo/transport, UAV/UAS, munitions
  - Coupled physics: **aerodynamics**, thermochemistry, **structural dynamics**, propulsion, flight controls, separation/contact/collision, 6-DoF motion w/ generalized constraints, aero-heating
  - Easy for users to learn, use, customize, and extend
    - "Simple things are easy, complex things are possible."
- Thanks to Dr. Steven Lamberson for this slide

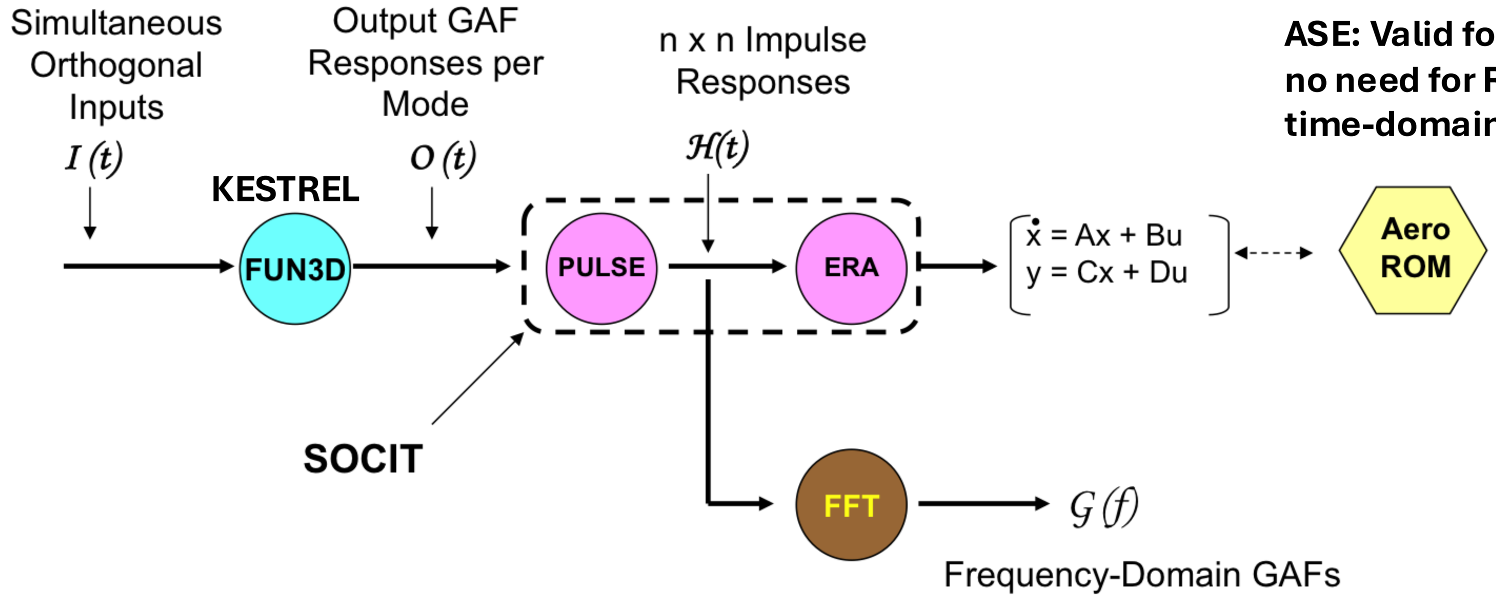


HIFIRE-6 Shroud Separation

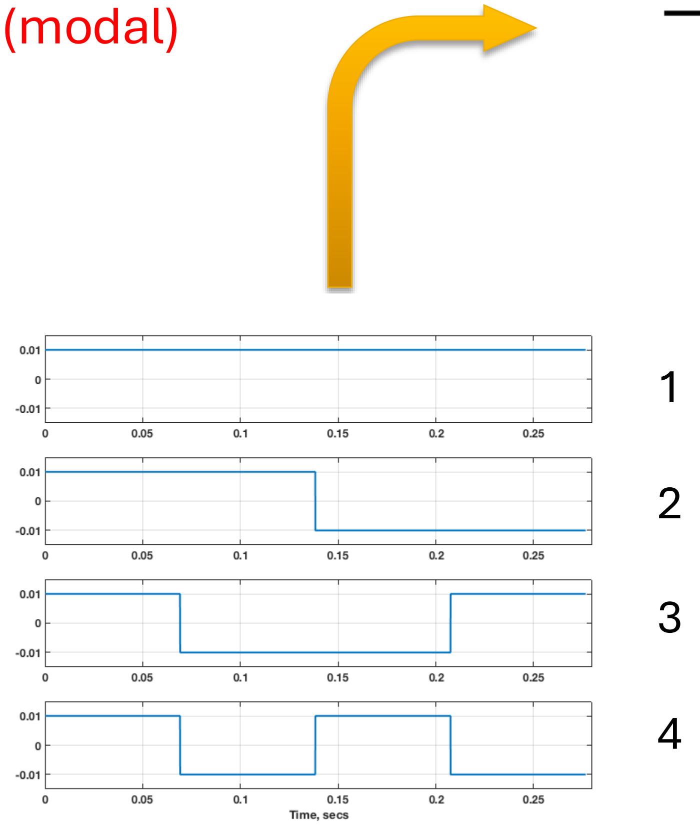
AEROM: ROM Development Process

Unsteady Aerodynamic State-Space ROM

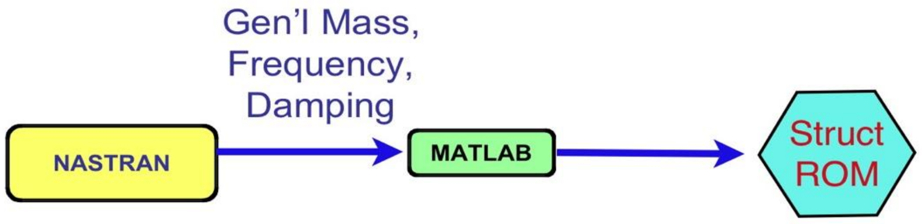
ASE: Valid for arbitrary motions; no need for RFAs as already in time-domain



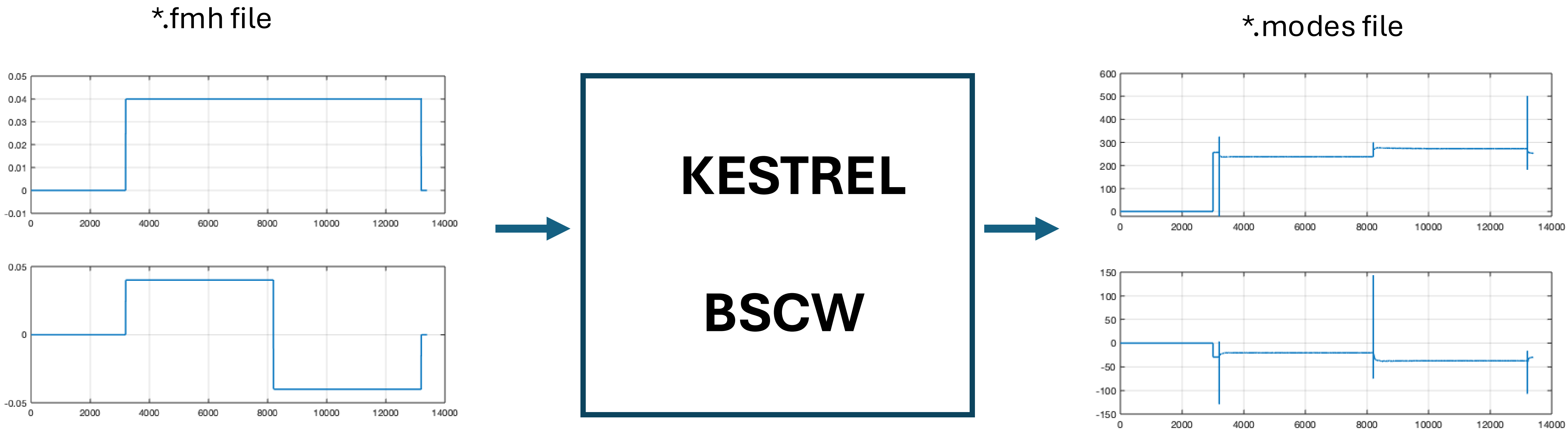
Walsh Functions (modal)



Structural state-space ROM



BSCW Application (KESTREL), Two modes



2 inputs x 2 outputs =
4 impulse responses/GAFs

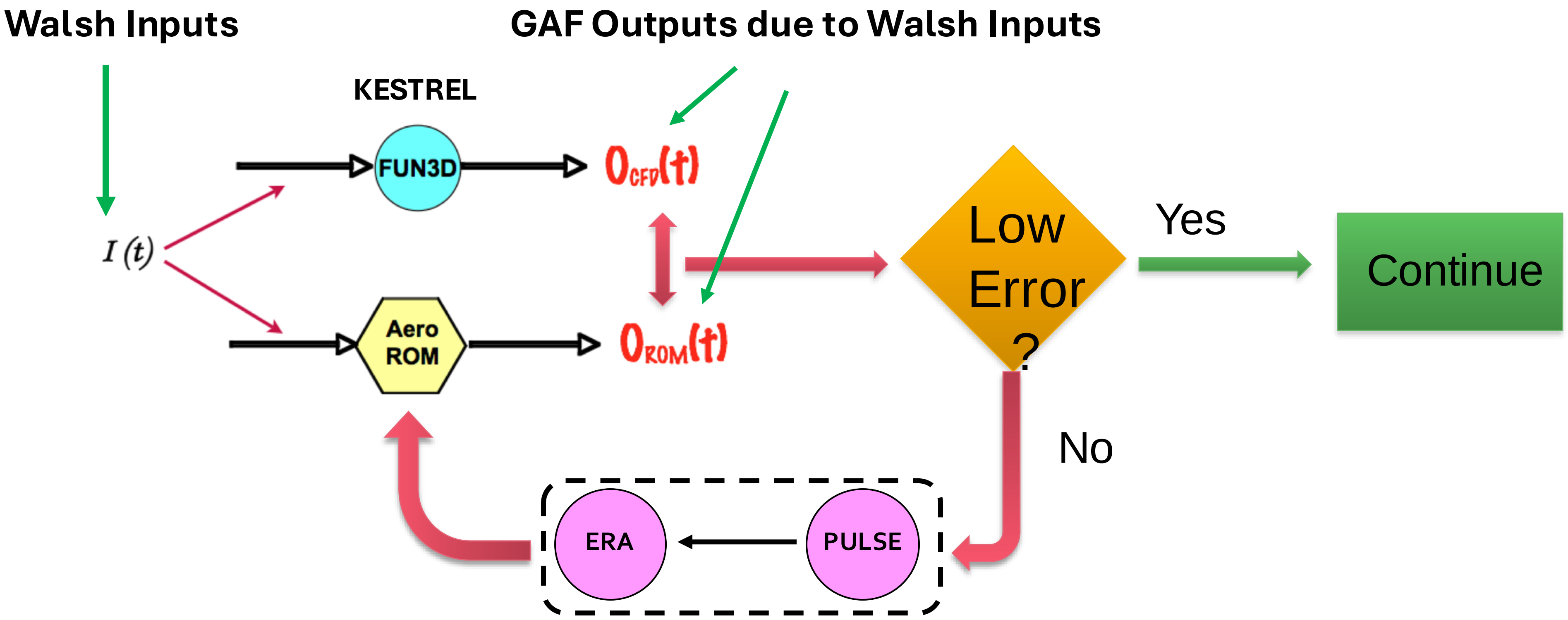
Two Walsh input functions

Two GAFs output functions

- **<u>Intentional</u> accounting for nonlinearity:**
  - **Input amplitude variation (<u>amplitude-dependent nonlinearity</u>)**
  - **<u>Simultaneous inputs</u> (capture nonlinear cross-terms missed by one-at-a-time inputs)**

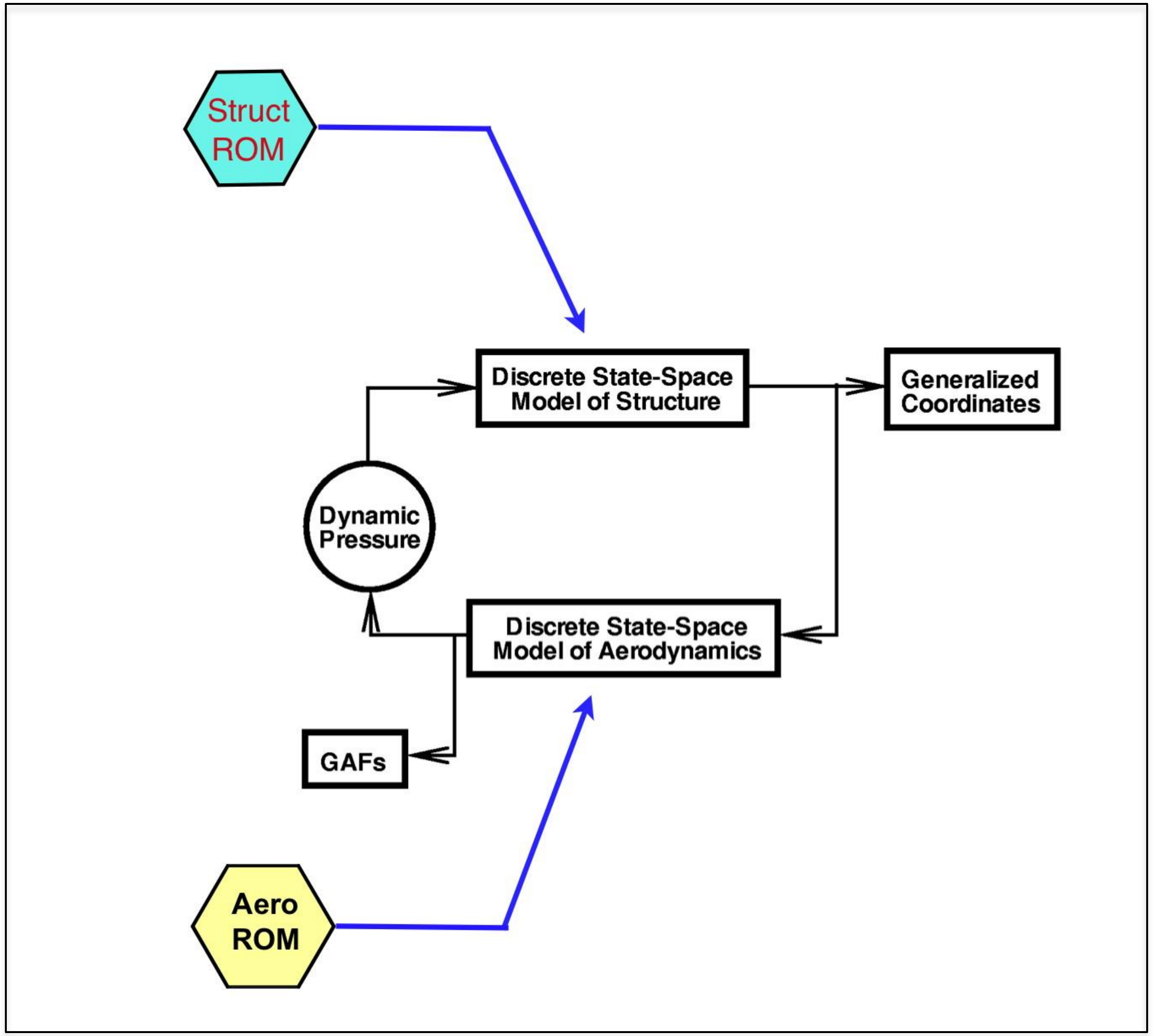
AEROM: ROM Development Process

Error Minimization (Unsteady Aerodynamics)



AEROM: ROM Development Process

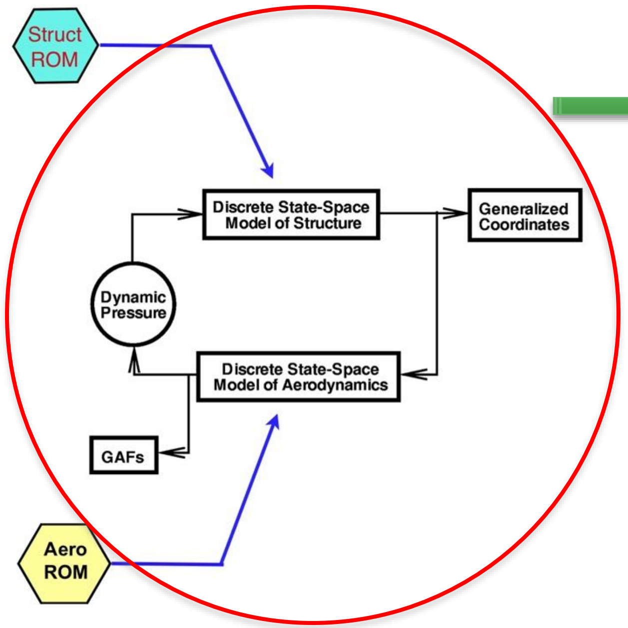
Aeroelastic Simulation ROM (Simulink Model)



- Includes Unsteady Aero ROM and Structural Dynamic ROM
- A MATLAB-based replica of the CFD aeroelastic solution process
- **Used to compare ROM responses at <u>any</u> dynamic pressure with full KESTREL or FUN3D solutions**
- Computes generalized coordinates and GAFs
- Can be used for static and dynamic AE solutions

AEROM: ROM Development Process

Aeroelastic <u>Root Locus</u> Plot Using Aeroelastic Simulation ROM



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

Eigenvalues

Z-Plane Root Locus

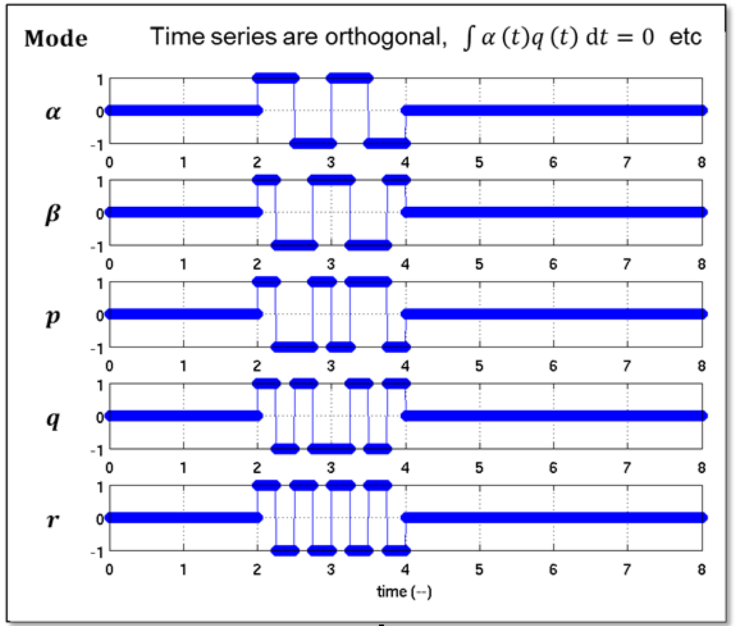
S-Plane Root Locus

Frequency vs Damping Ratio Root Locus

System Identification for MIMO Stability & Control Systems

"Characterizing Aerodynamic Damping of a Supersonic Missile with CFD", Shelton (AF), Martin (AF), Silva (NASA), SciTech 2018

Walsh Function Training Motion → **Aerodynamic Impulse Response**



Impulse Responses: $Y(k) = \begin{bmatrix} h_{N,\alpha}(k) & \cdots & h_{N,r}(k) \\ \vdots & \ddots & \vdots \\ h_{n,\alpha}(k) & \cdots & h_{n,r}(k) \end{bmatrix}$

with $Y(k) = \begin{cases} D & k = 0 \\ CA^{k-1}B & k \geq 1 \end{cases}$

State space model
$\dot{x} = Ax + Bu$
$y = Cx + Du$

Input, $u(t) = (\alpha, \beta, p, q, r)$
Output, $y(t) = (C_A, C_S, C_N, C_l, C_m, C_n)$

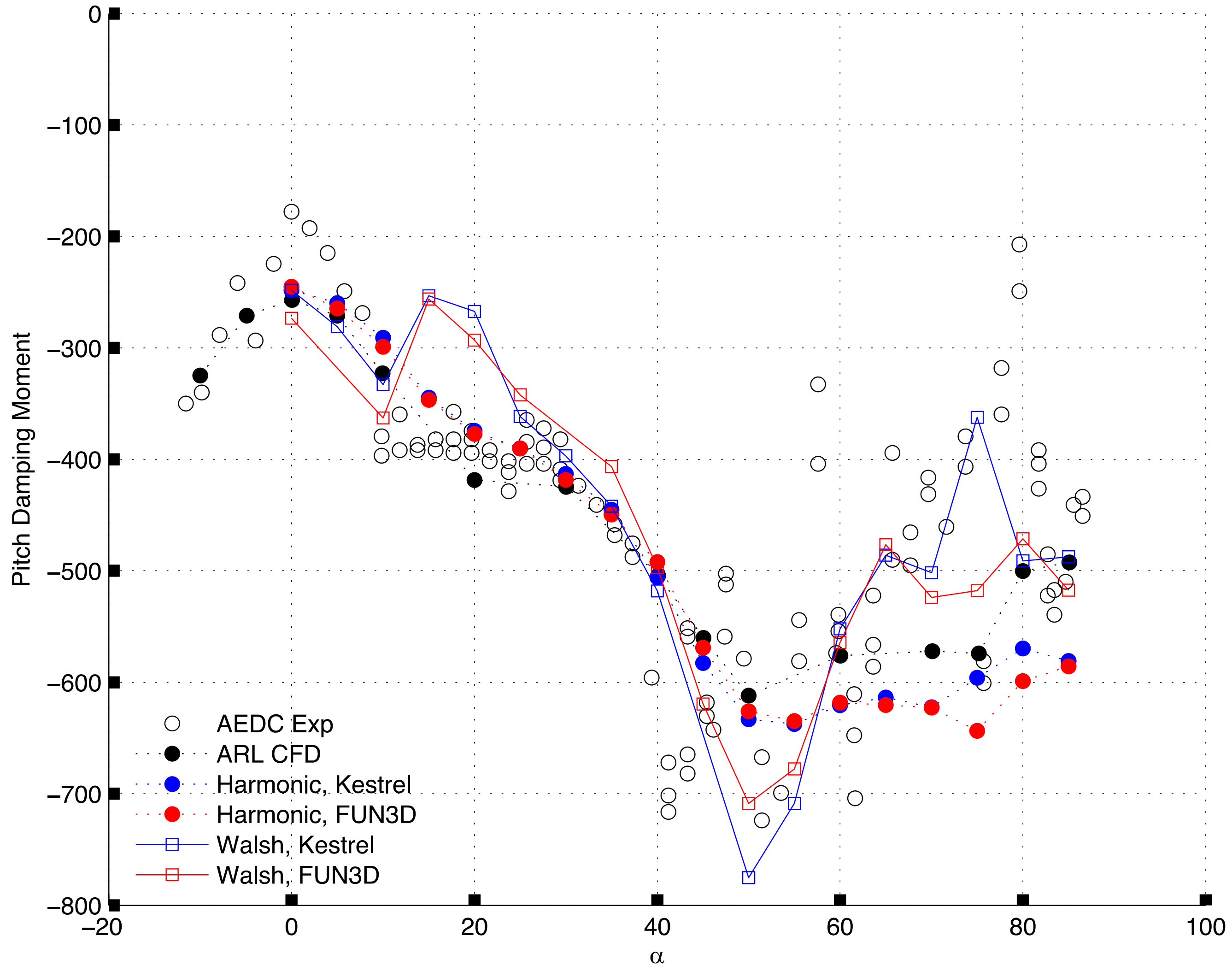
Computational Fluid Dynamics (Kestrel or FUN3D)

System ID
- Observer/Kalman Identification
- Eigenvalue Realization Algorithm

System/Observer/Controller Identification Toolbox (SOCIT)

Pitch Moment Damping

Walsh Functions vs Harmonic Motion and Reference



Walsh Function Amplitudes and Alphas
Coarse Mesh

Modal Amp/Alpha (deg)	0 (K)	1	3 (K)	5 (K)
0.04	M8A0a	M8A1a	M8A3a	M8A5a
0.01	M8A0b	M8A1b	M8A3b	M8A5b
0.08	M8A0c	M8A1c	M8A3c	M8A5c
0.001	M8A0d	M8A1d	M8A3d	M8A5d

