BSCW Computations Using KESTREL and AEROM

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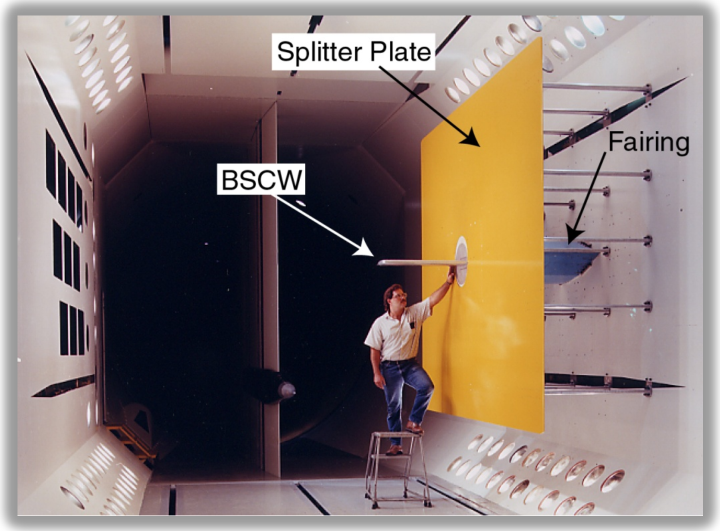
Presentation to the AePW Team

Outline

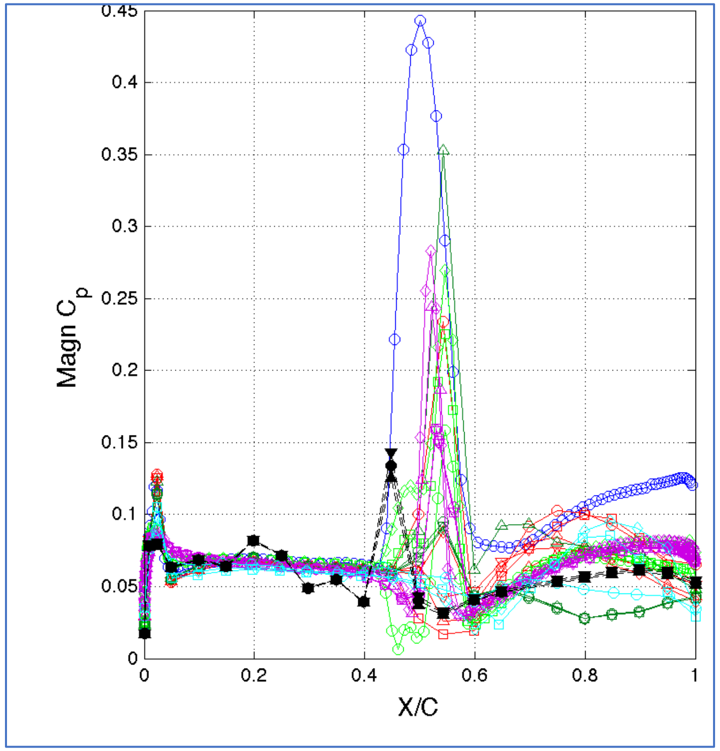
- Benchmark SuperCritical Wing (BSCW), Aeroelastic Prediction Workshop (AePW)
- Background
- AEROM
- Results
  - Alpha=0, 1, 3, and 5 degs (skip alpha=1 deg; similar to alpha=0 deg)
  - Amplitudes = 0.04, 0.01, 0.08, and 0.001 (modal)
  - Comparison of full solution GAFs vs ROM GAFs (error quantification)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