K = comparison with full KESTREL solution available or underway; using 'Venkat' limiter

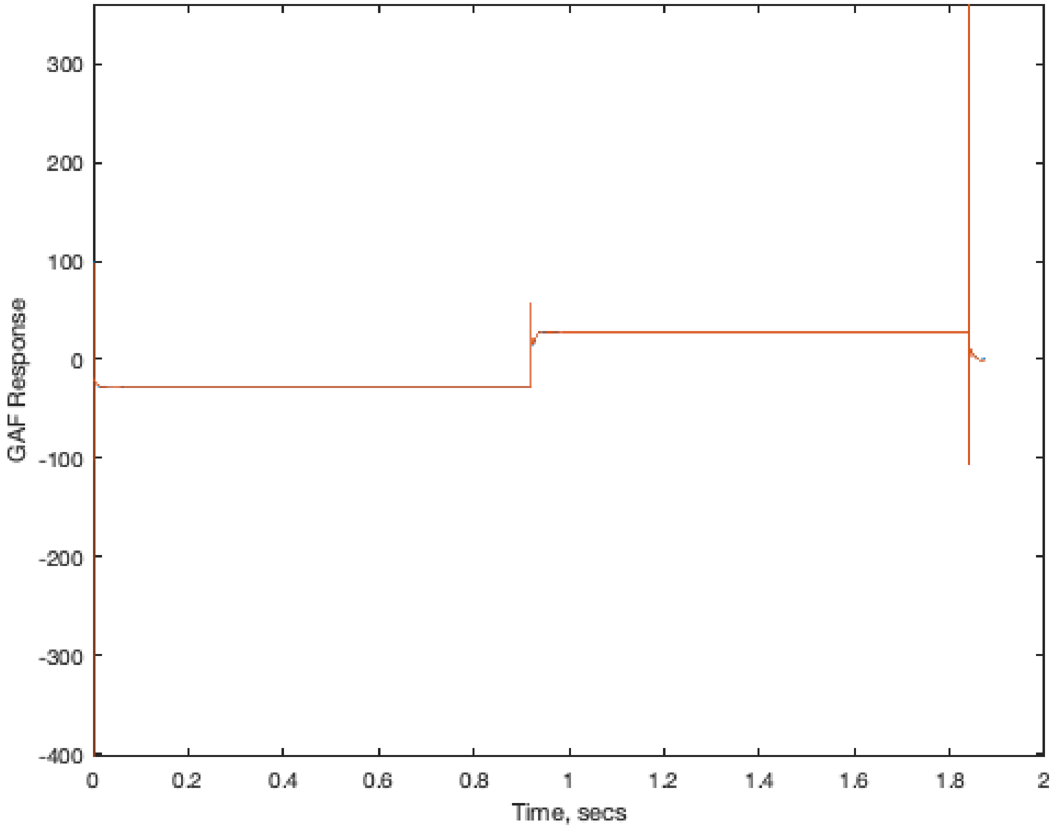
KESTREL Solutions: Alpha = 0 deg, Q = 100 psf, Initial Modal Velocity = 5
Alpha = 3 deg, Q = 100 psf, Initial Modal Velocity = 5
Alpha = 5 deg, Q = 50 psf, 130 psf, Initial Modal Velocity = 5

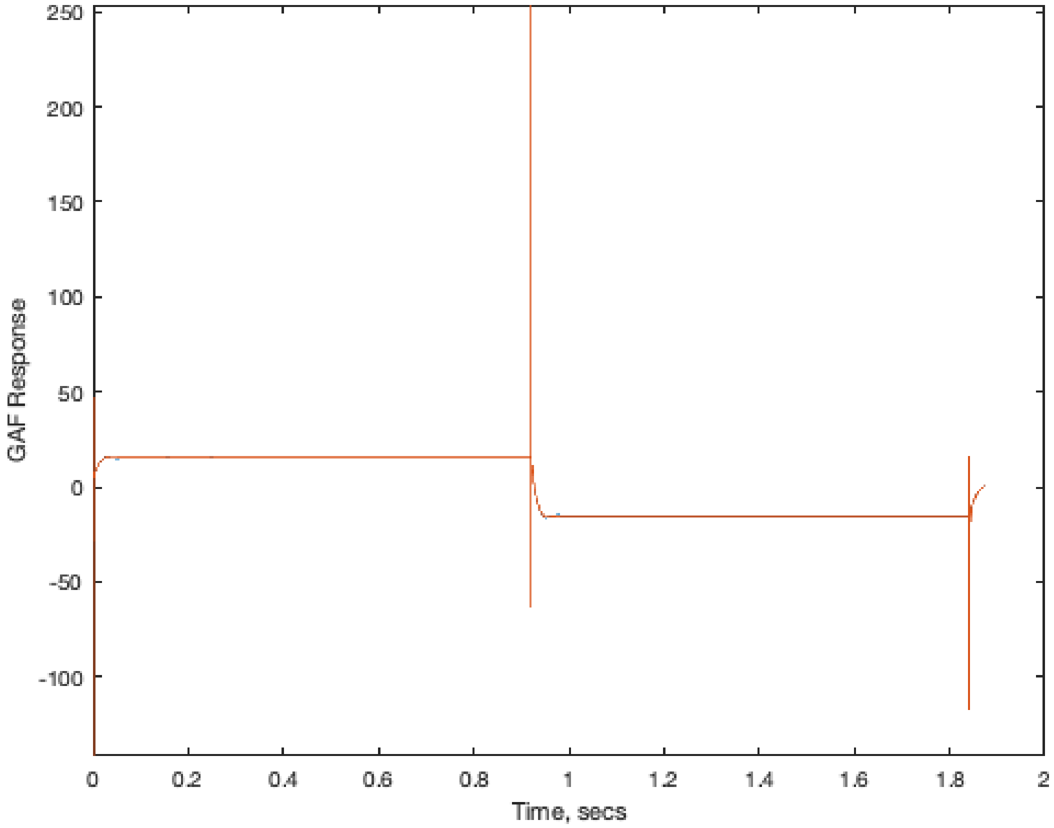
NAS CPU Cost
Single ROM solution: 10K steps, 240 cores, 9hrs 45min (set up for high alpha case; shorter duration for benign cases)
Full Solution per Q: 15K steps, 240 cores, 53 hrs 04min (~5.5 cycles)

Alpha = 0 deg

M8A0a – ROM/KESTREL GAFs

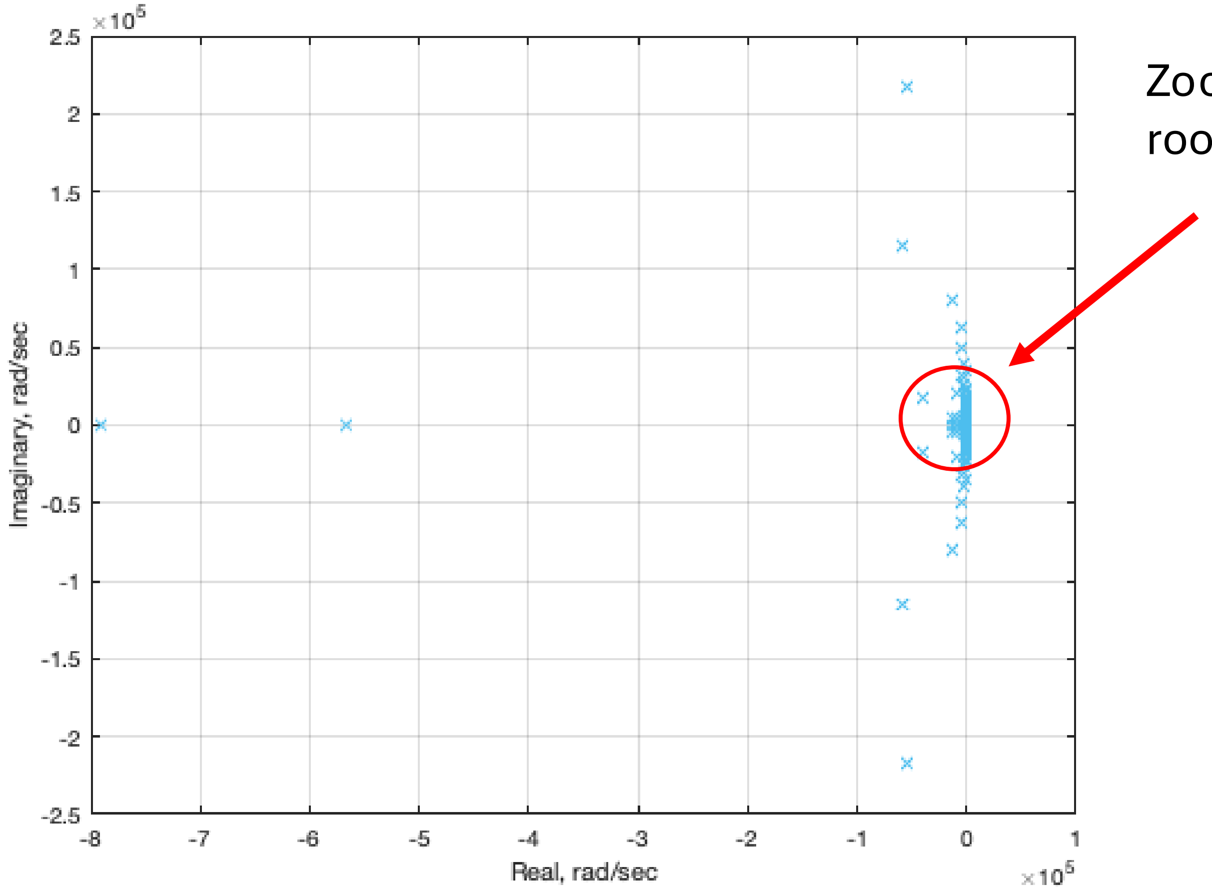
a	.04
b	.01
c	.08
d	.001





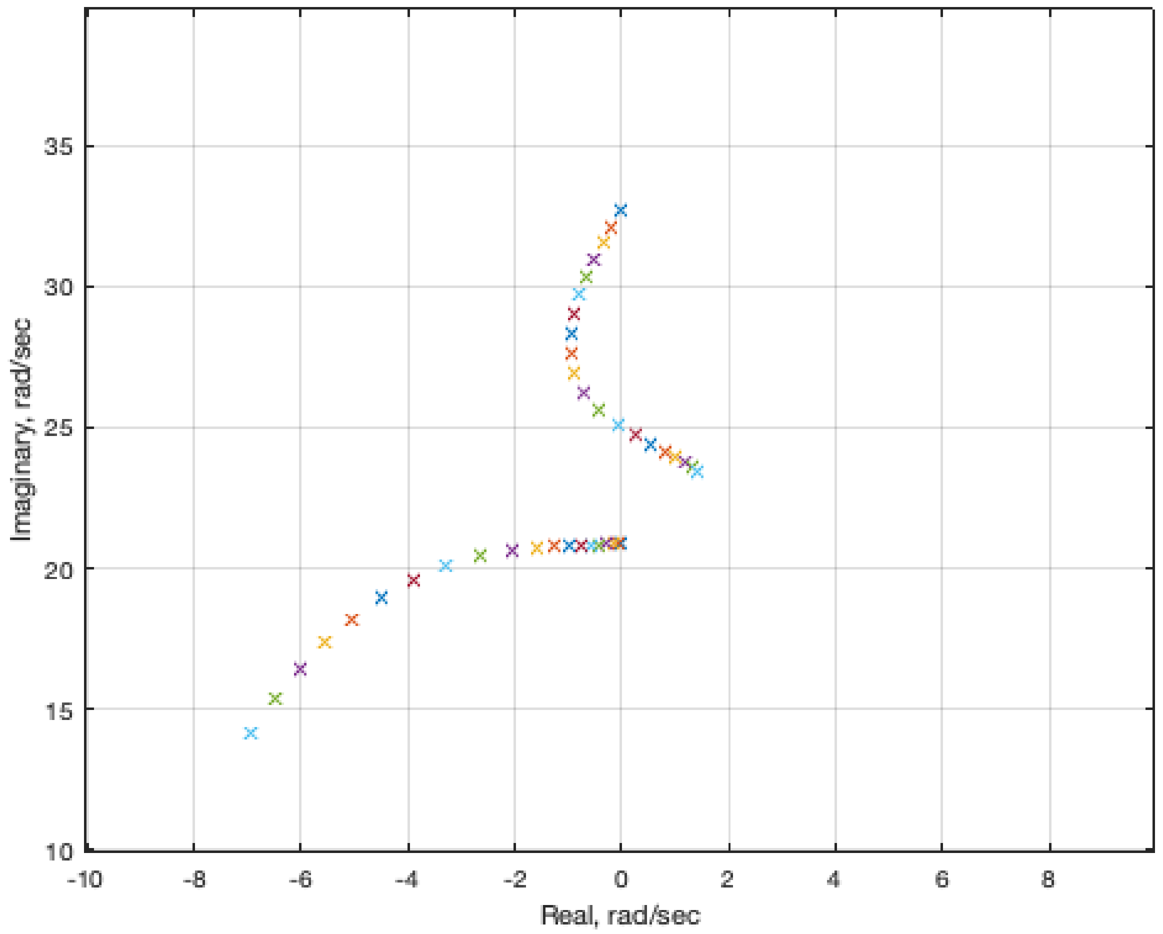
M8A0a – ROM/KESTREL Root Locus

Full set of unsteady aerodynamic roots



Zoom into structural/aeroelastic roots ...

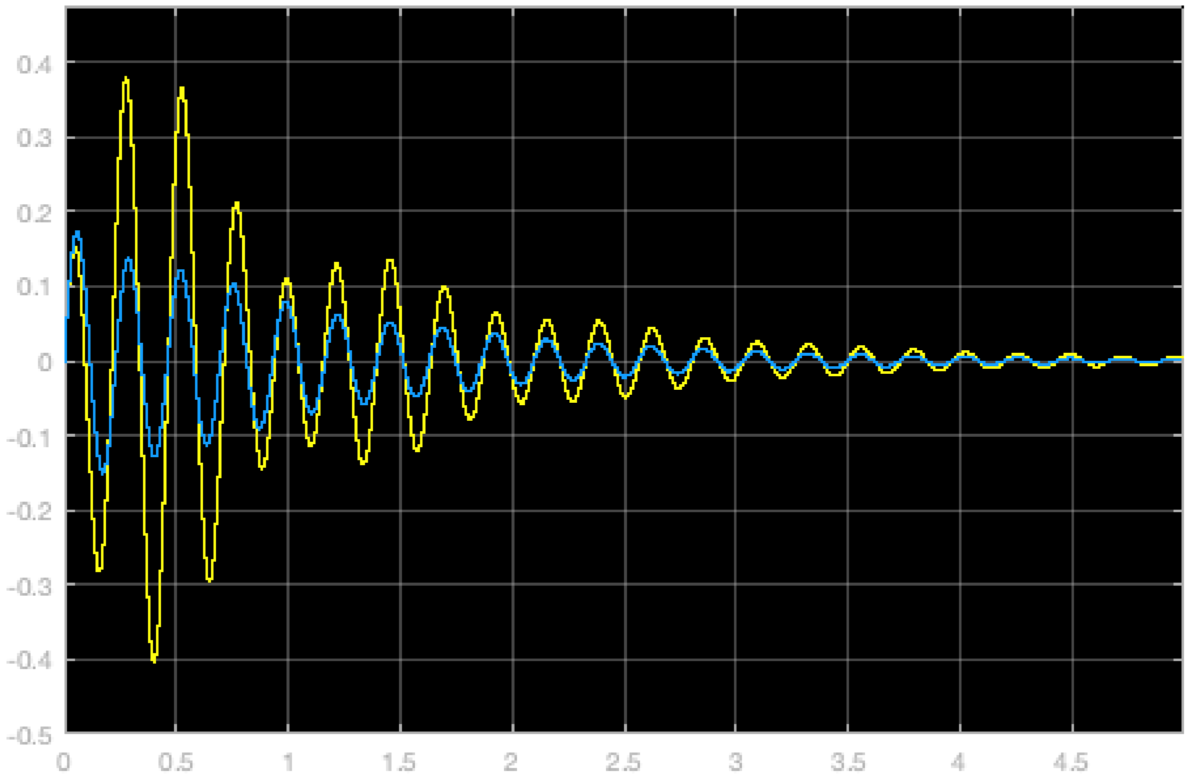
M8A0a – ROM/KESTREL Root Locus



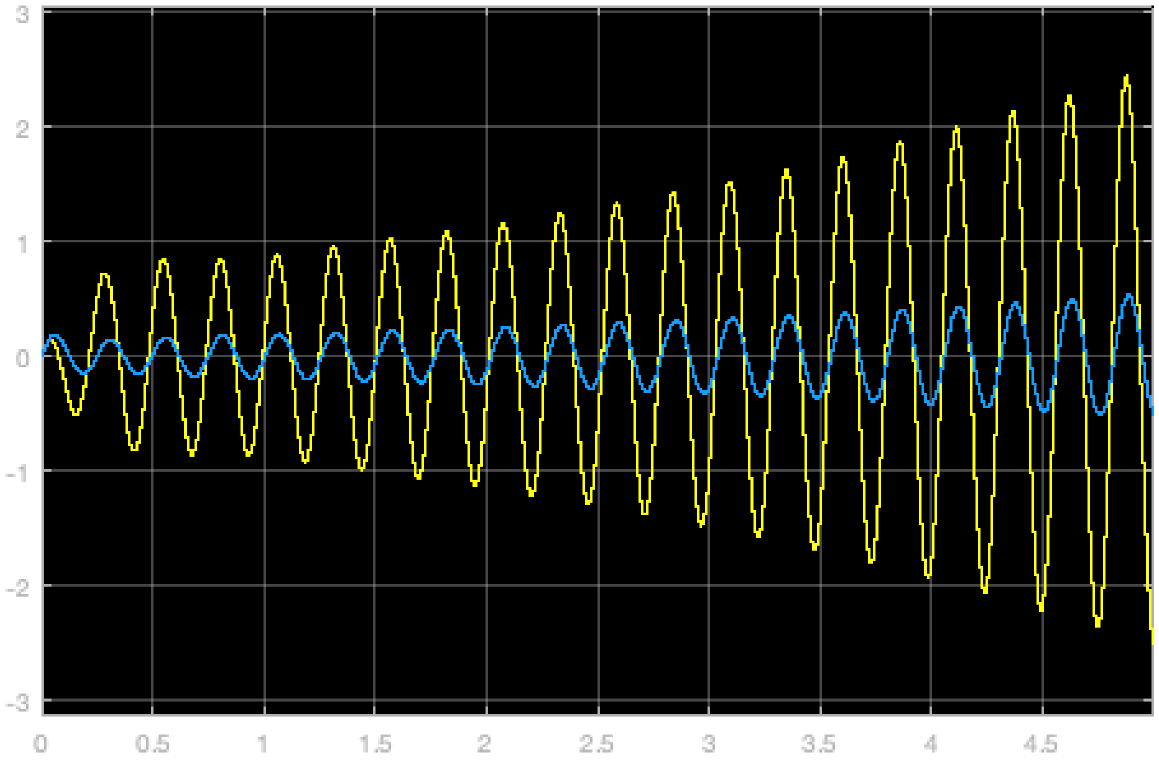
Qf = 178.8 psf

M8A0a – ROM Responses (SIMULINK)

Q = 129.6 psf

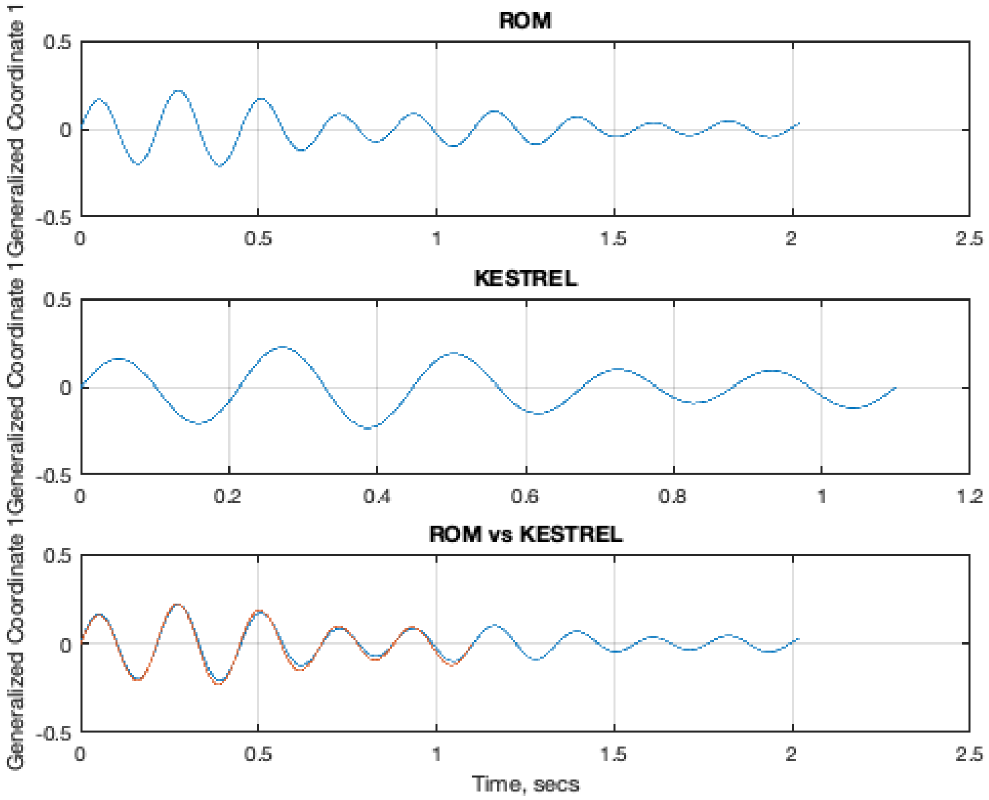


Q = 187.2 psf

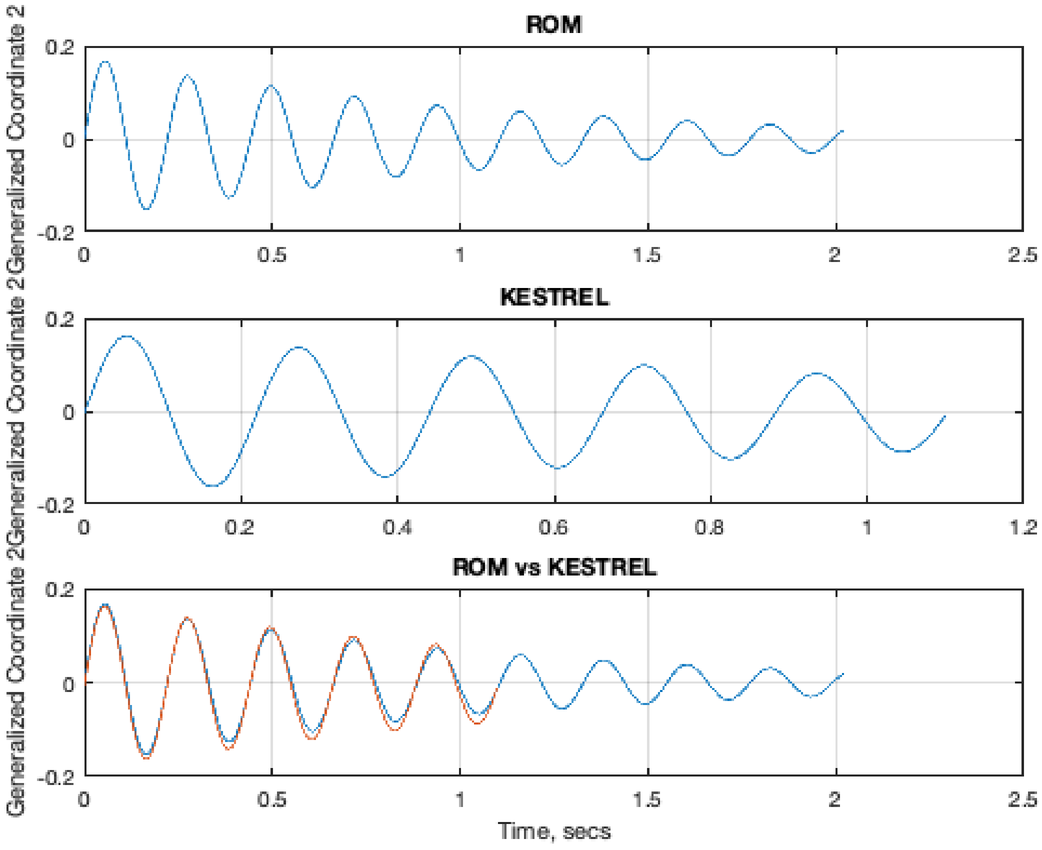


M8A0a – ROM/KESTREL Responses, Q=100 psf

Mode 1

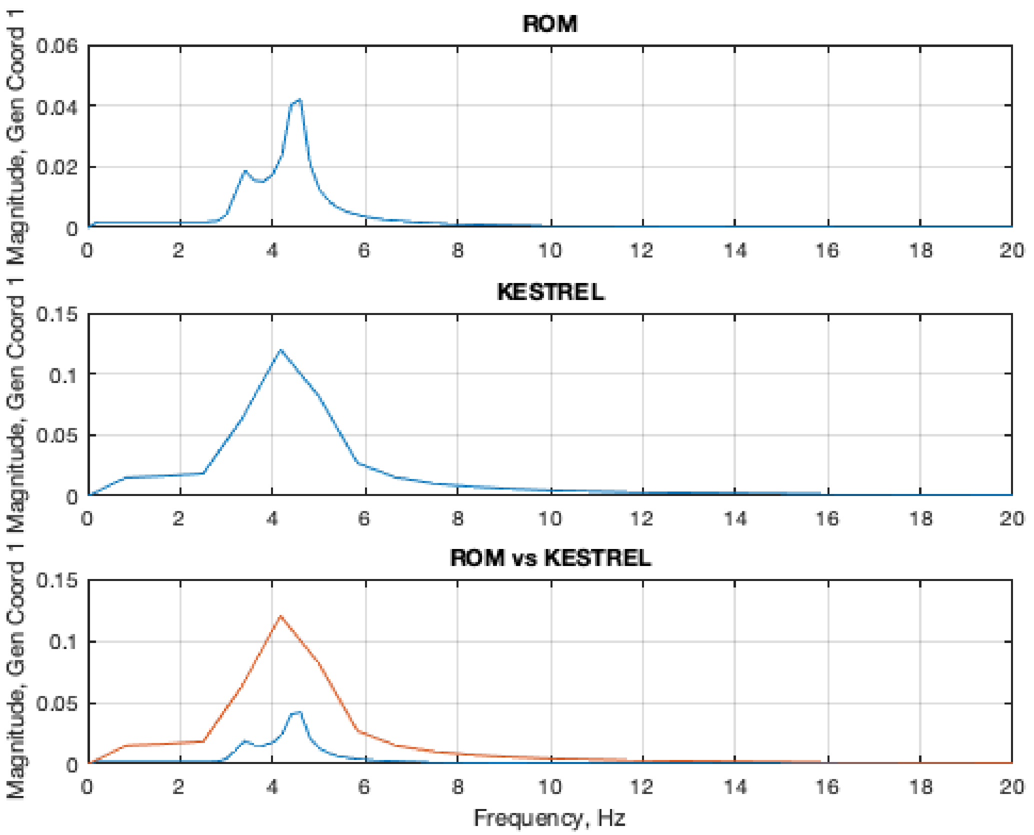


Mode 2

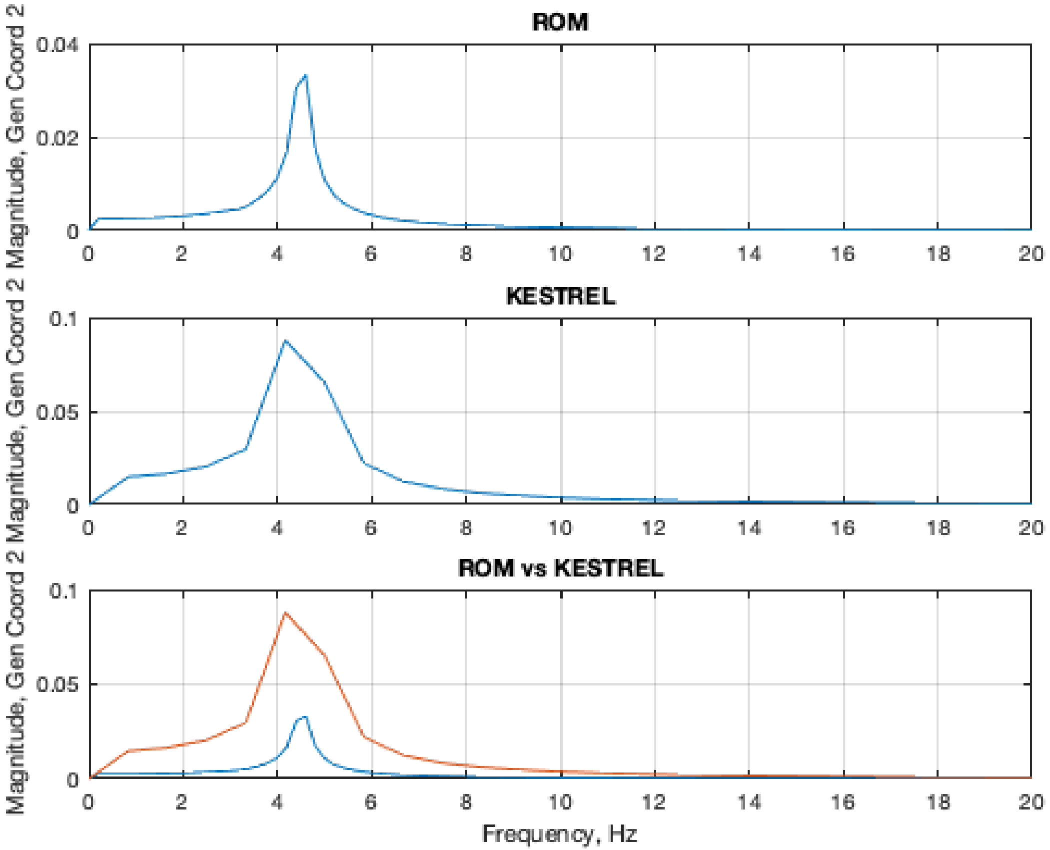


M8A0a – ROM/KESTREL Responses, Q=100 psf

Mode 1

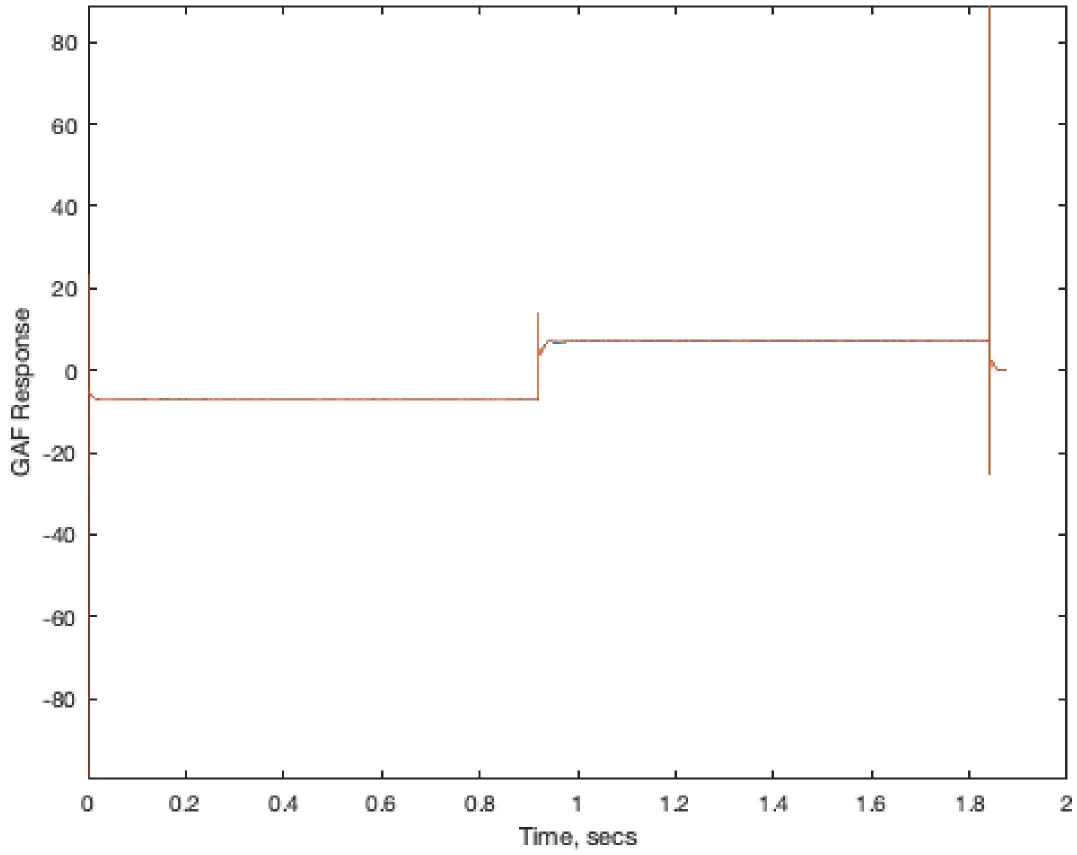


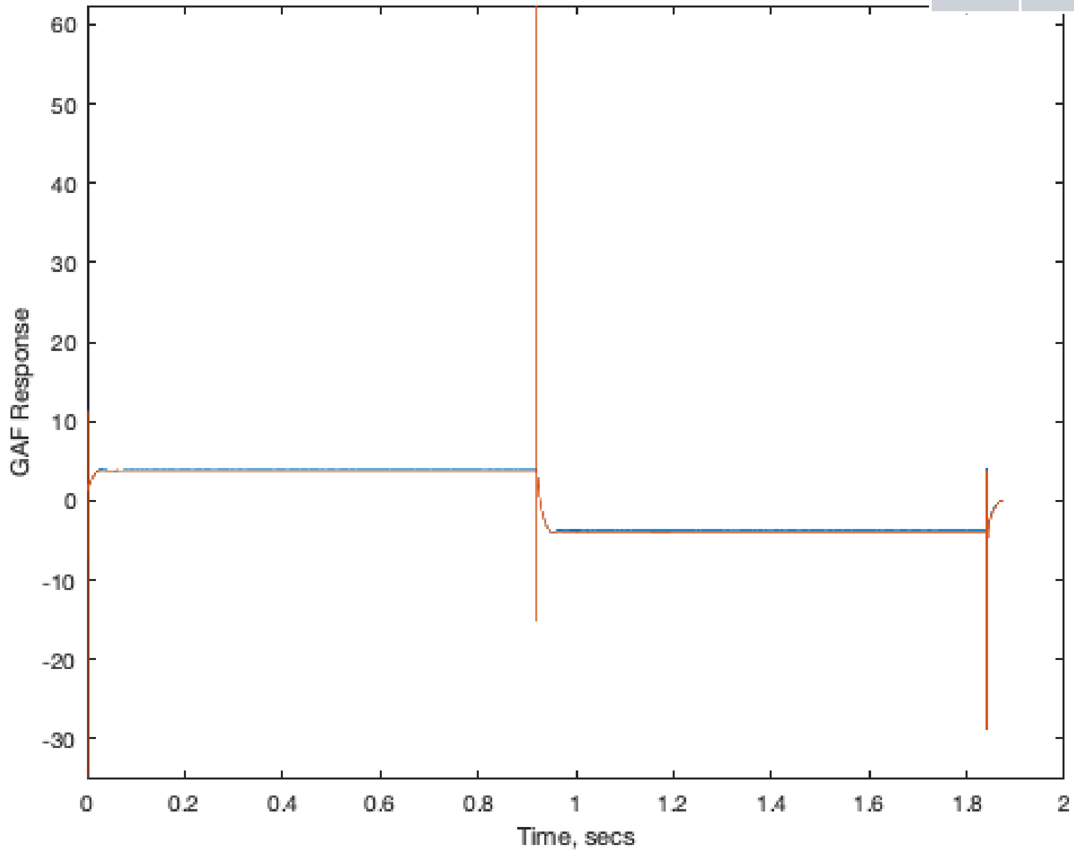
Mode 2



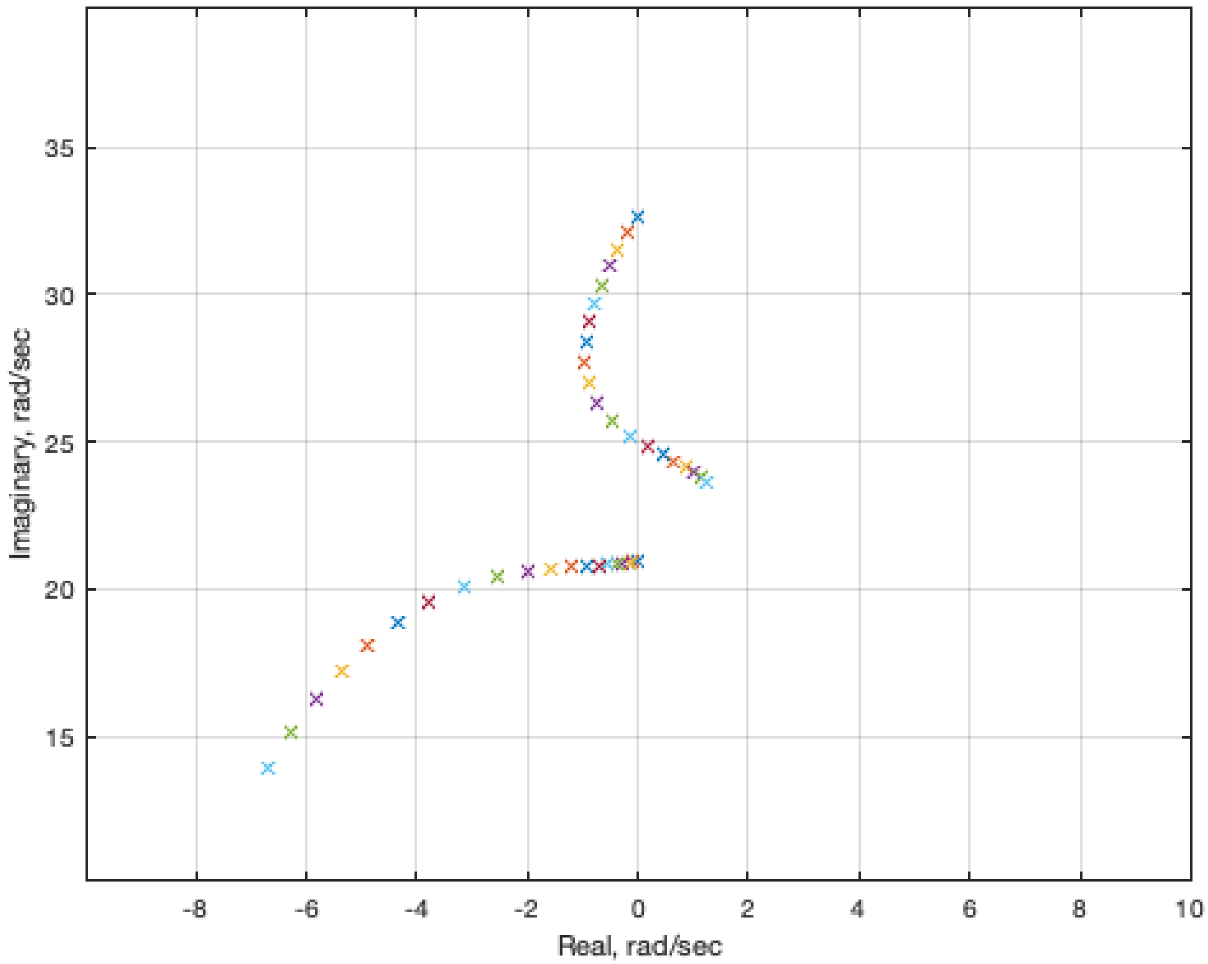
M8A0b – ROM/KESTREL GAFs

a	.04
b	.01
c	.08
d	.001



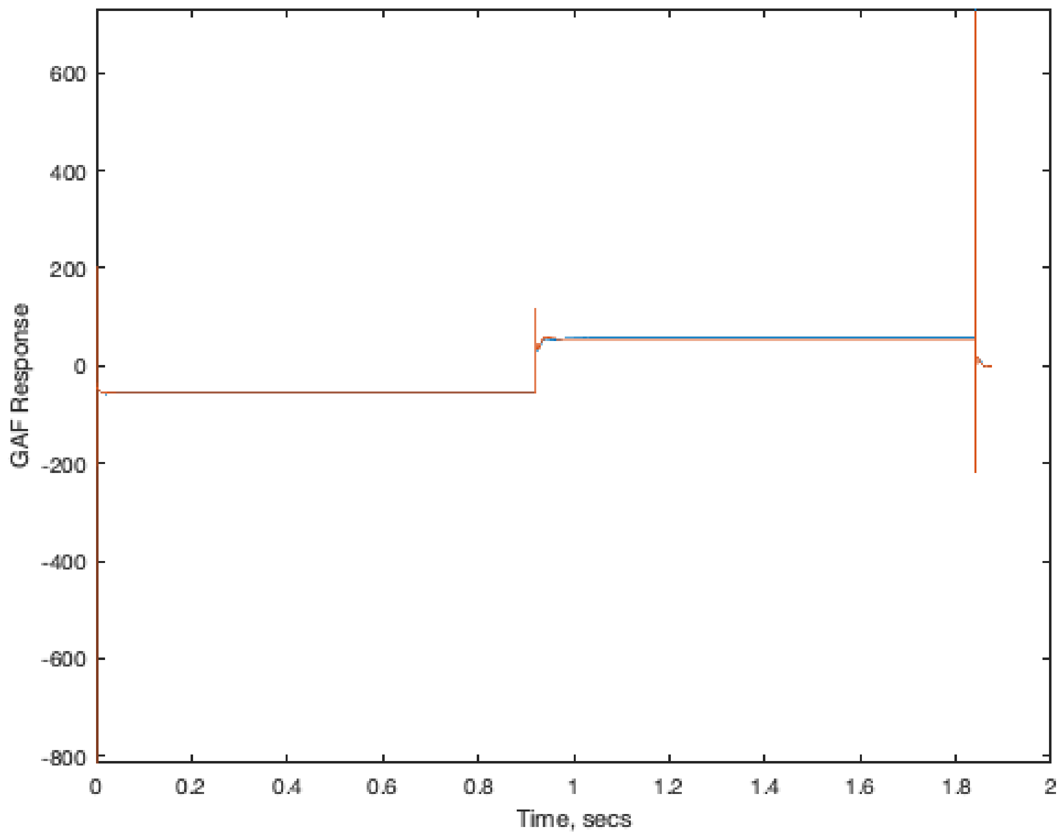


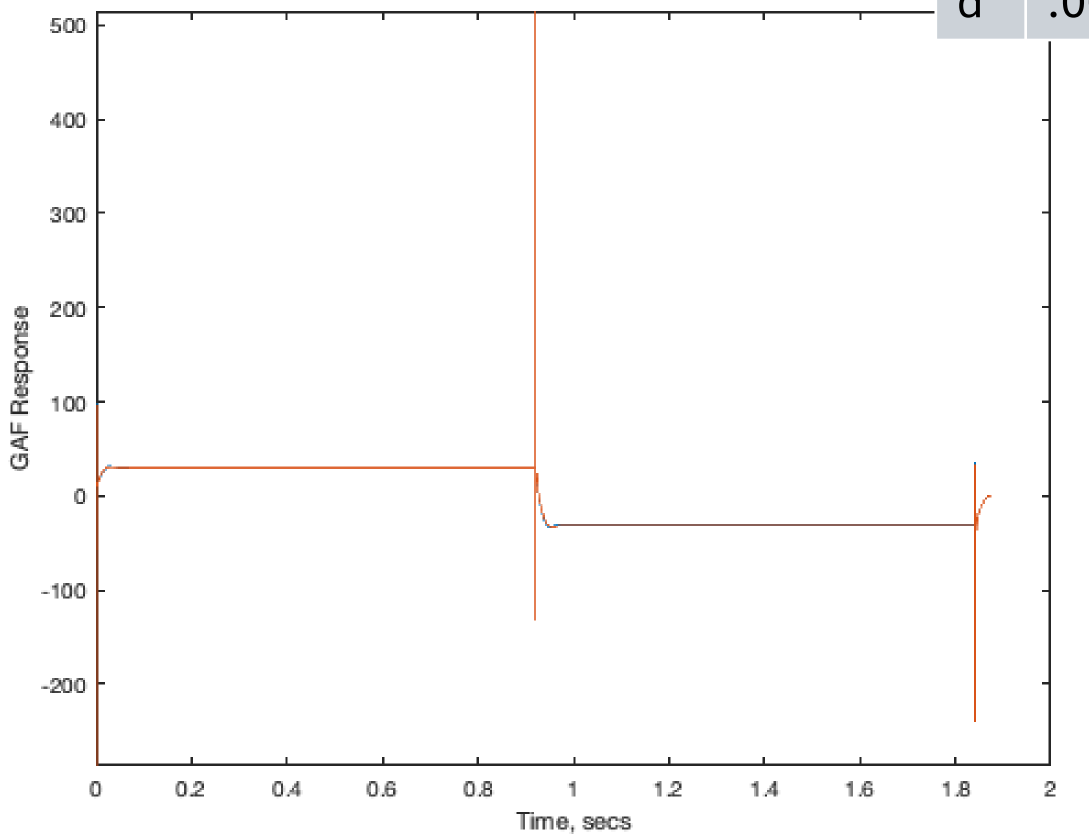
M8A0b – ROM/KESTREL Root Locus



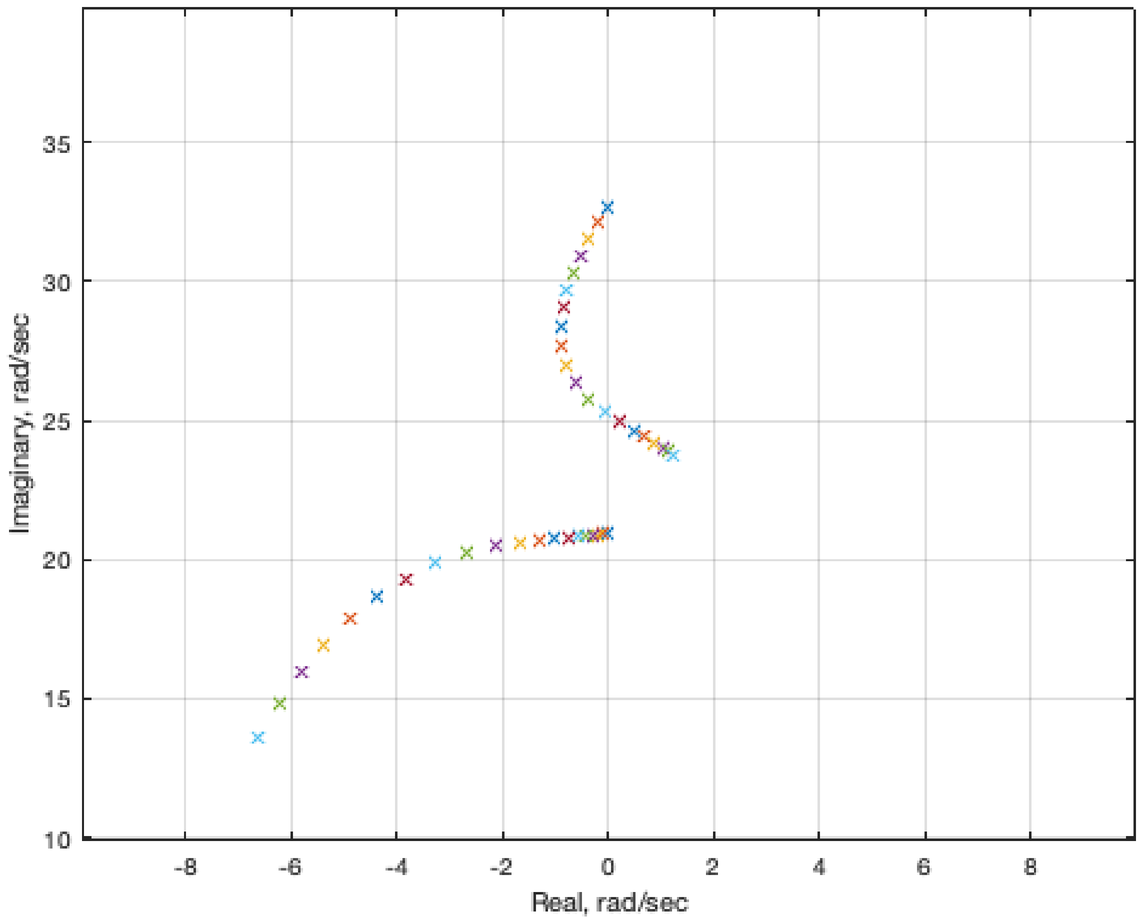
M8A0c – ROM/KESTREL GAFs

a	.04
b	.01
c	.08
d	.001



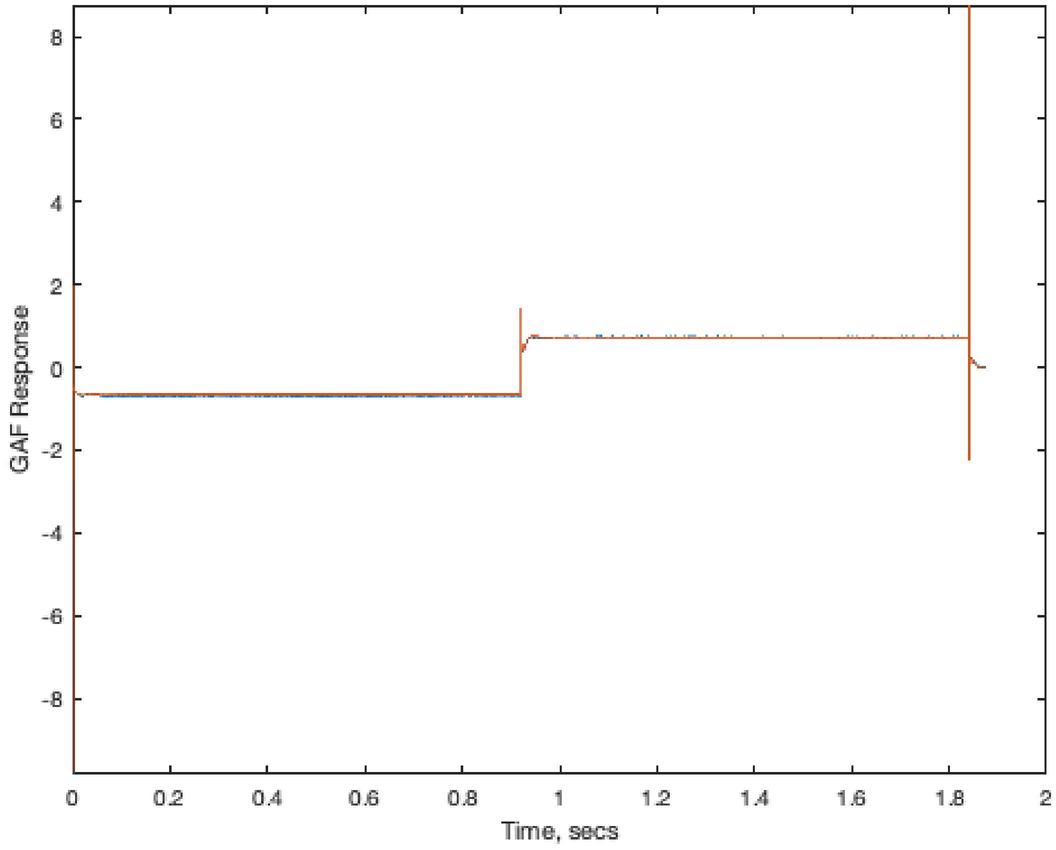