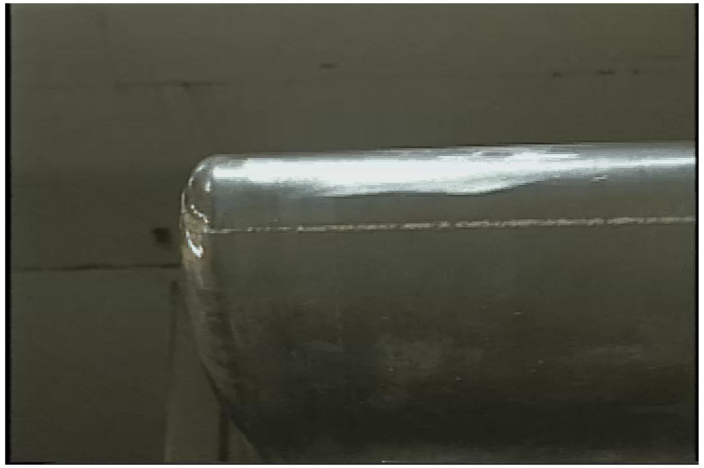


M=0.85, Re_c=4.49 million, test medium: R-134a, α = 5°, θ = 1°, freq 1 & 10 Hz



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

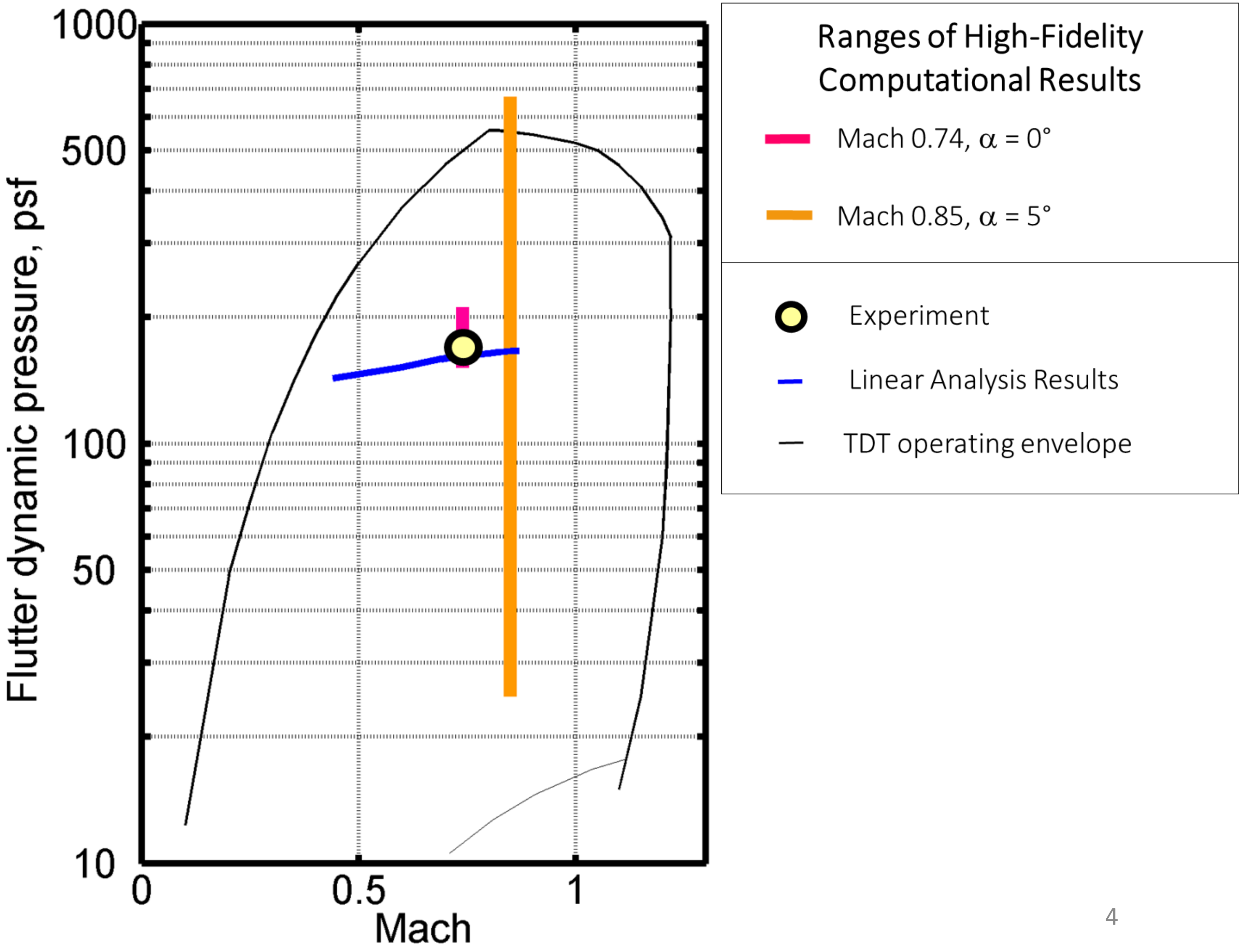
- Form technical working group of BSCW analysts
- Extensive study of available experimental data; characterize different flow phenomena
- Benchmark against more benign cases- lower Mach number, lower angle of attack
- Analyze the static (unforced) problem using time-accurate evaluation methods
- Study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