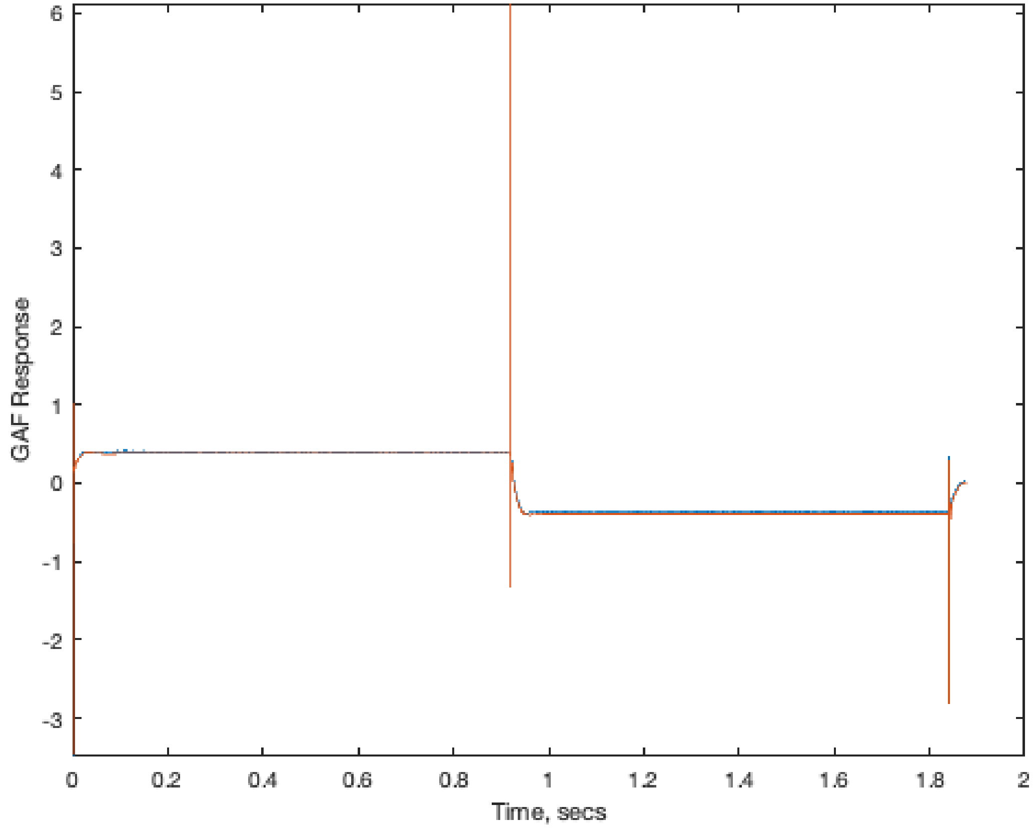
M8A0c – ROM/KESTREL Root Locus



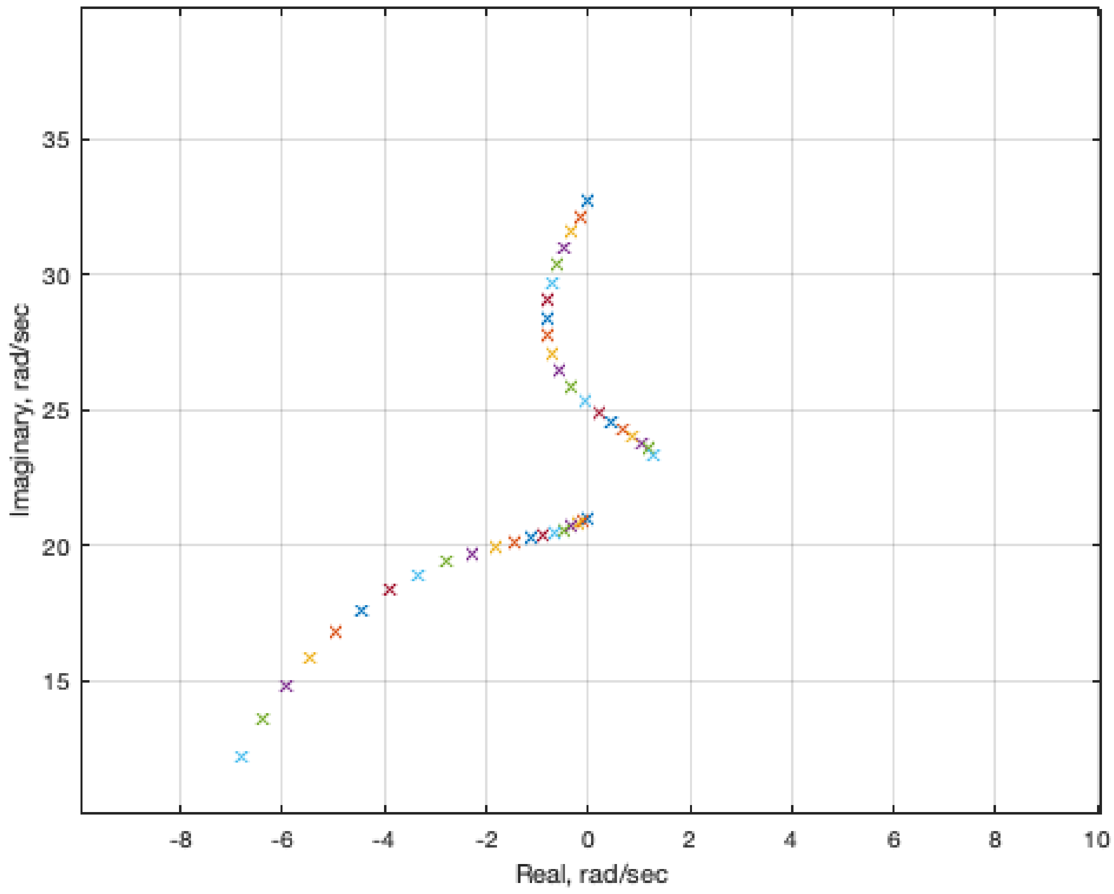
M8A0d – ROM/KESTREL GAFs

a	.04
b	.01
c	.08
d	.001





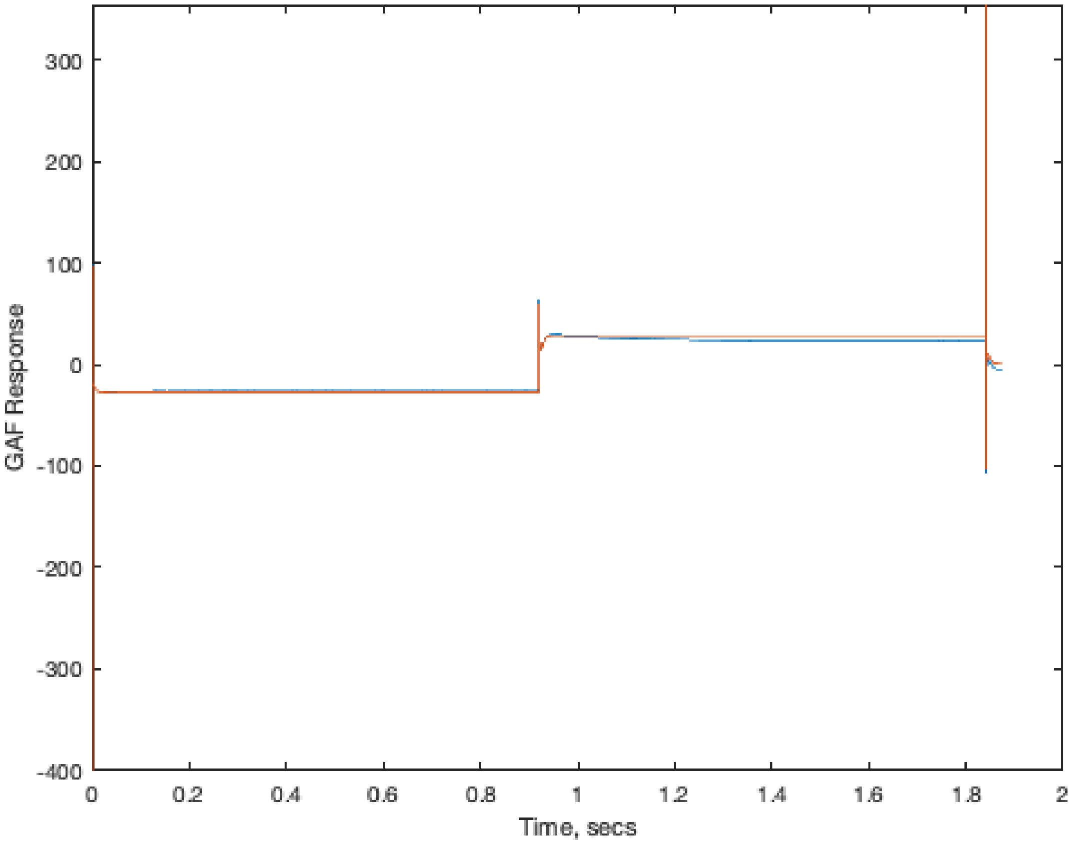
M8A0d – ROM/KESTREL Root Locus

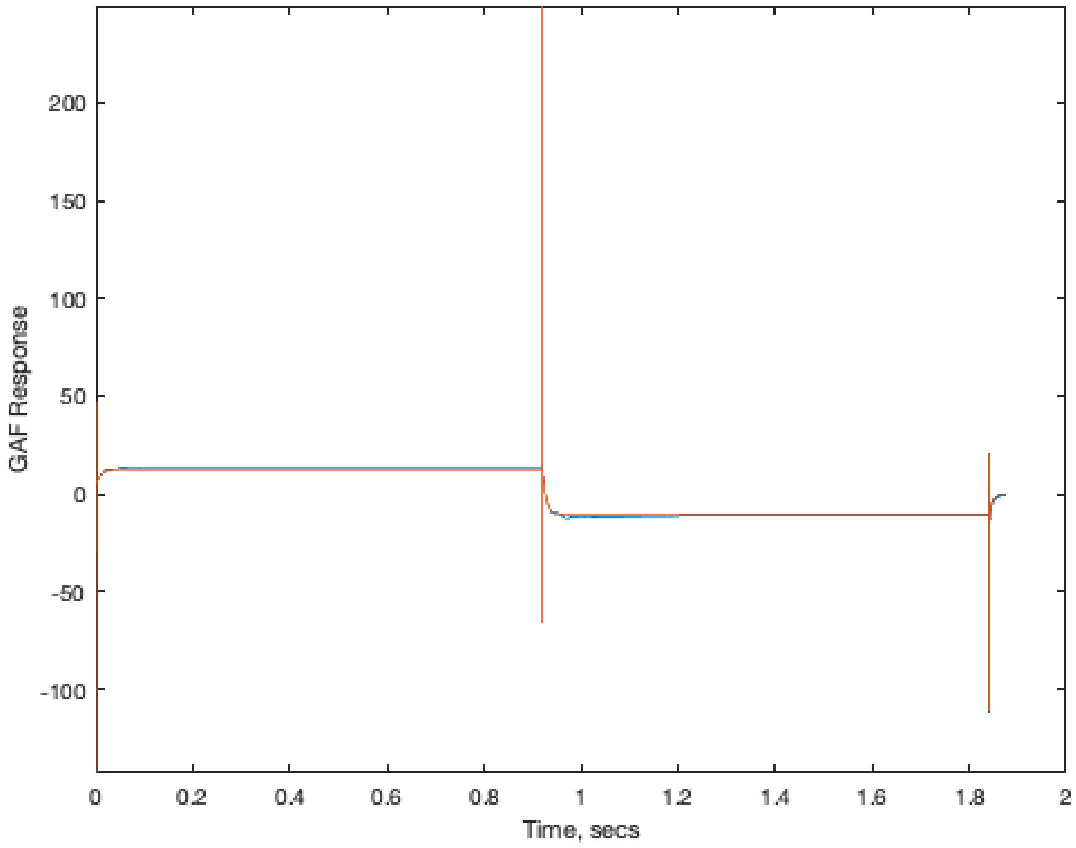


Alpha = 3 deg

M8A3a – ROM/KESTREL GAFs

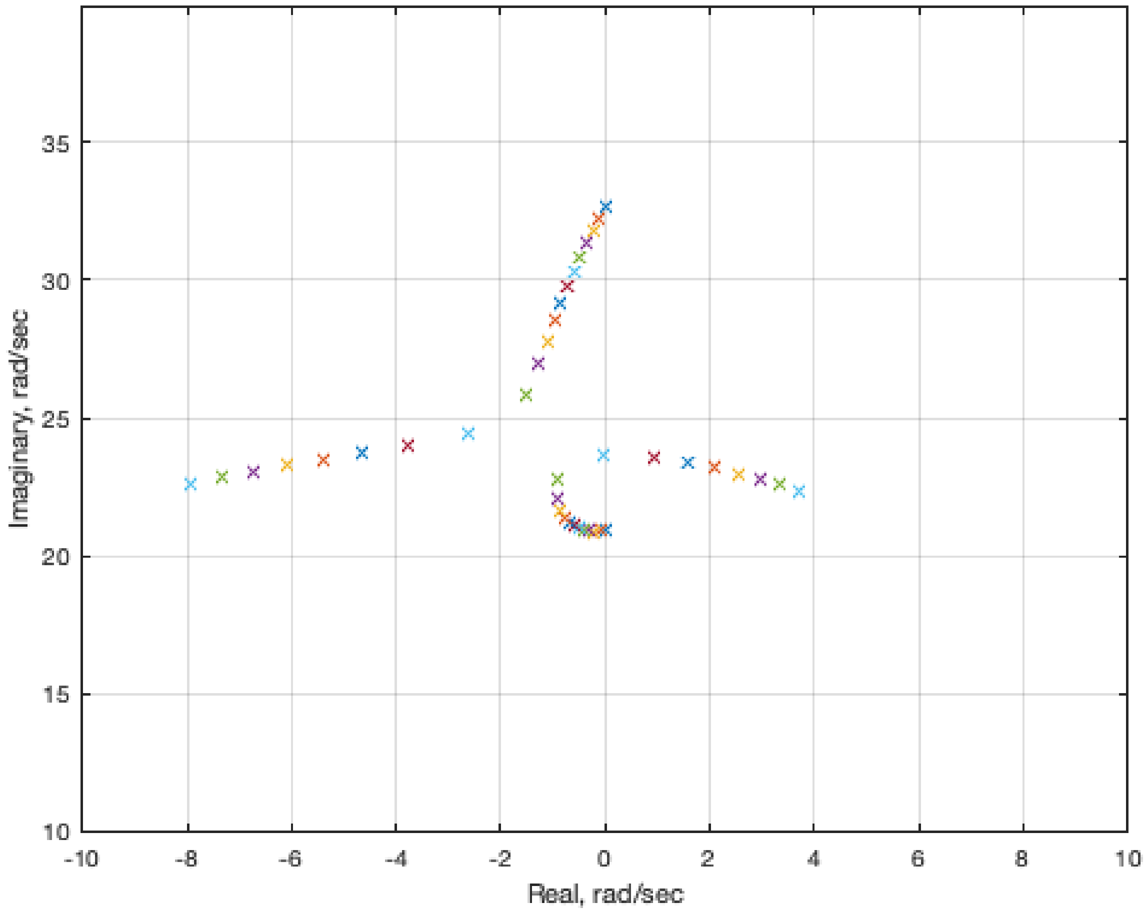
a	.04
b	.01
c	.08
d	.001





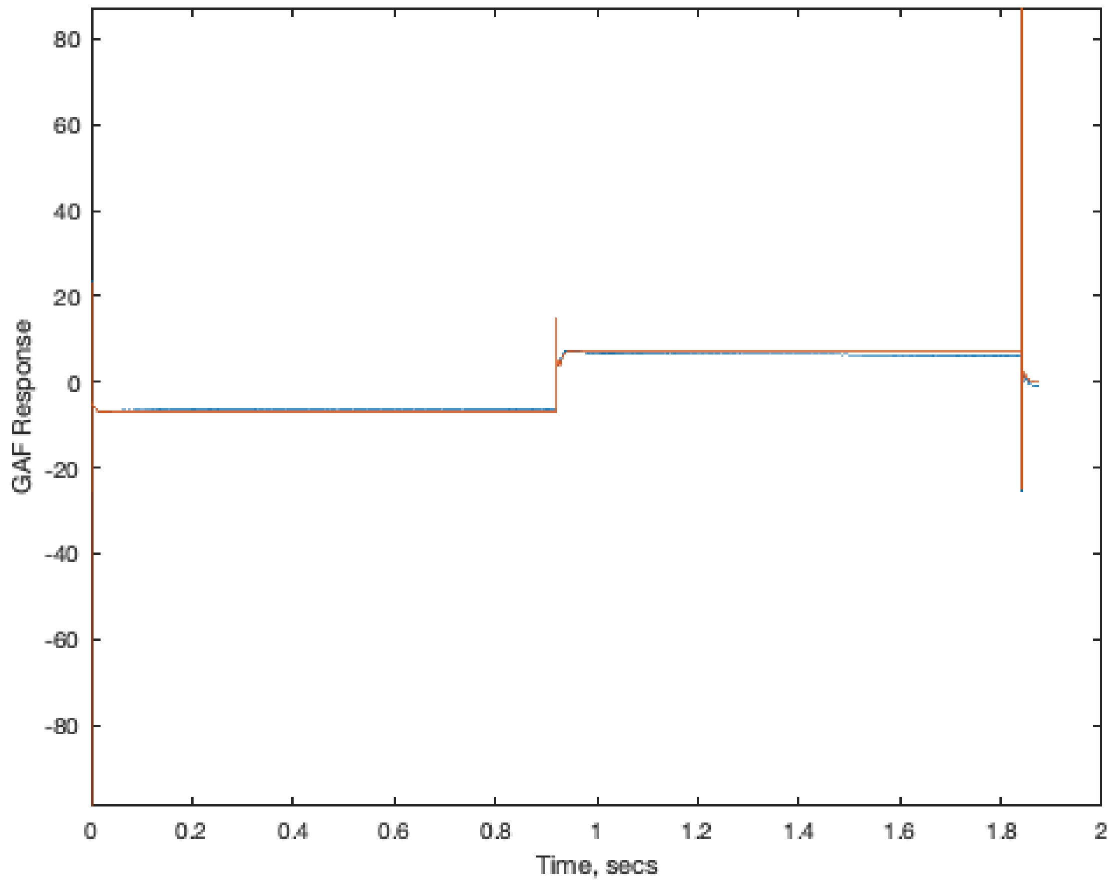
M8A3a – ROM/KESTREL Root Locus

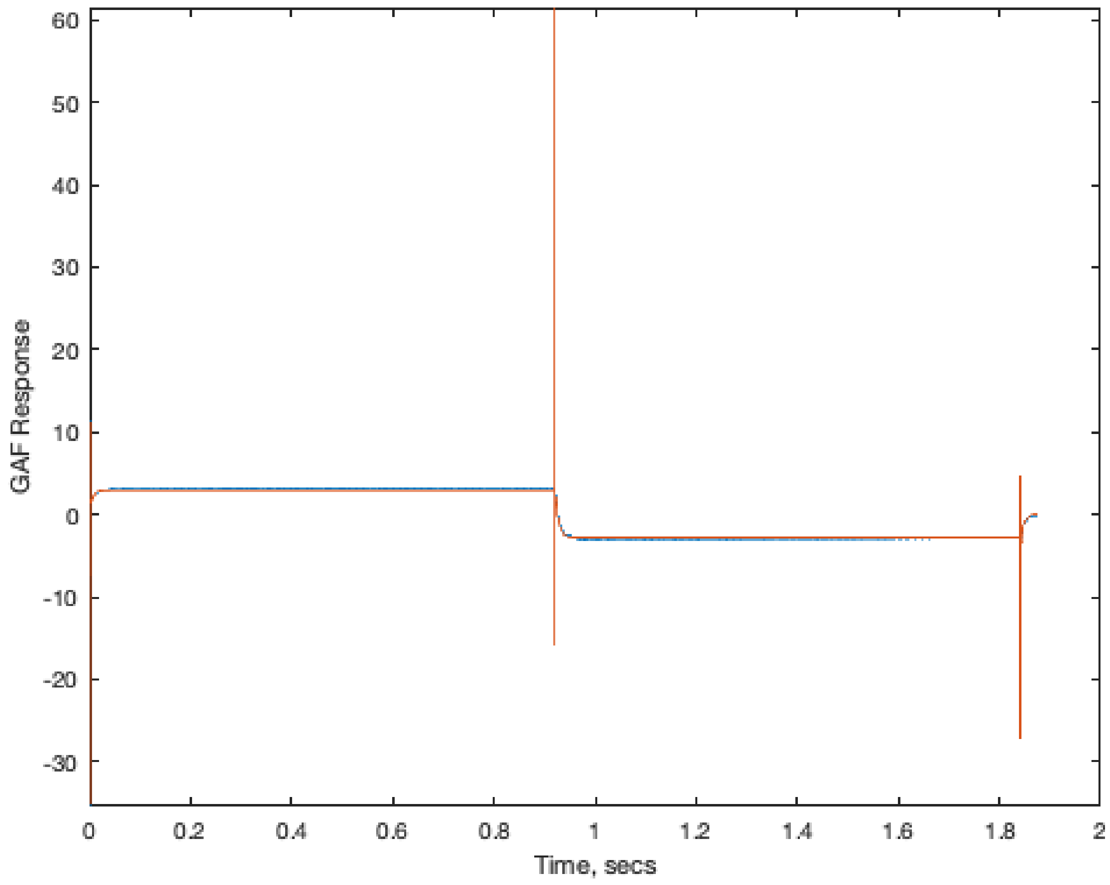
a	.04
b	.01
c	.08
d	.001



M8A3b – ROM/KESTREL GAFs

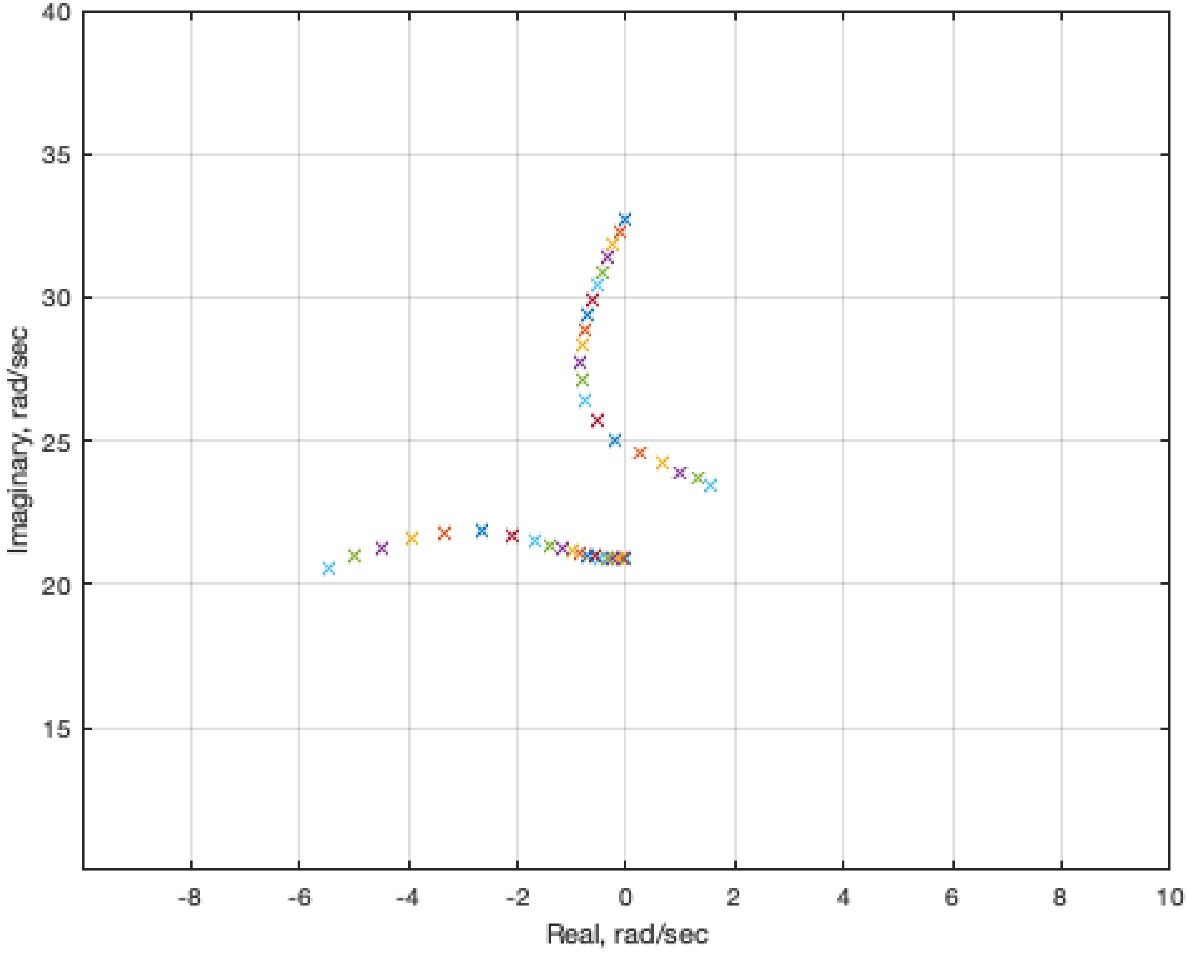
a	.04
b	.01
c	.08
d	.001





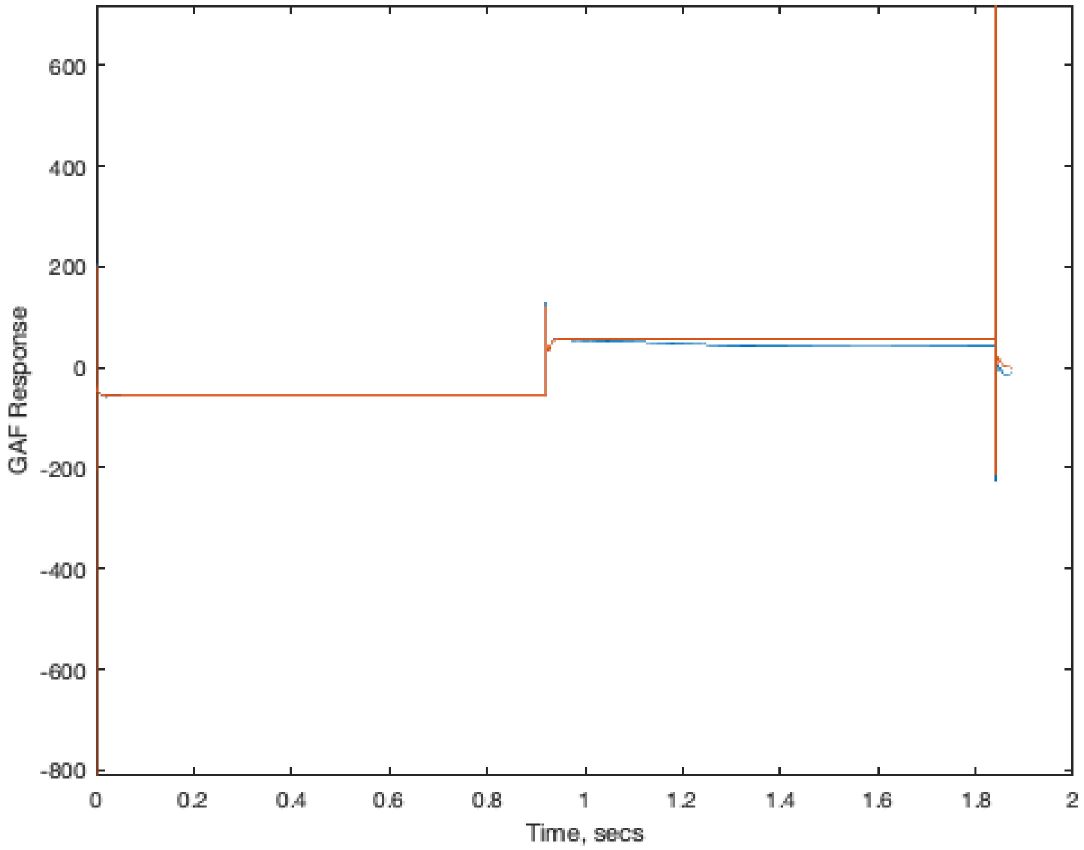
a	.04
b	.01
c	.08
d	.001