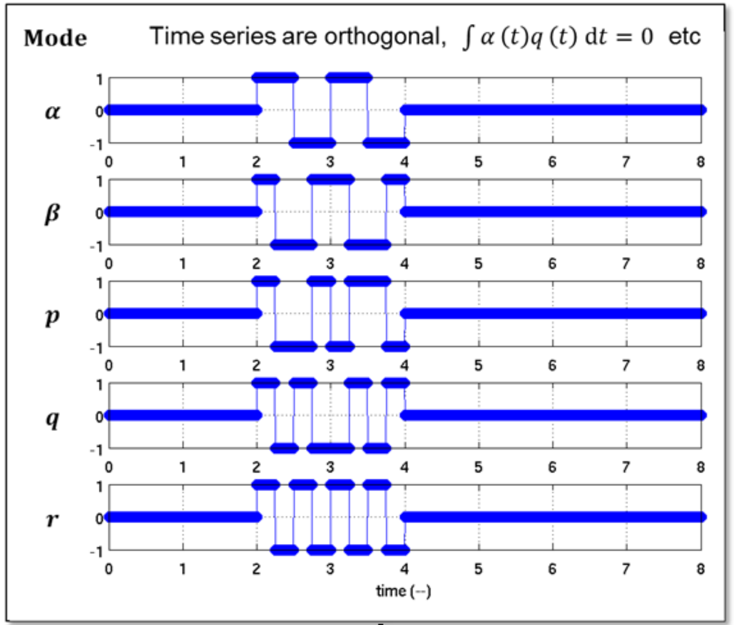


Background

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

System Identification for Multiple Input-Output (cont)

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, $y(t) = (C_A, C_S, C_N, C_l, C_m, C_n)$

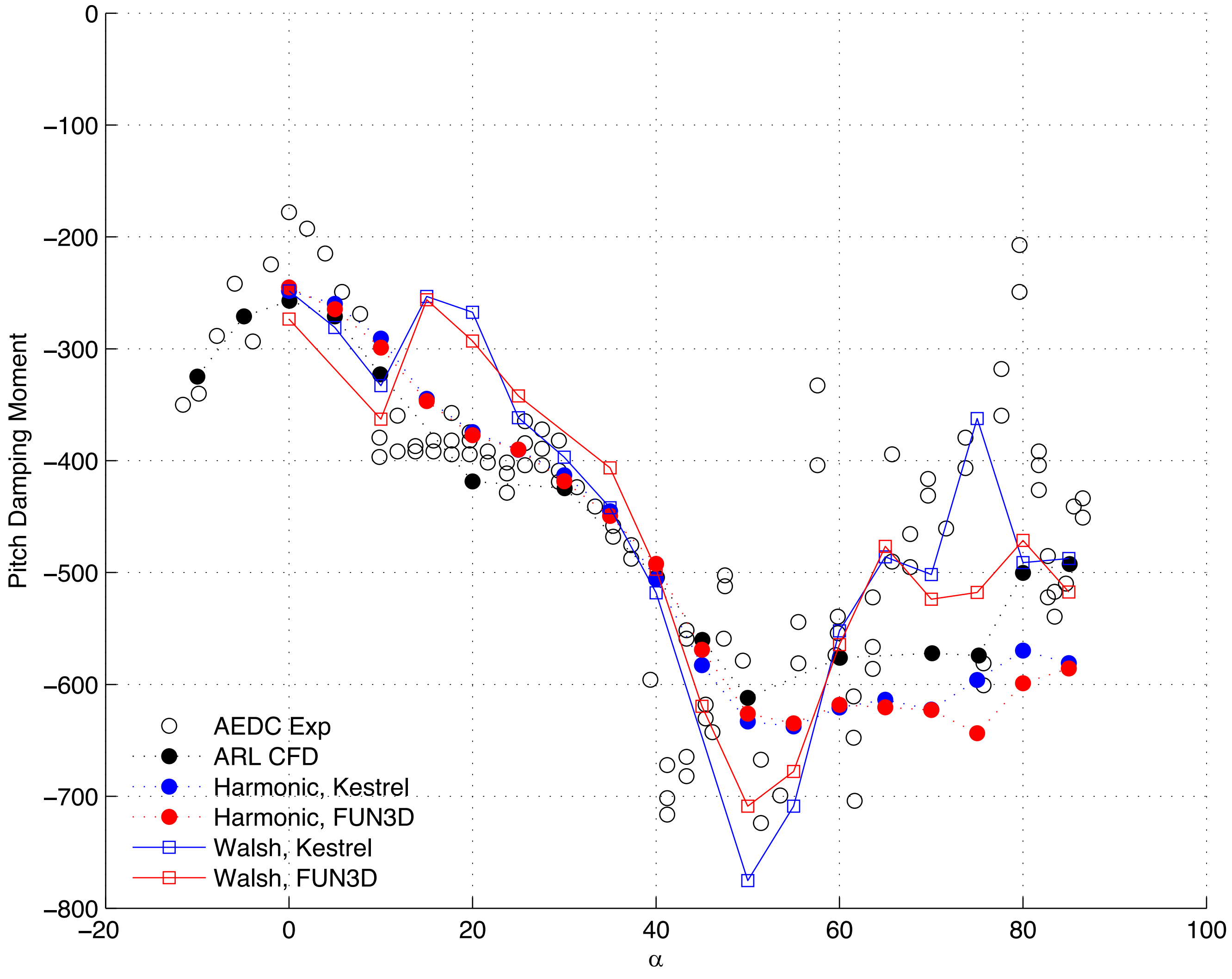
System ID
- Observer/Kalman Identification
- Eigenvalue Realization Algorithm