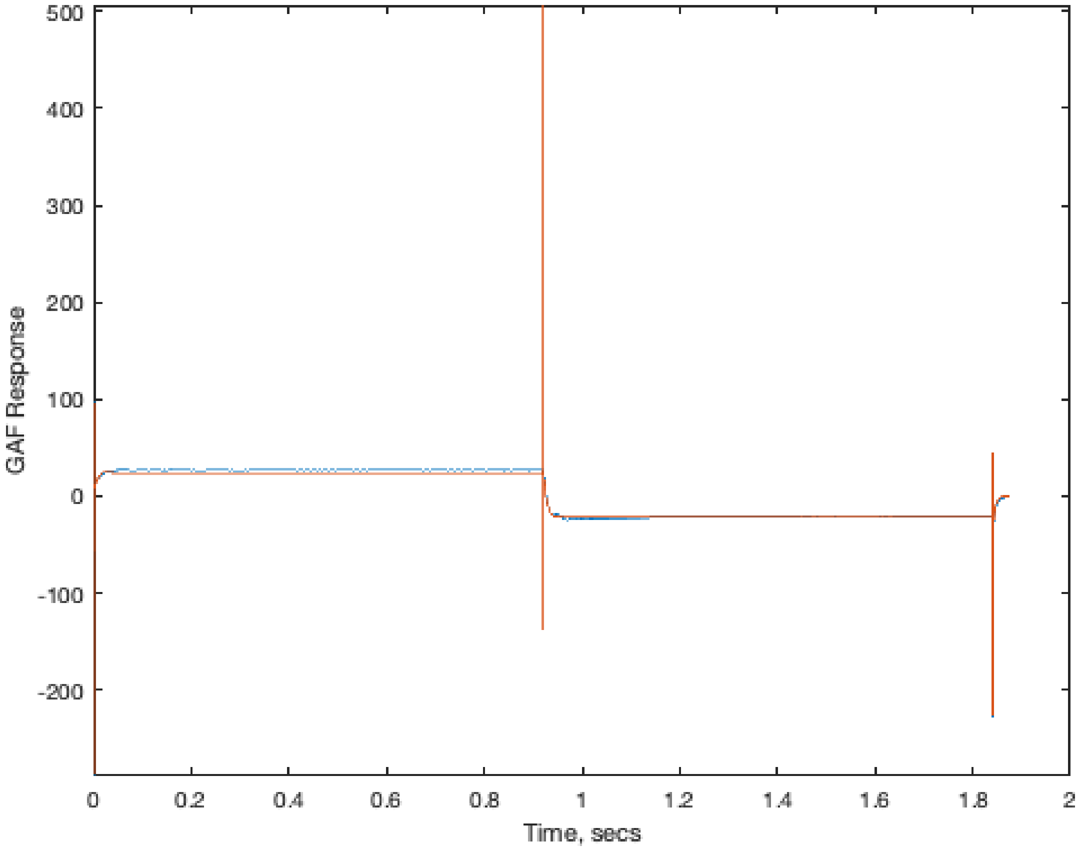
M8A3b – ROM/KESTREL Root Locus



M8A3c – ROM/KESTREL GAFs

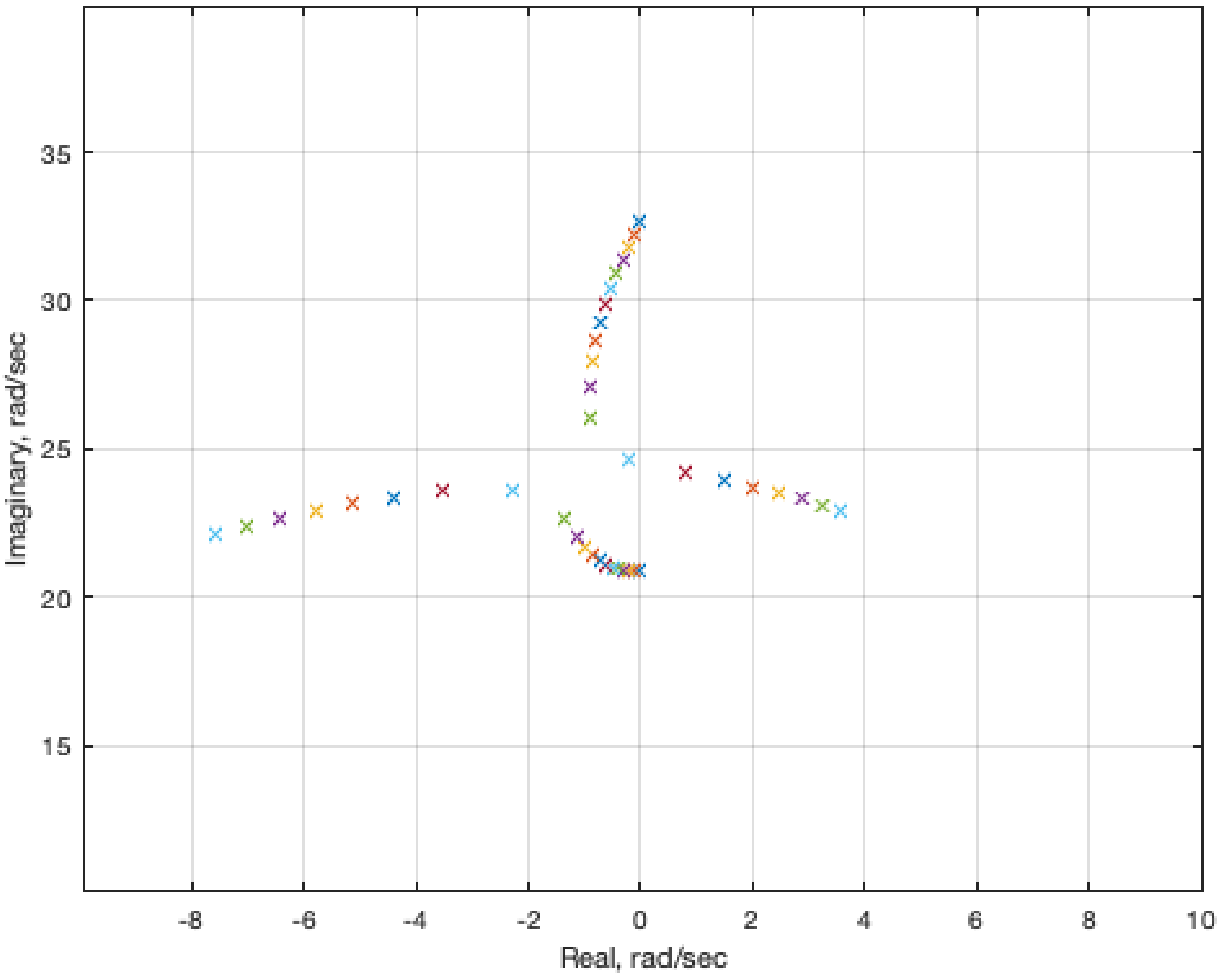
a	.04
b	.01
c	.08
d	.001





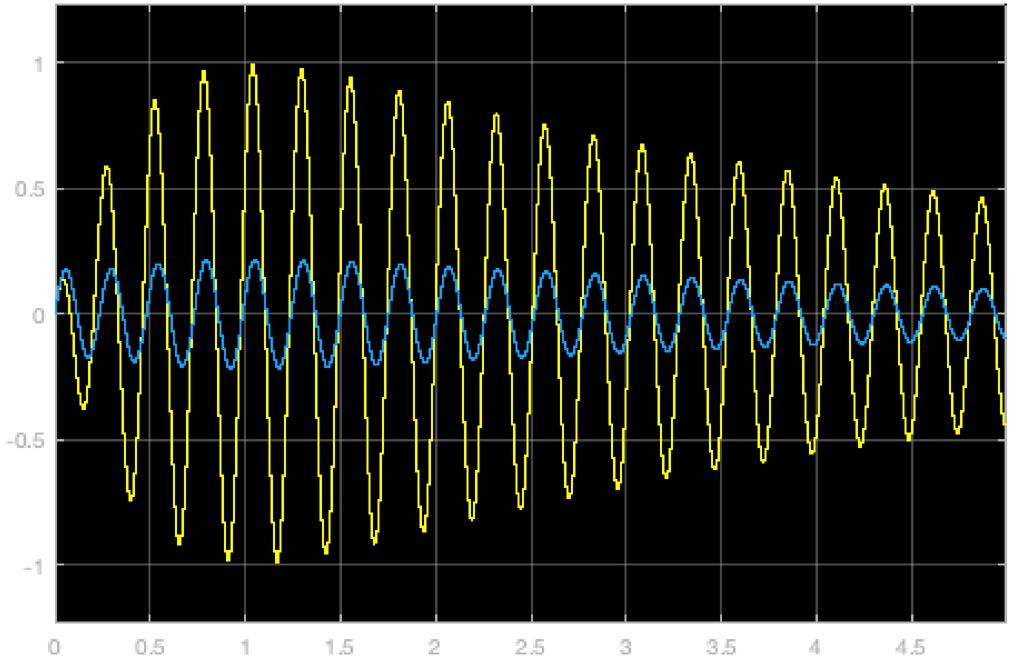
M8A3c – ROM/KESTREL Root Locus

a	.04
b	.01
c	.08
d	.001

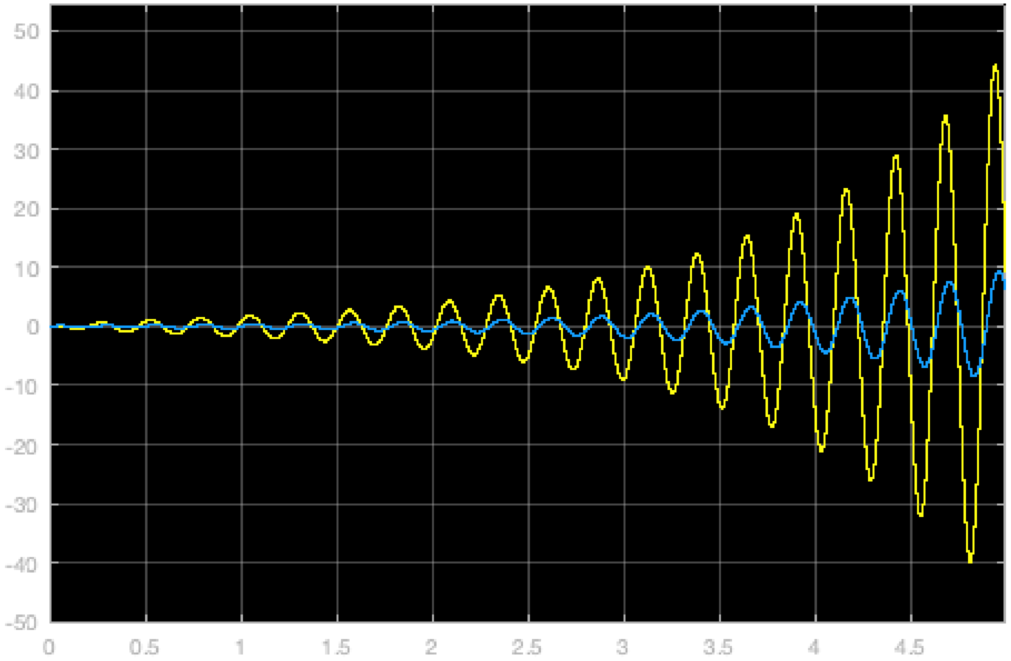


M8A3c – ROM Responses

Q = 172.8 psf

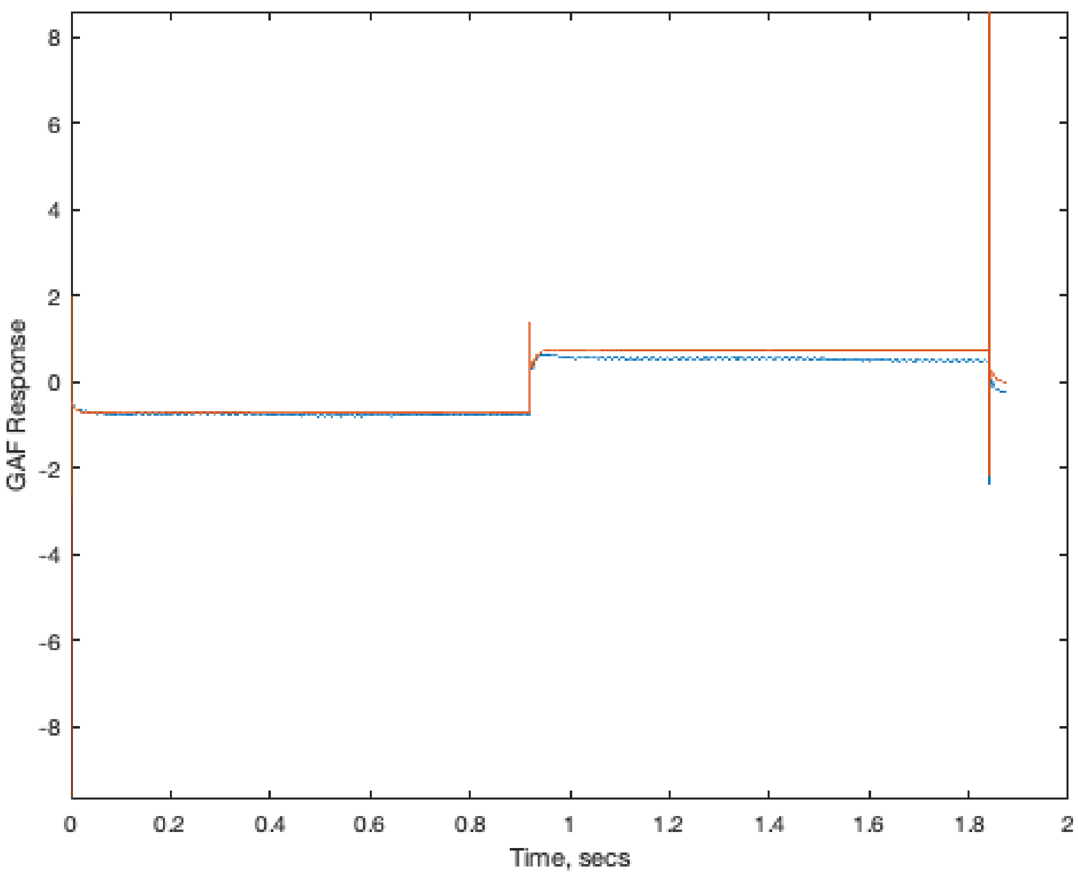


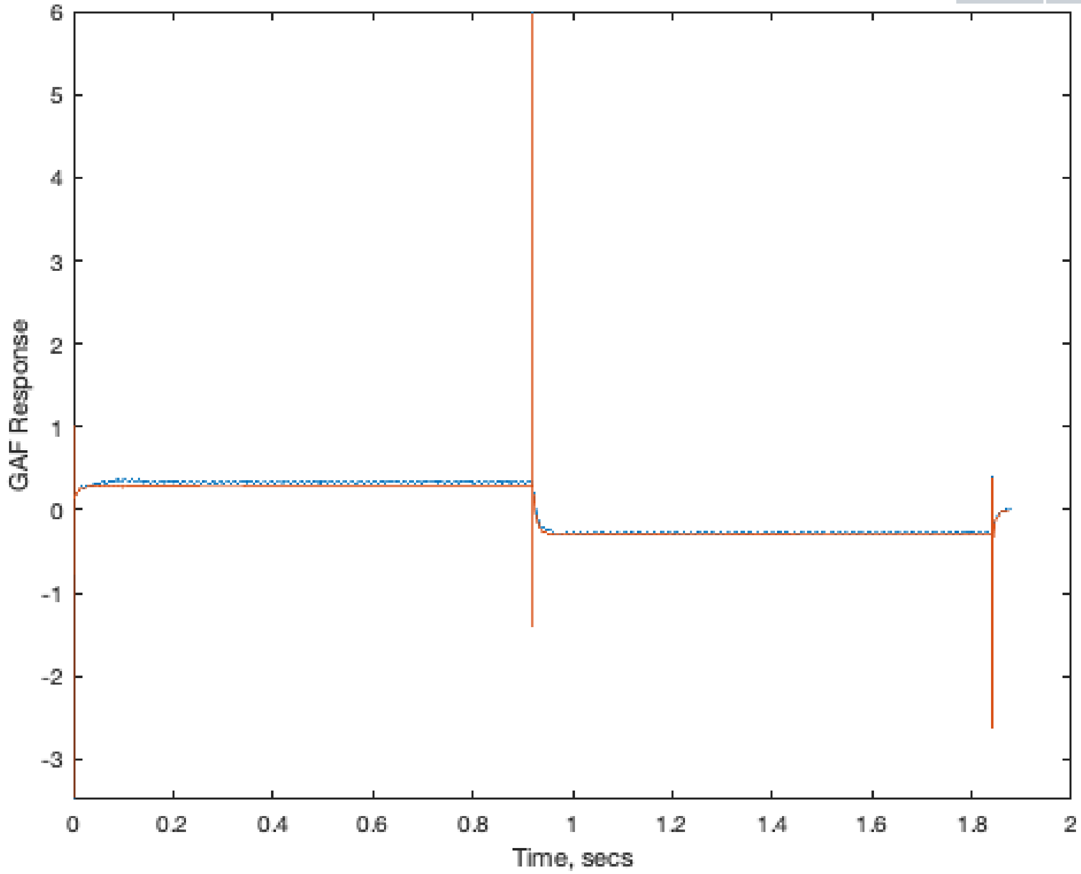
Q = 187.2 psf



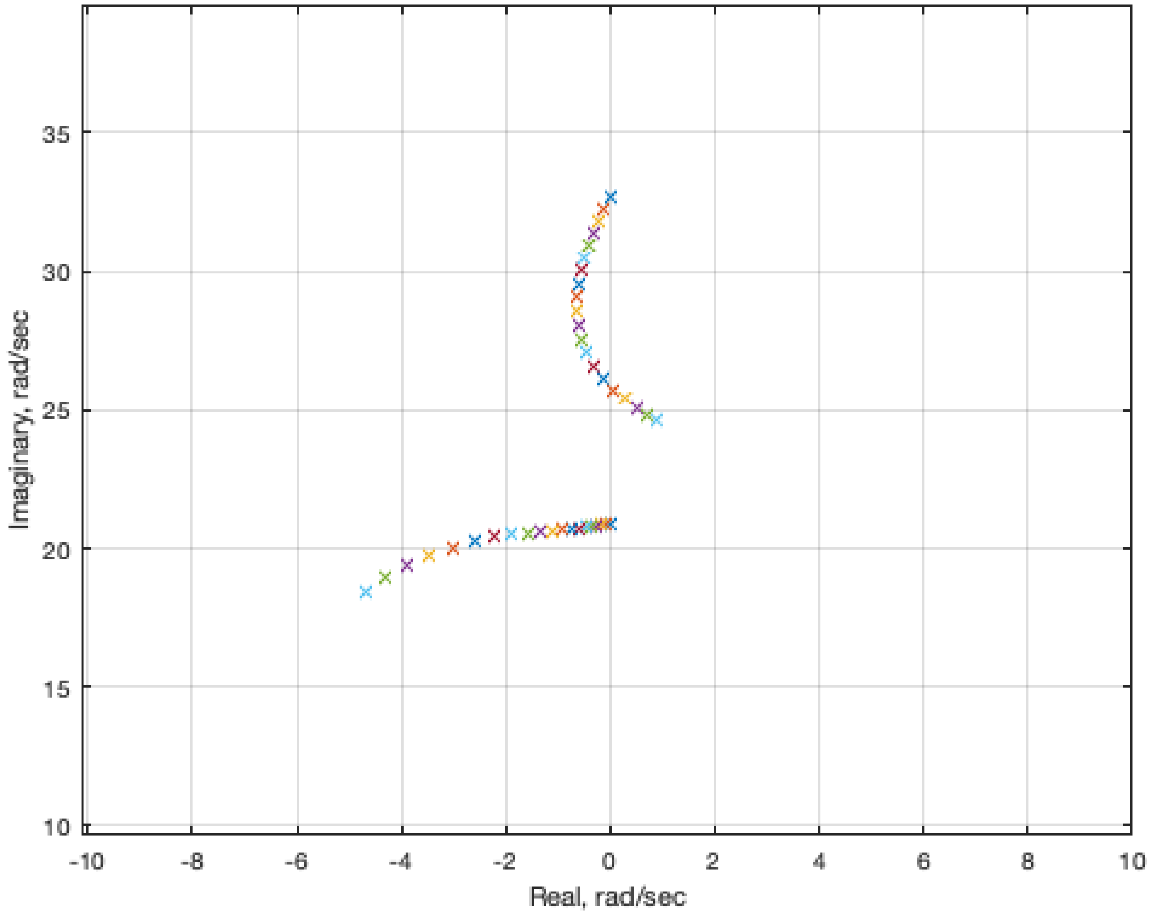
M8A3d – ROM/KESTREL GAFs

a	.04
b	.01
c	.08
d	.001



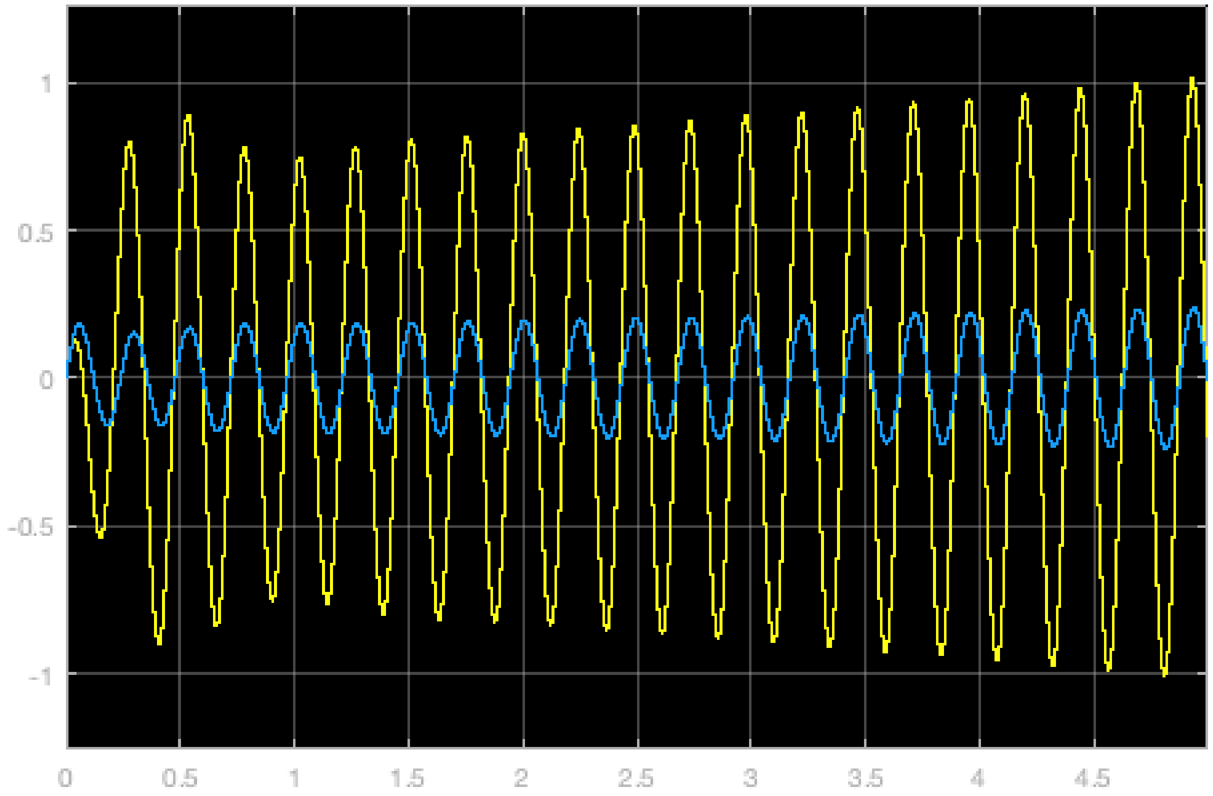


M8A3d – ROM/KESTREL Root Locus



M8A3d – ROM Responses

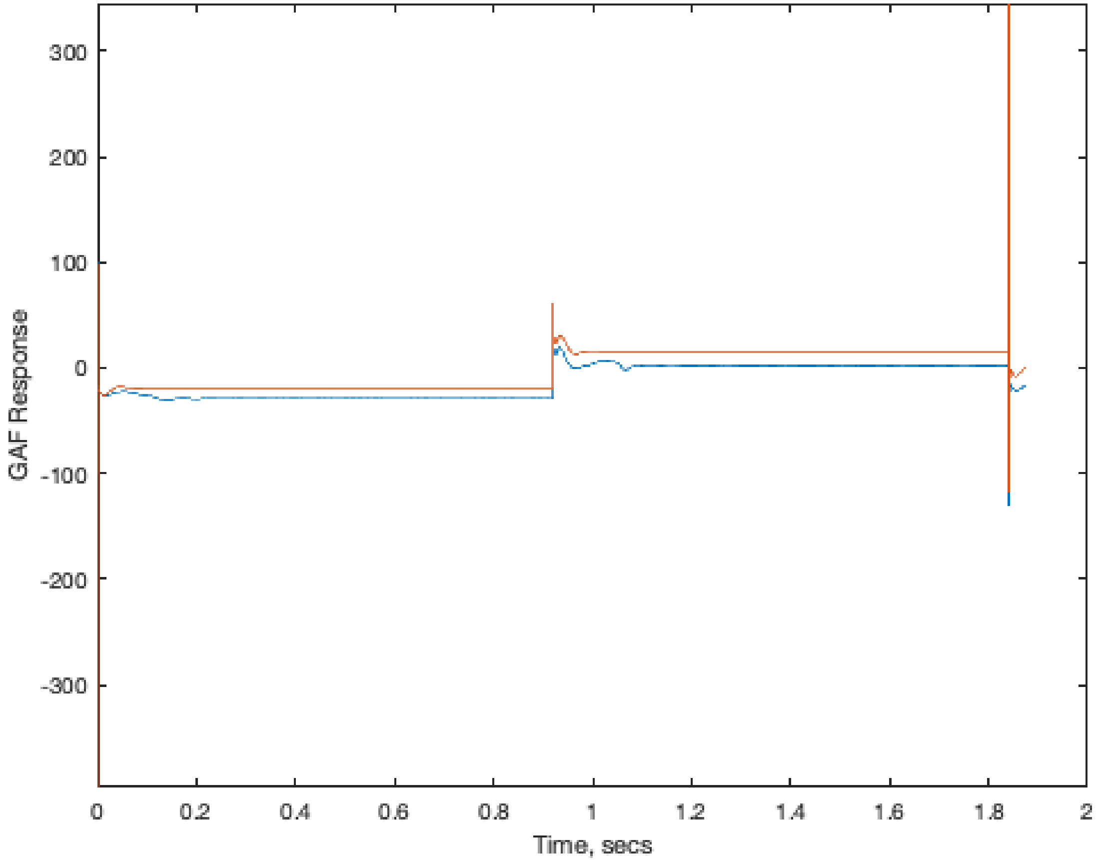
Q = 216 psf

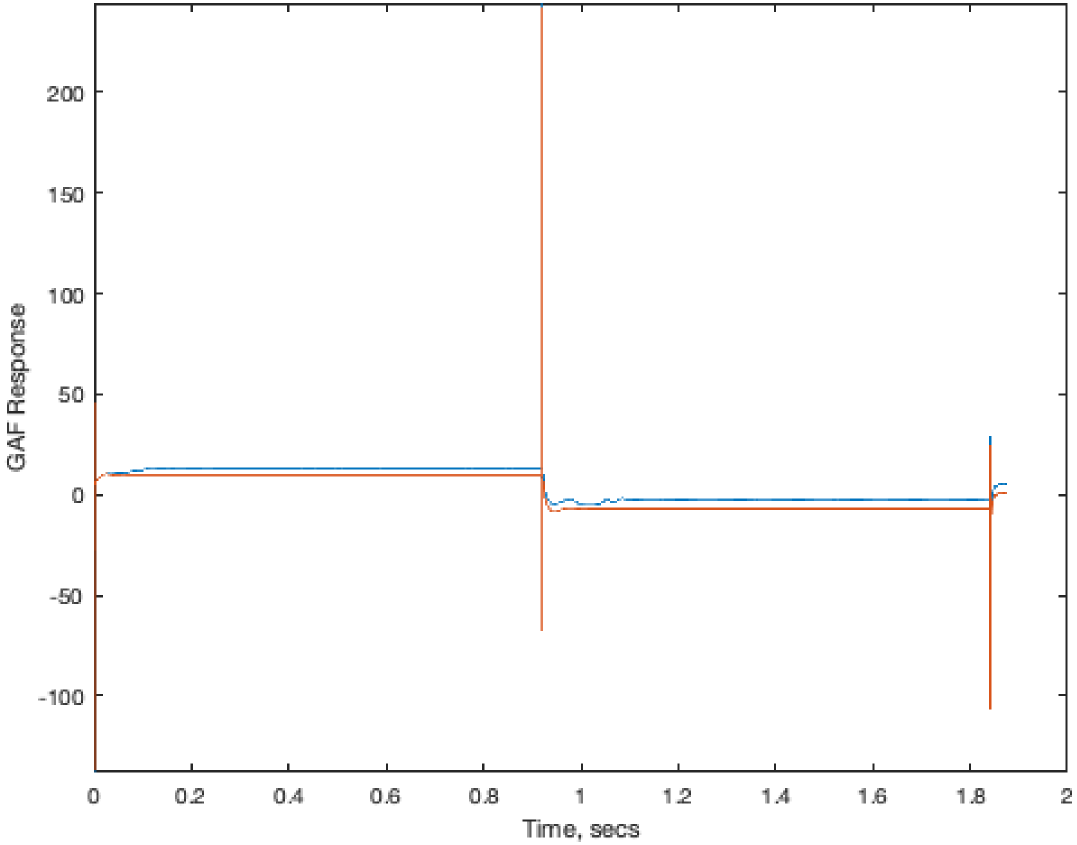