Computational Fluid Dynamics (Kestrel or FUN3D)

System/Observer/Controller Identification Toolbox (SOCIT)

Pitch Moment Damping

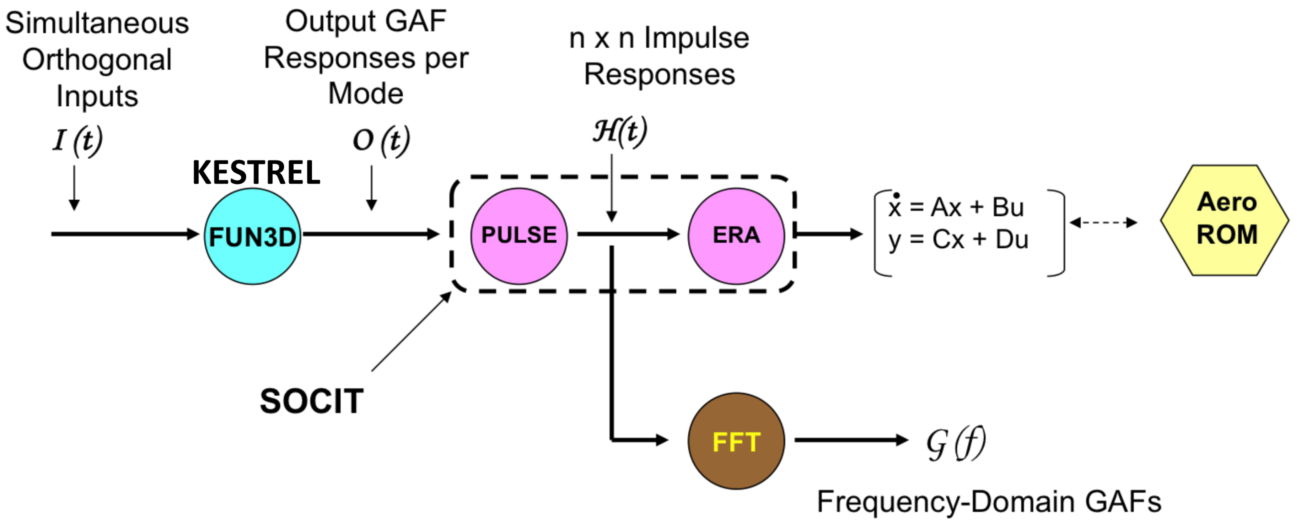
Walsh Functions vs Harmonic Motion and Reference

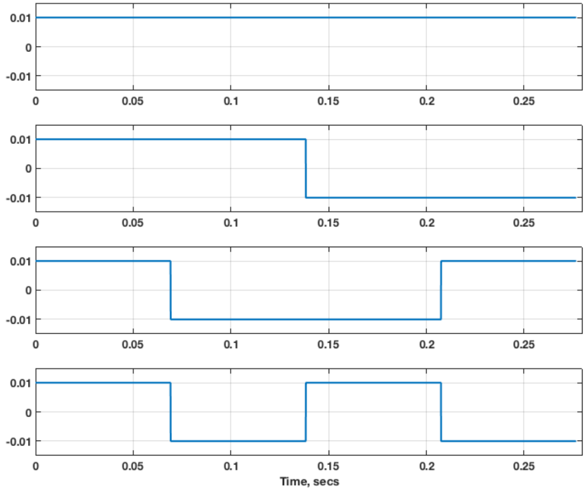


AEROM: ROM Development Process

Unsteady Aerodynamic State-Space ROM

Walsh Functions
(modal)





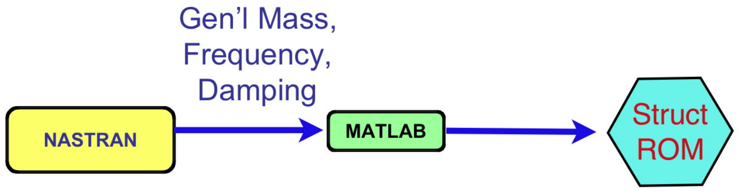
1

2

3

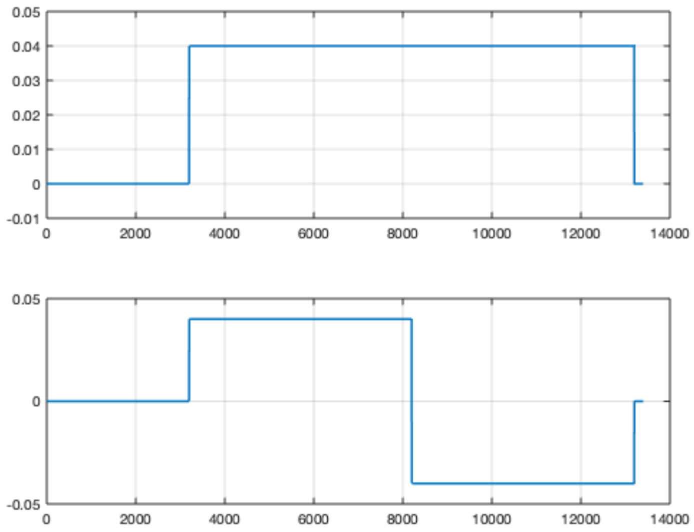
4

Structural state-space ROM



BSCW Application (KESTREL), Two modes

*.fmh file

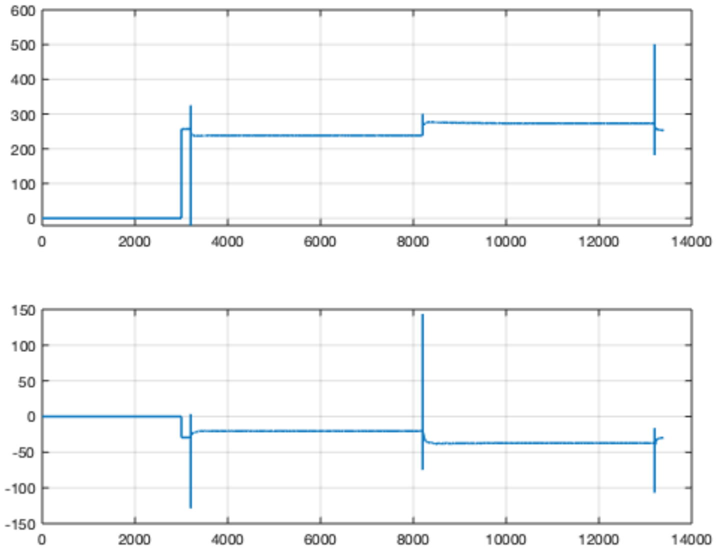


Two Walsh input functions

KESTREL

BSCW

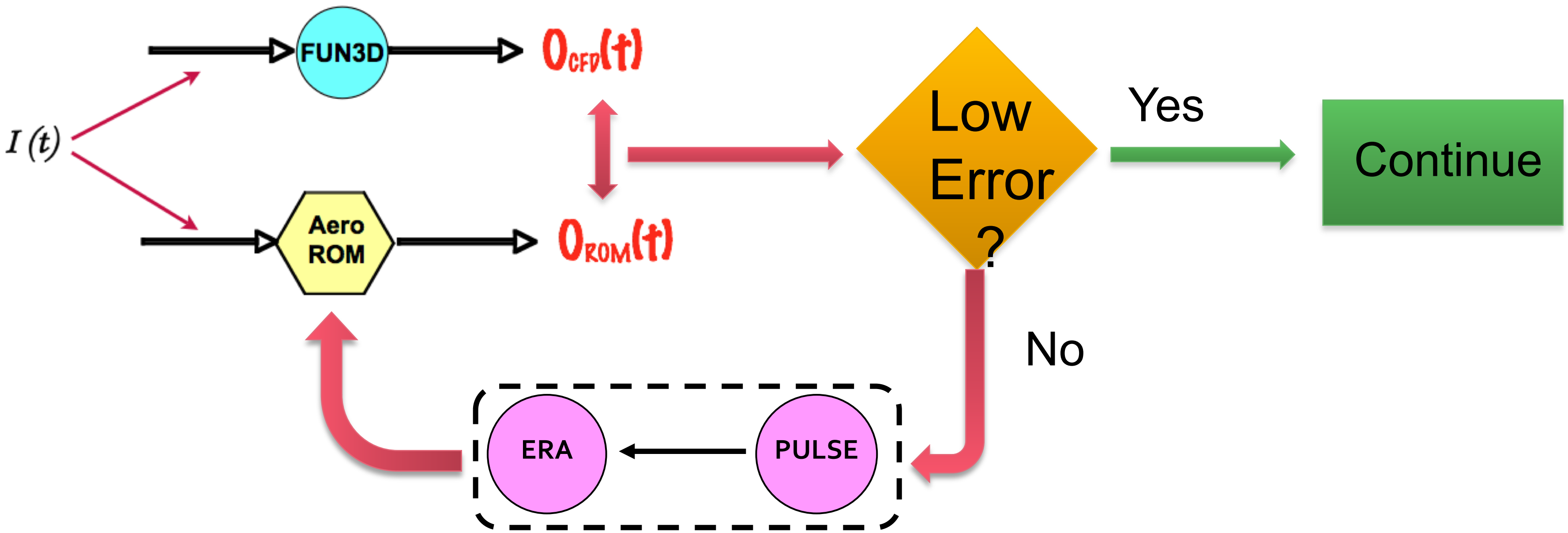
*.modes file



Two GAFs output functions

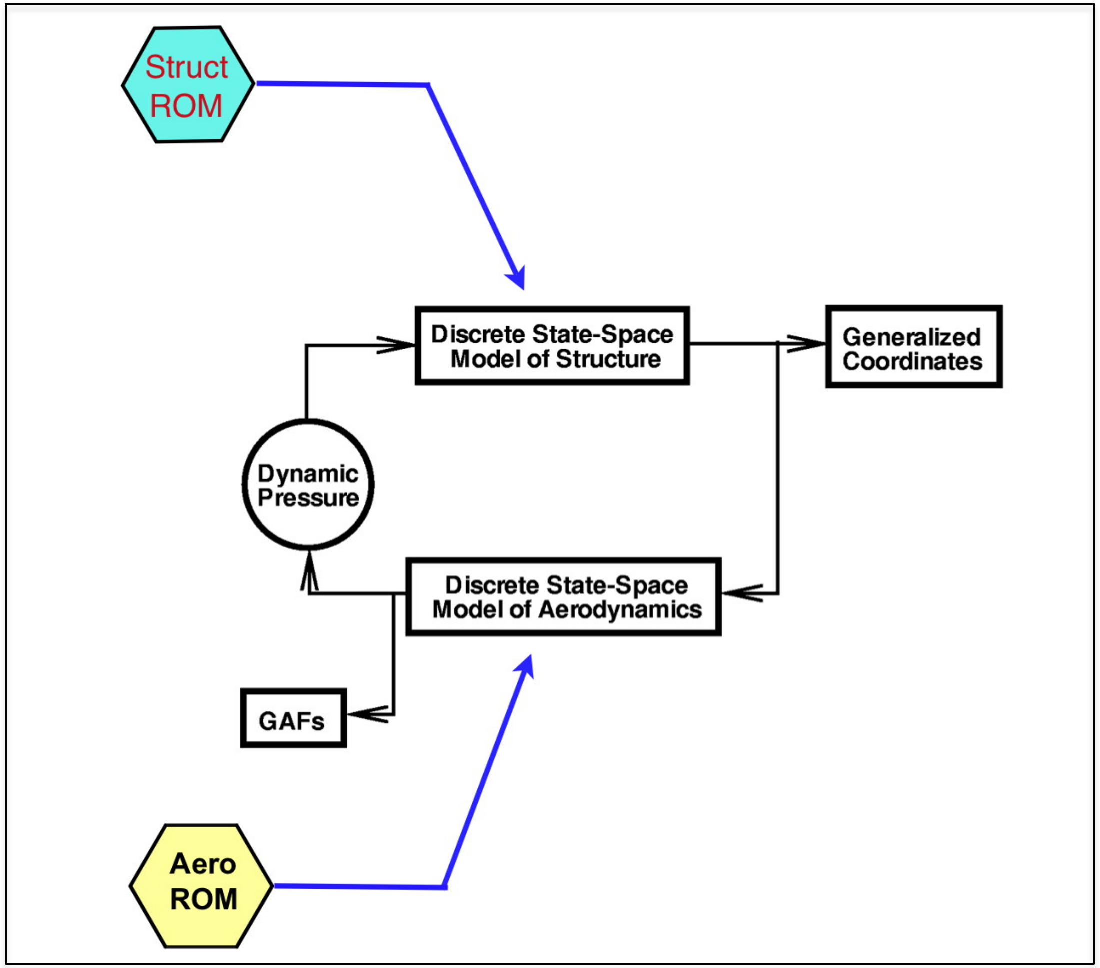