Alpha = 5 deg

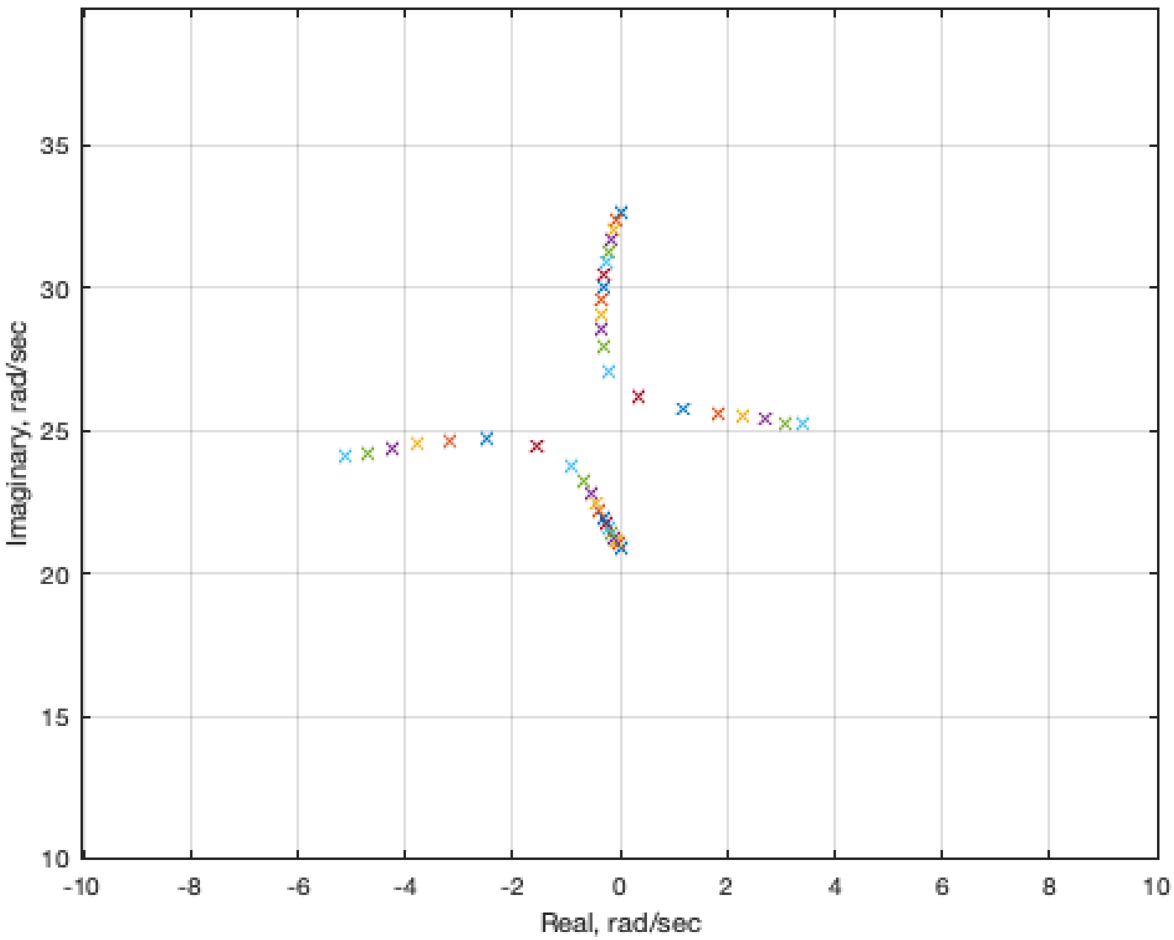
a	.04
b	.01
c	.08
d	.001

M8A5a – ROM/KESTREL GAFs





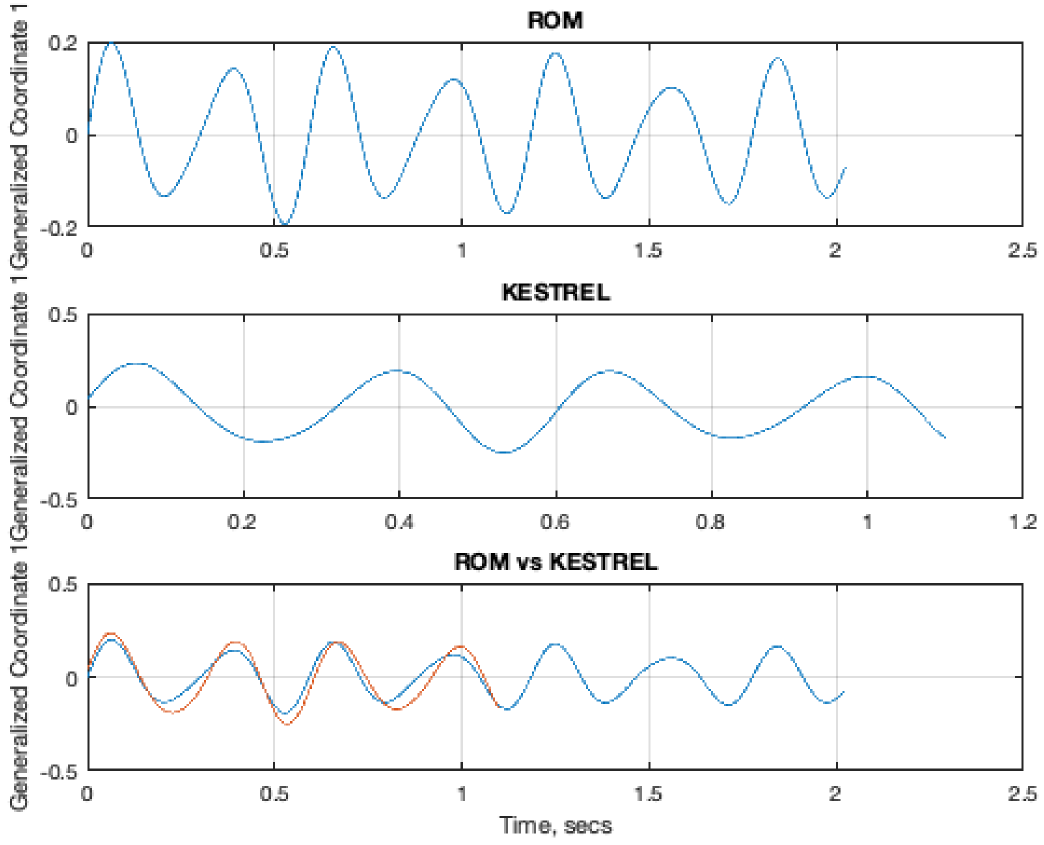
M8A5a – ROM/KESTREL Root Locus



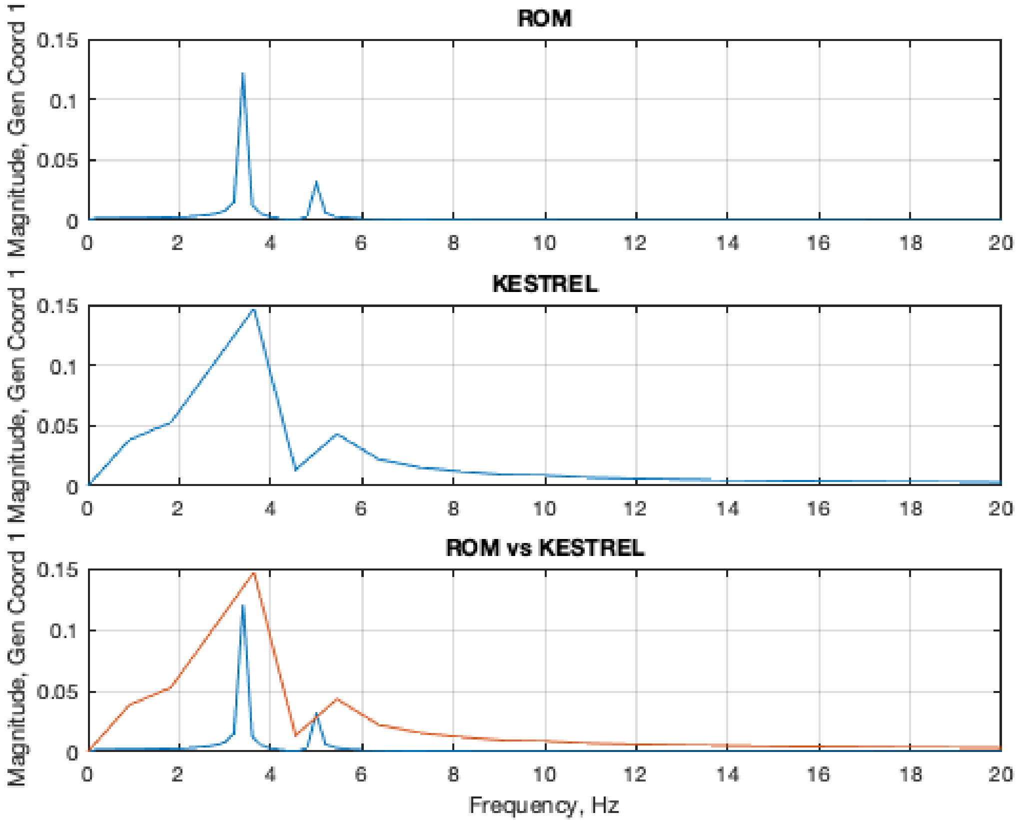
M8A5a – ROM and KESTREL Responses

Q = 50 psf, Mode 1

Time



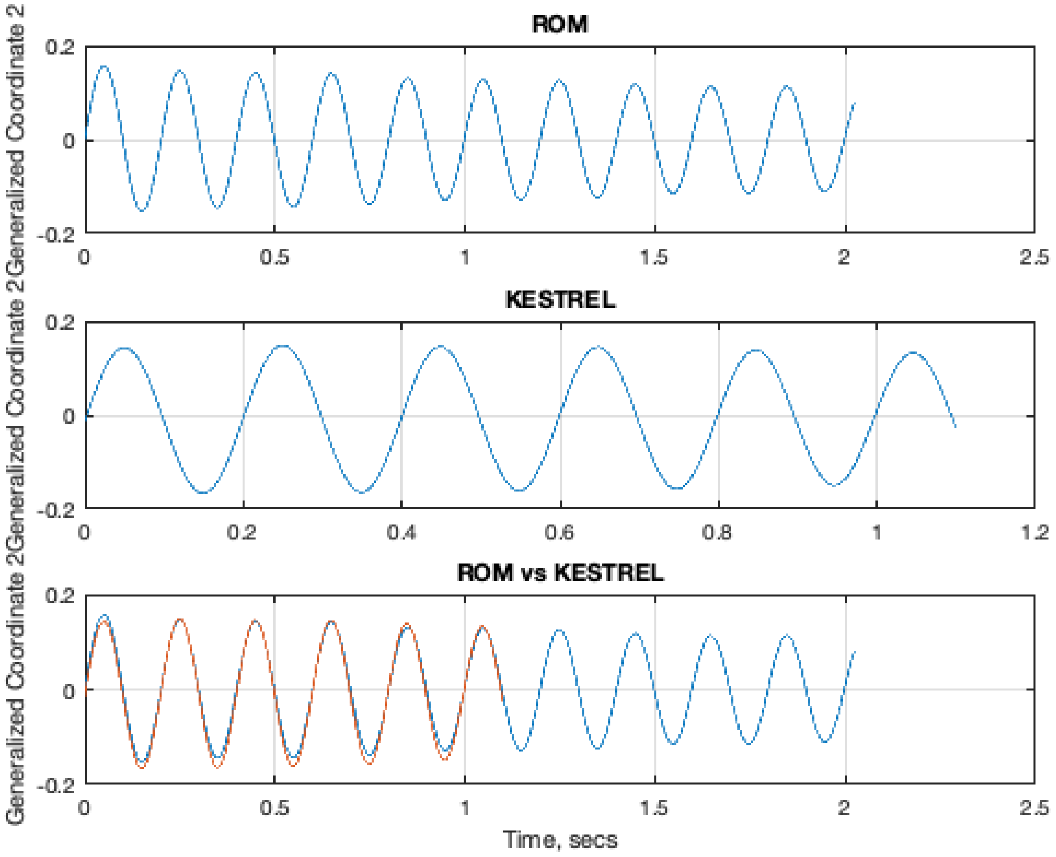
Frequency



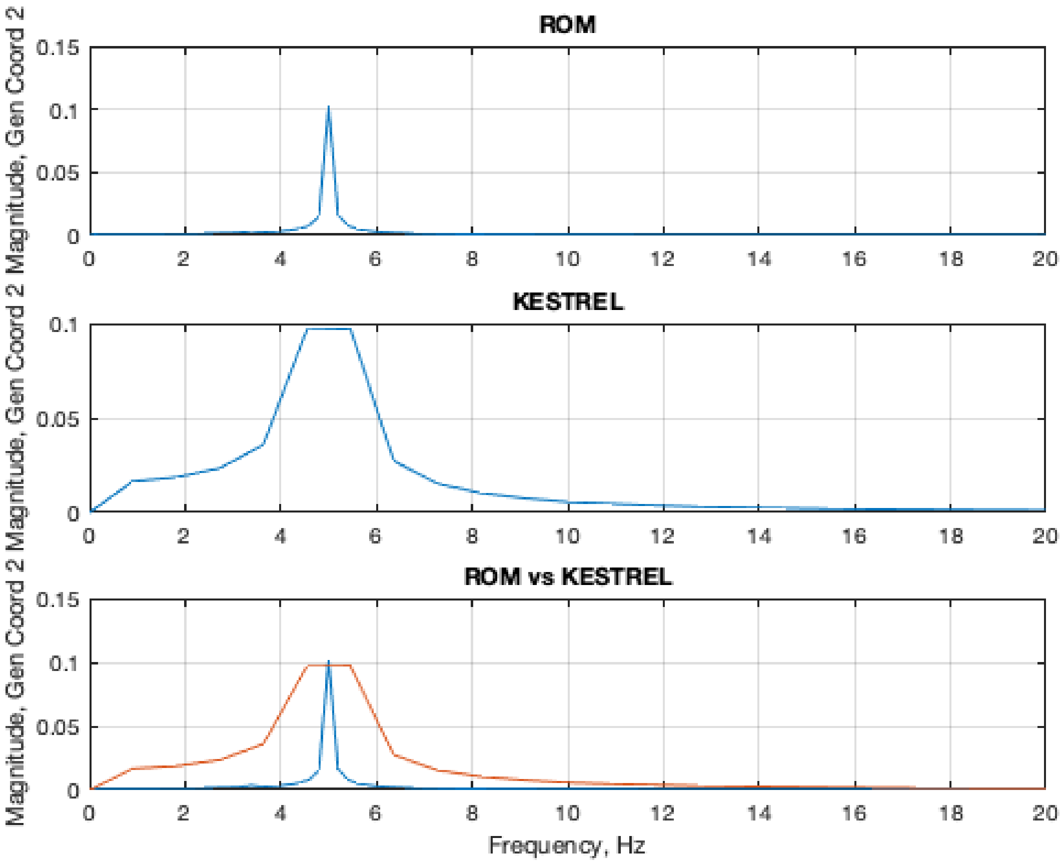
M8A5a – ROM and KESTREL Responses

Q = 50 psf, Mode 2

Time



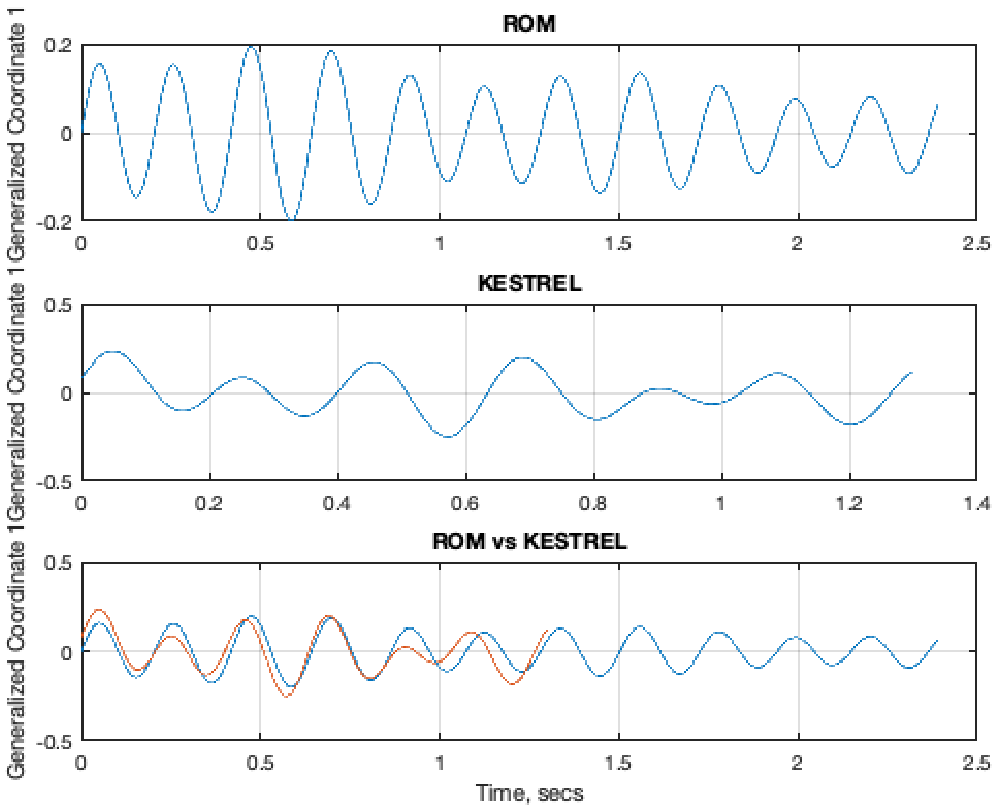
Frequency



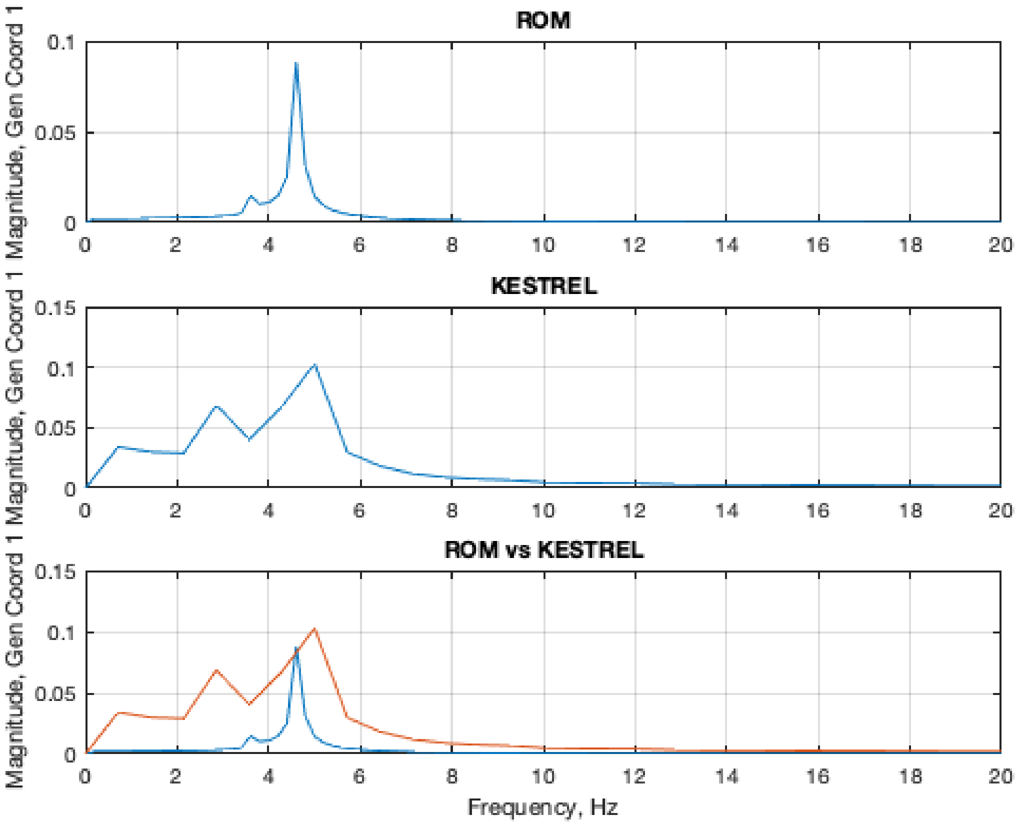
M8A5a – ROM and KESTREL Responses

Q = 130 psf, Mode 1

Time



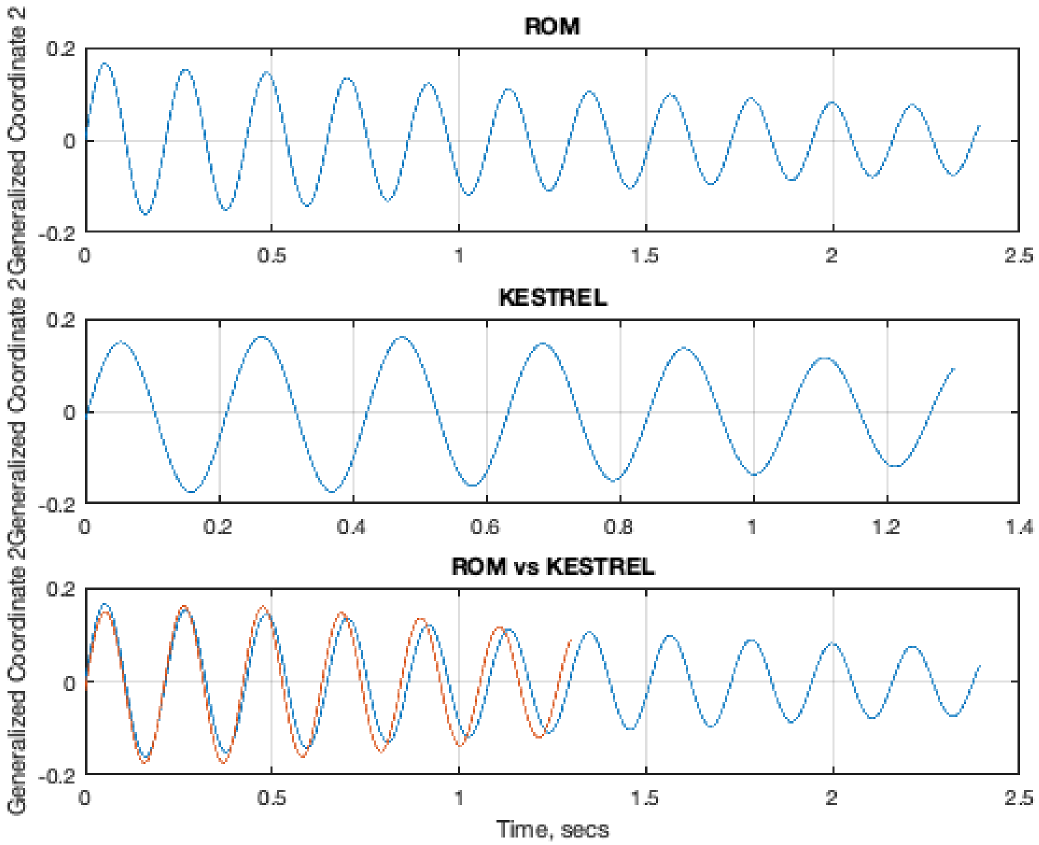
Frequency



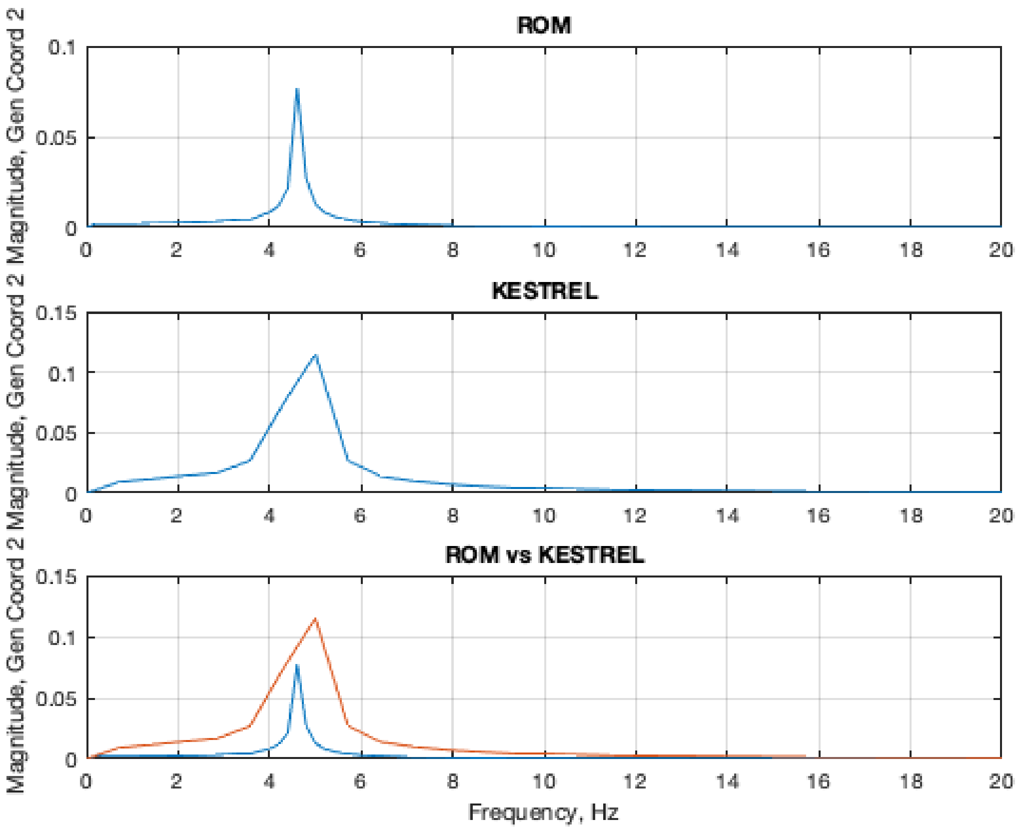
M8A5a – ROM and KESTREL Responses