AEROM: ROM Development Process

Error Minimization (Unsteady Aerodynamics)



AEROM: ROM Development Process

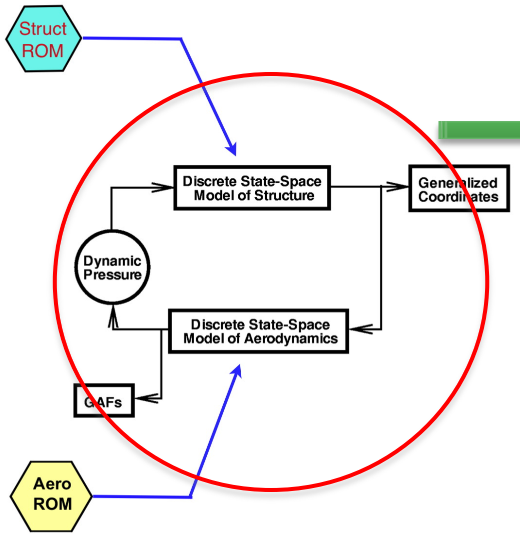
Aeroelastic Simulation ROM (Simulink)



Simulink model that includes Unsteady Aero ROM and Structural Dynamic ROM used to compare ROM responses at any Dynamic pressure with full KESTREL Solutions.