Q = 130 psf, Mode 2

Time

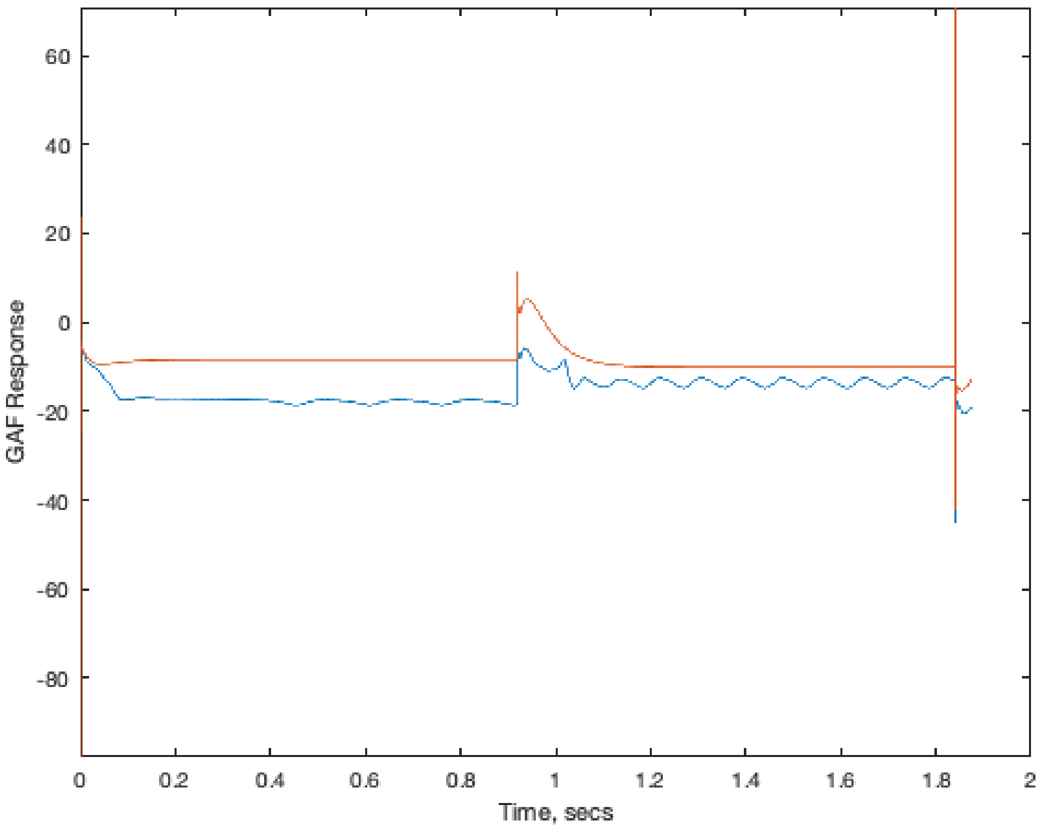


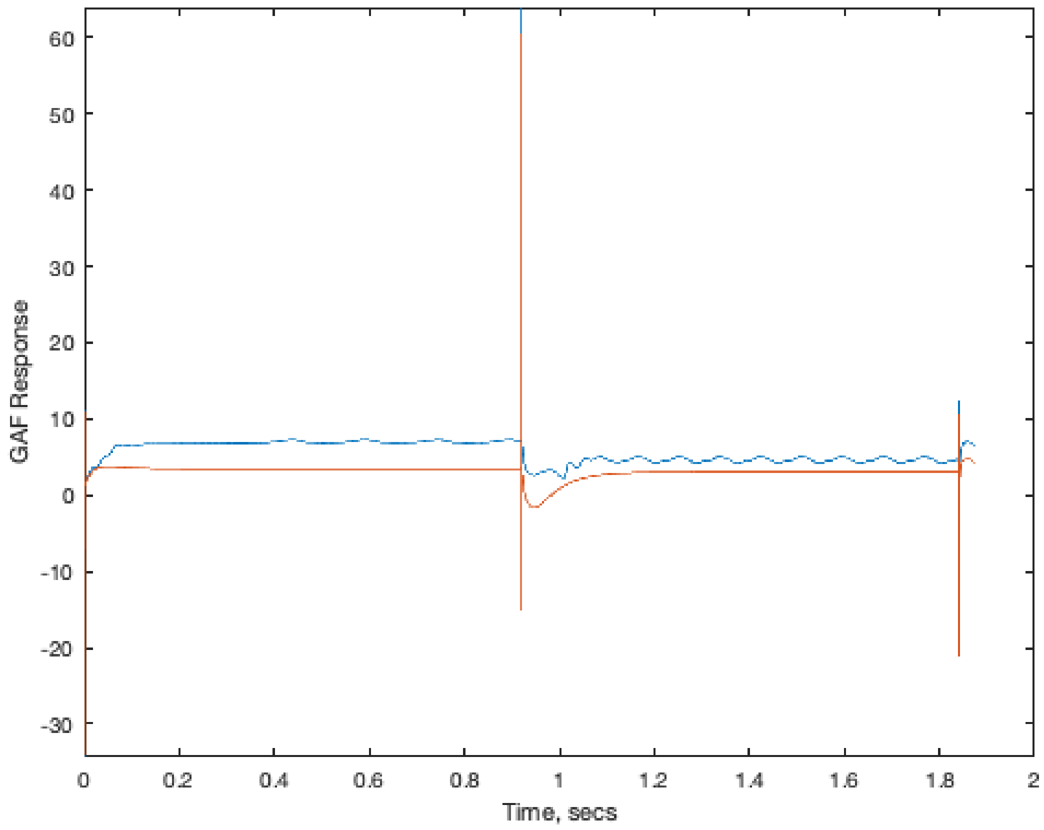
Frequency



a	.04
b	.01
c	.08
d	.001

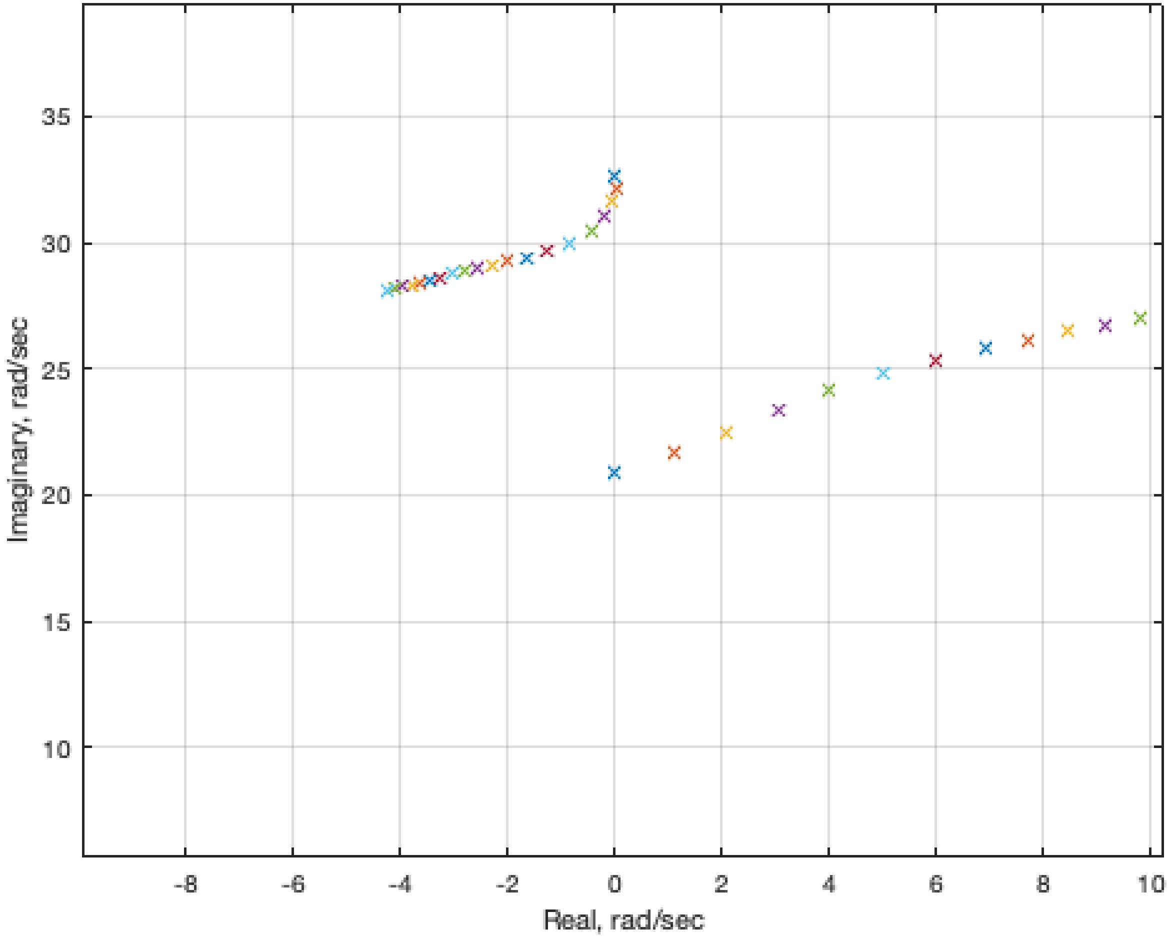
M8A5b – ROM/KESTREL GAFs





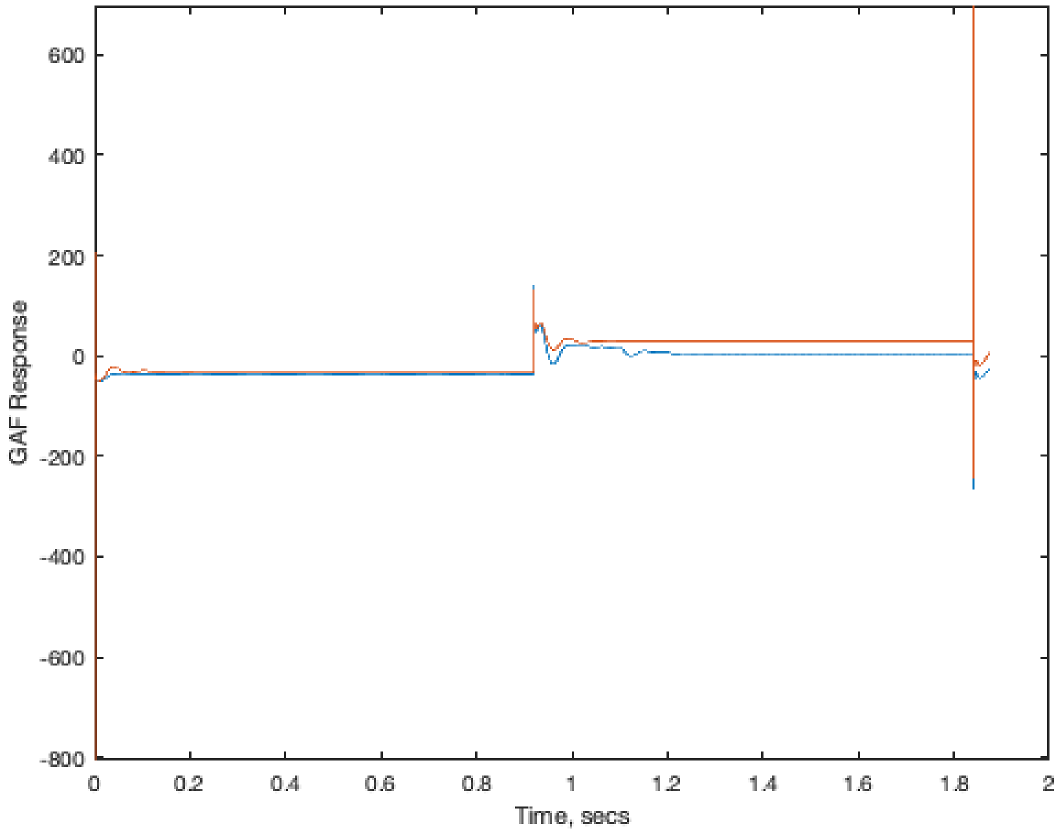
M8A5b – ROM/KESTREL Root Locus

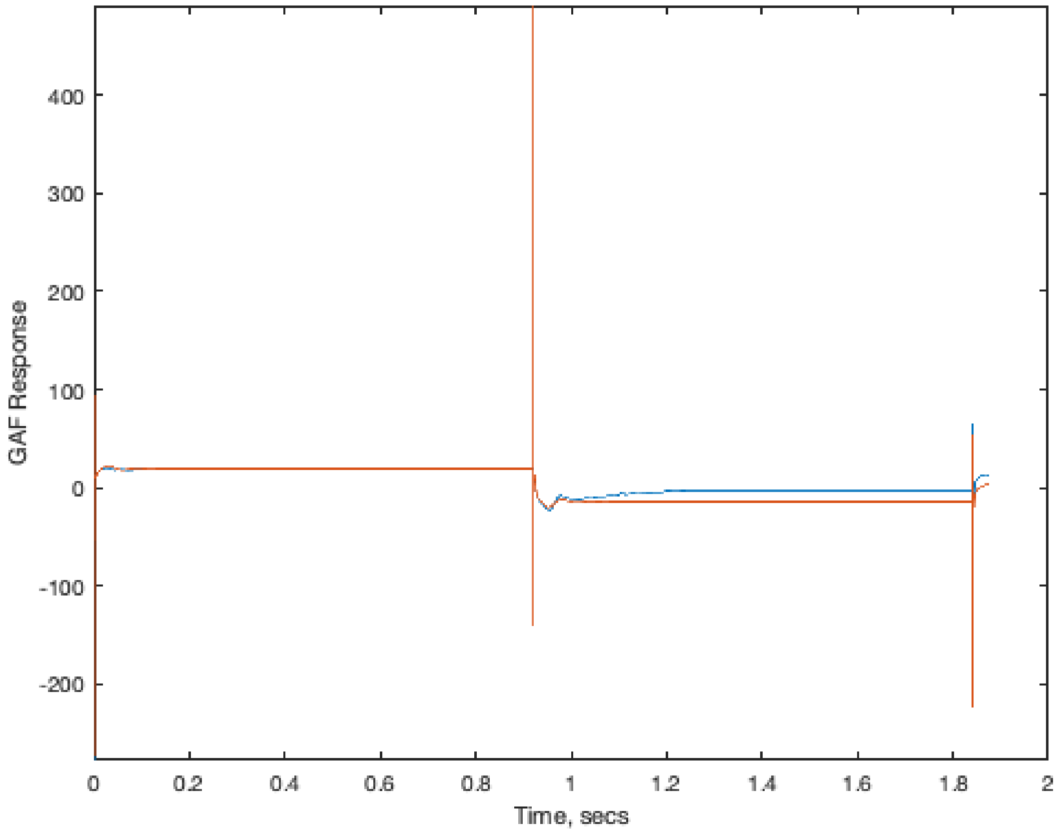
a	.04
b	.01
c	.08
d	.001



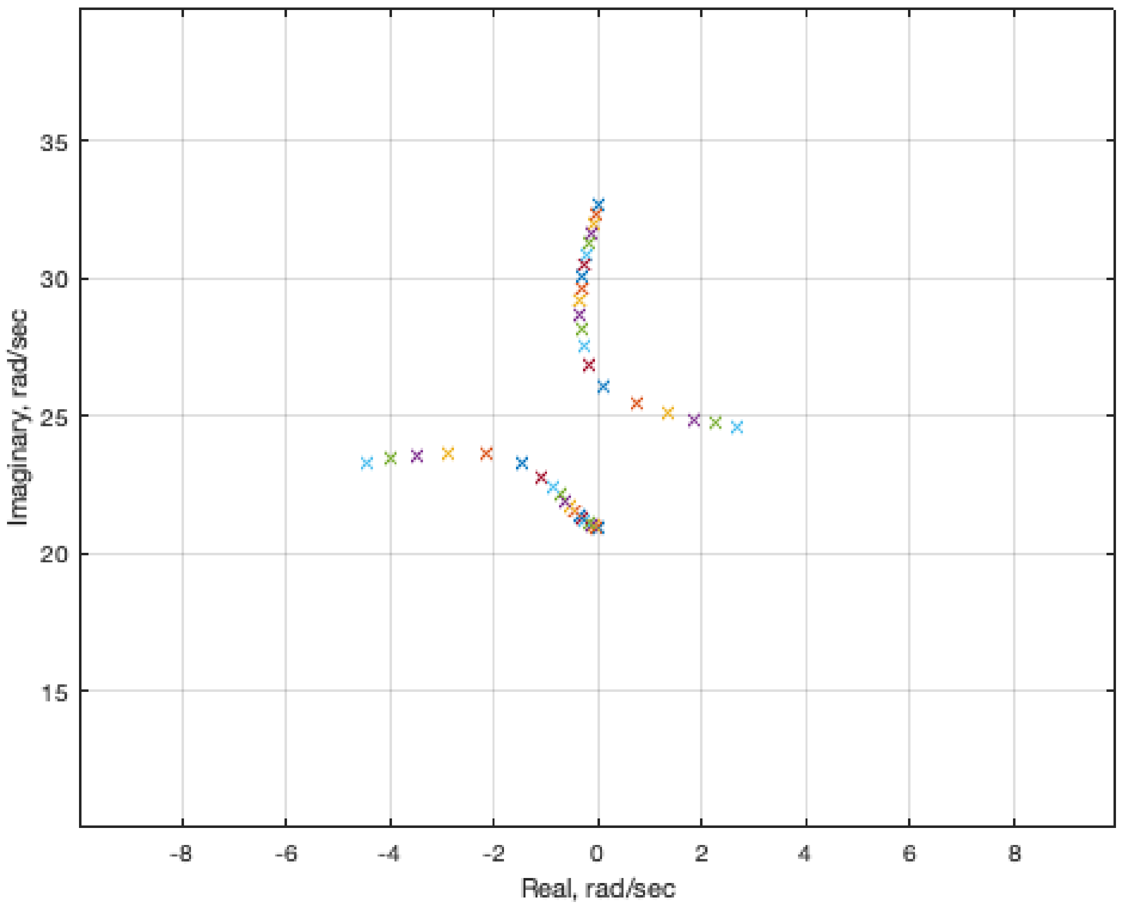
M8A5c – ROM/KESTREL GAFs

a	.04
b	.01
c	.08
d	.001



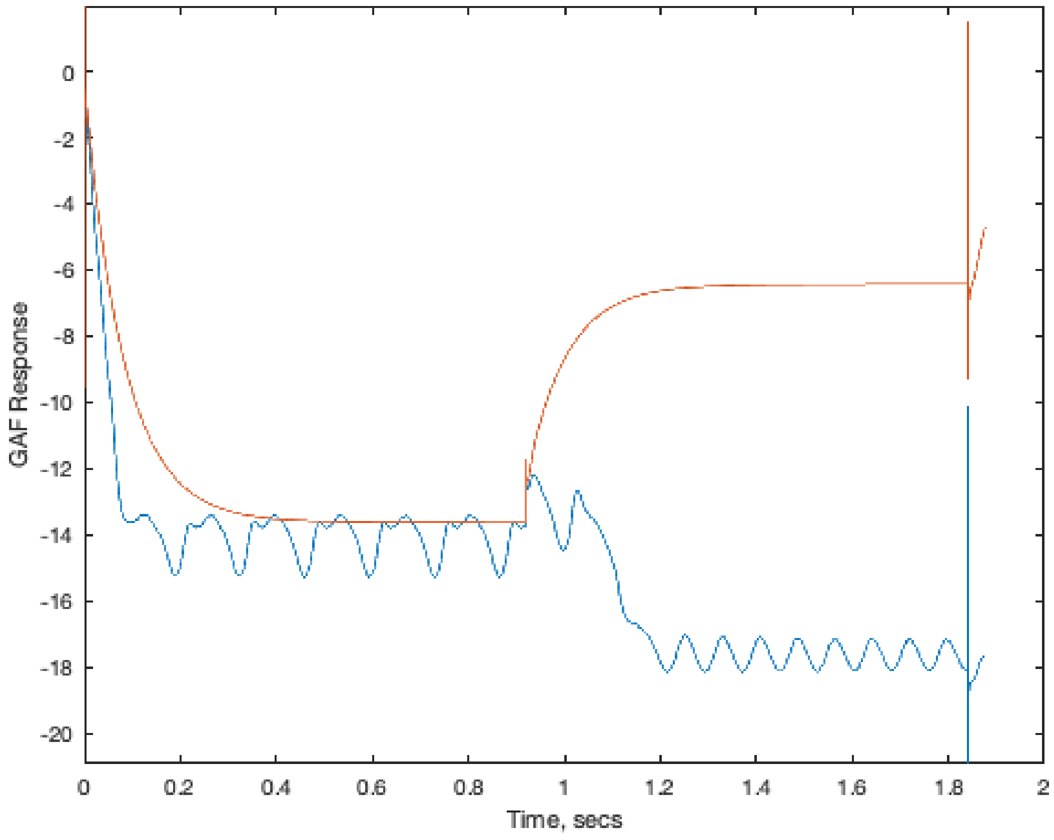


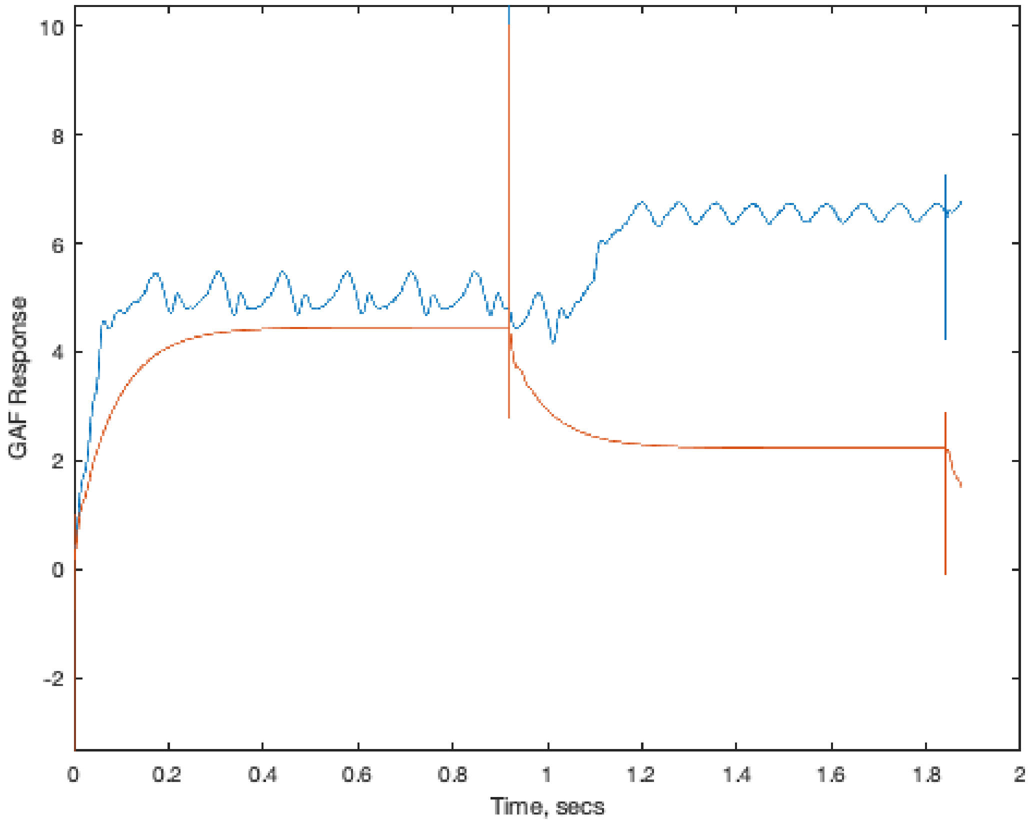
M8A5c – ROM/KESTREL Root Locus



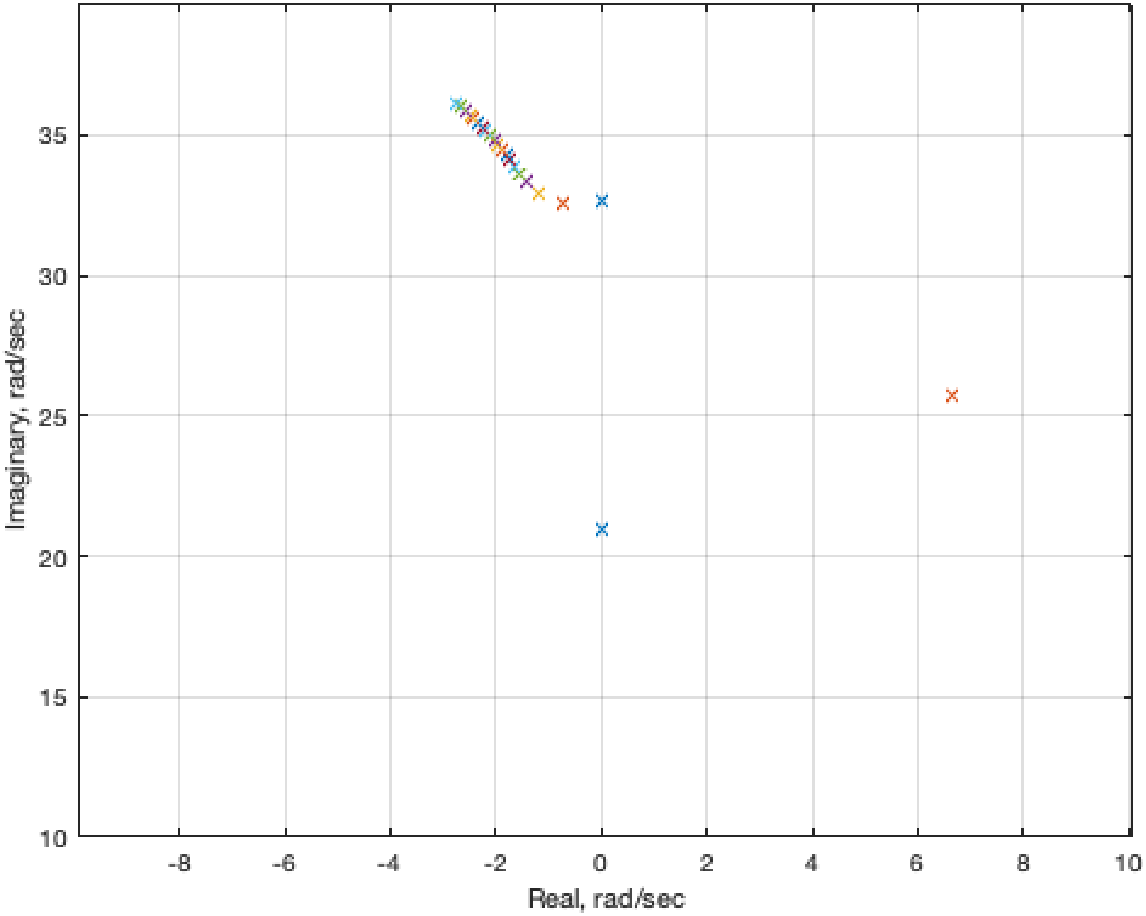
M8A5d – ROM/KESTREL GAFs

a	.04
b	.01
c	.08
d	.001



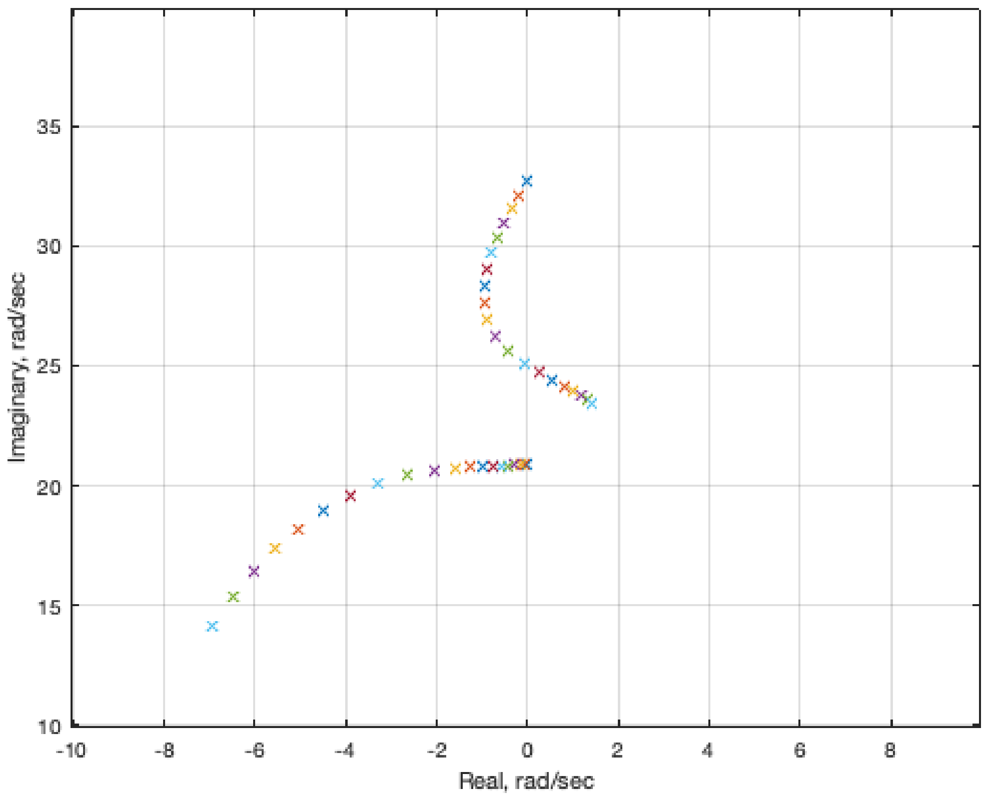


M8A5d – ROM/KESTREL Root Locus