AEROM: 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

Walsh Function Amplitudes and Alphas

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

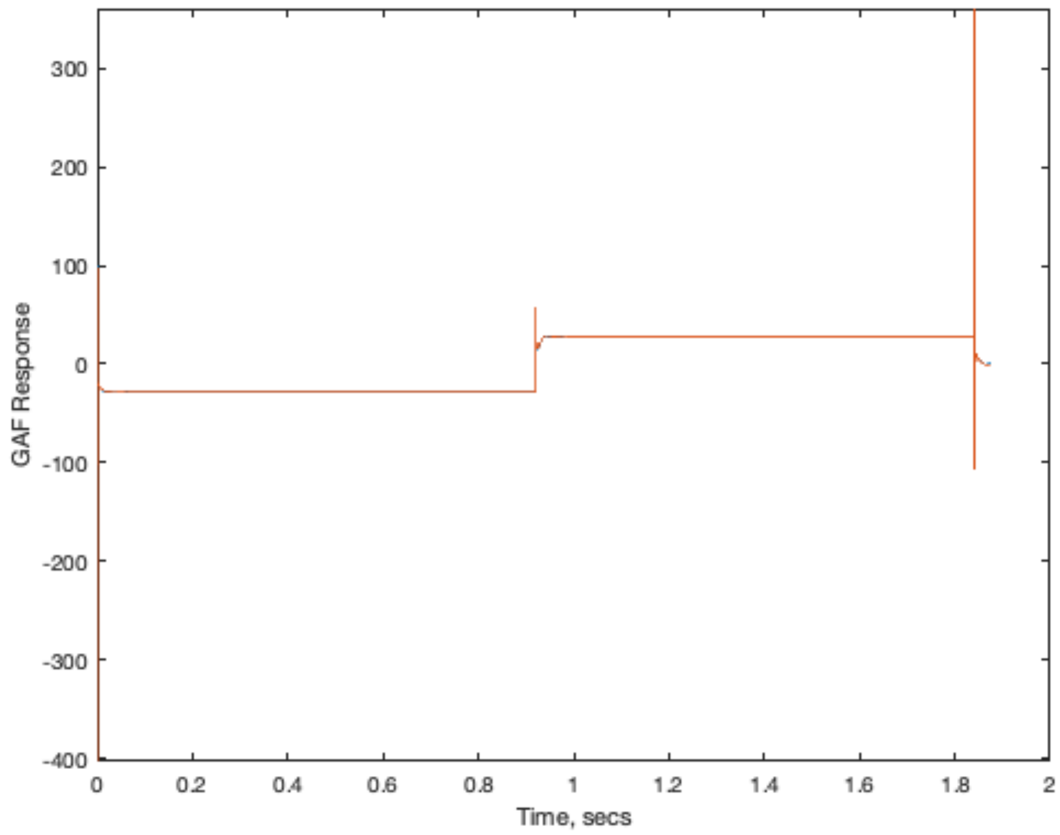
KESTREL Solutions: Alpha = 0 deg, Q = 100 psf, Initial Modal Velocity = 5
Alpha = 3 deg, Q = 100 psf, Initial Modal Velocity = 5
Alpha = 5 deg, Q = 50 psf, 130 psf, Initial Modal Velocity = 5