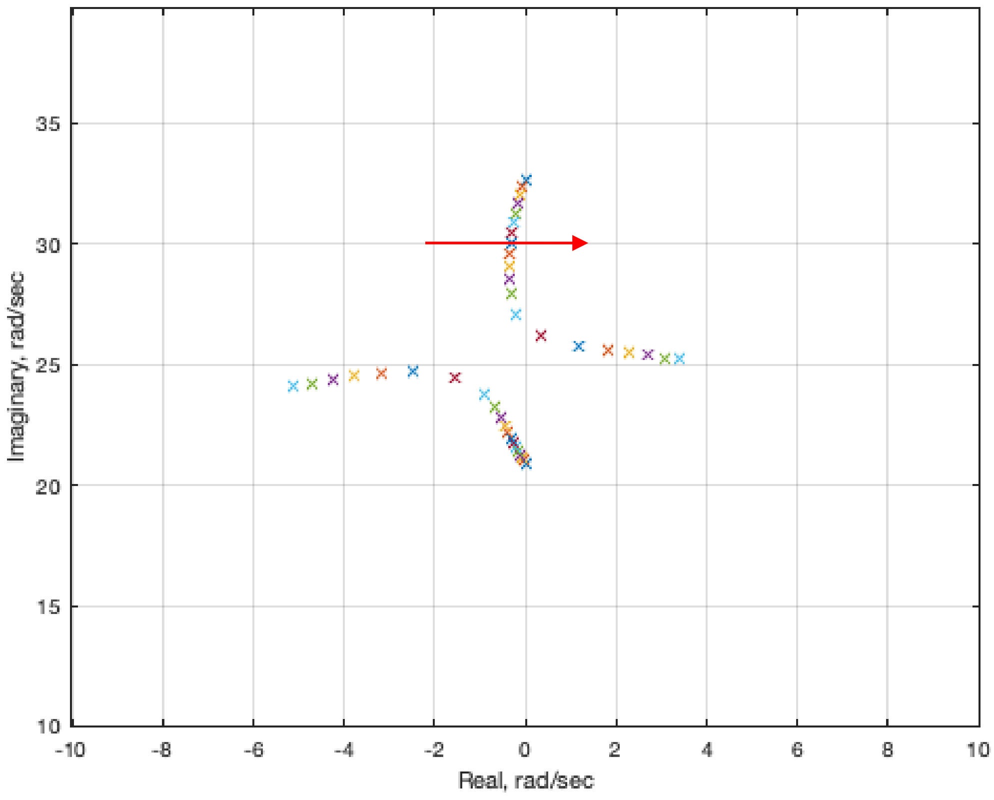


ROM/KESTREL
Root Locus Plot Comparison
M=0.80, alpha=0, 5 deg

Alpha=0 deg



Alpha=5 deg



Conclusions (Thus Far)

- At benign conditions (alpha=0 deg), all ROMs provide same result; gratifying, as it indicates linearized flow dynamics
- As alpha is increased, variations between the different ROMs (amplitudes) start to become obvious
- At alpha=5 deg, there are noticeable differences between the ROMs, indicating that the higher-amplitude ROMs do a better job (at this condition) of predicting the aeroelastic responses at multiple dynamic pressures
- So far, ROM Flutter Q=179 psf; KESTREL Flutter Q=168 psf (~6.5%)
- Will continue analyses at AePW-4 recommended conditions.