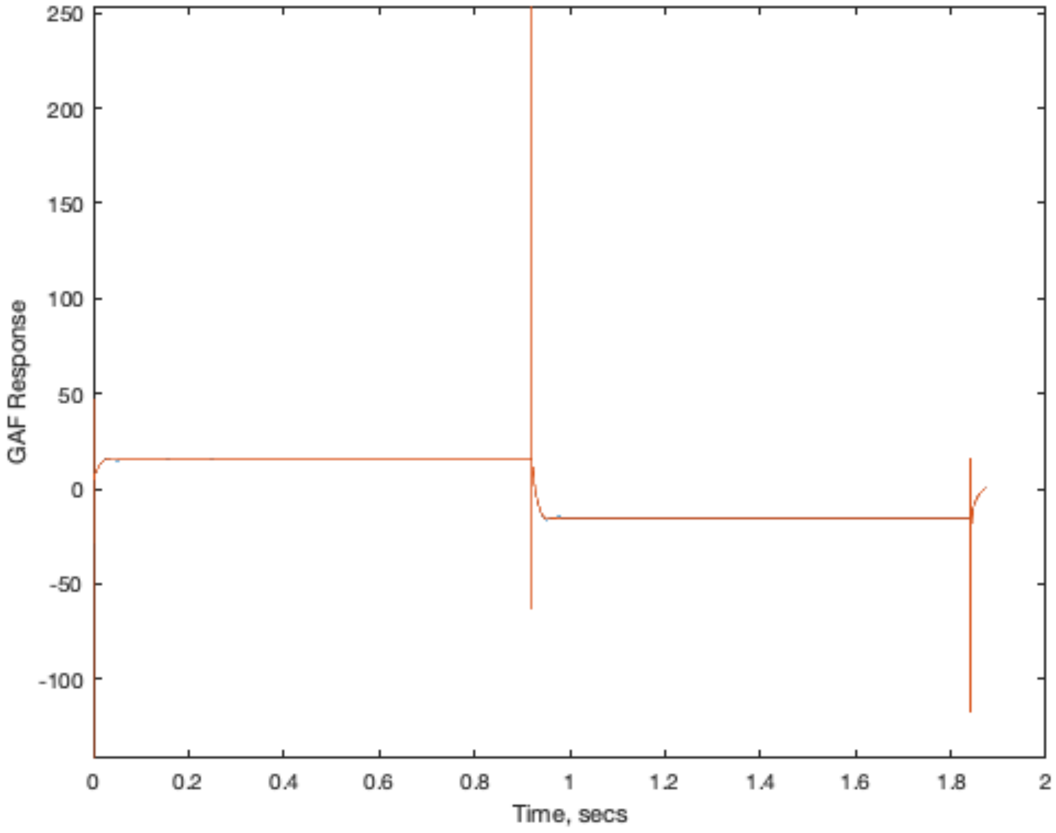
CPU Cost (NAS)
ROM solution: 10K steps, 240 cores, 9hrs 45min (set up for high alpha case; shorter duration for benign cases)
Full Solution <u>per Q</u>: 15K steps, 240 cores, 53 hrs 04min (~5.5 cycles)

Alpha = 0 deg

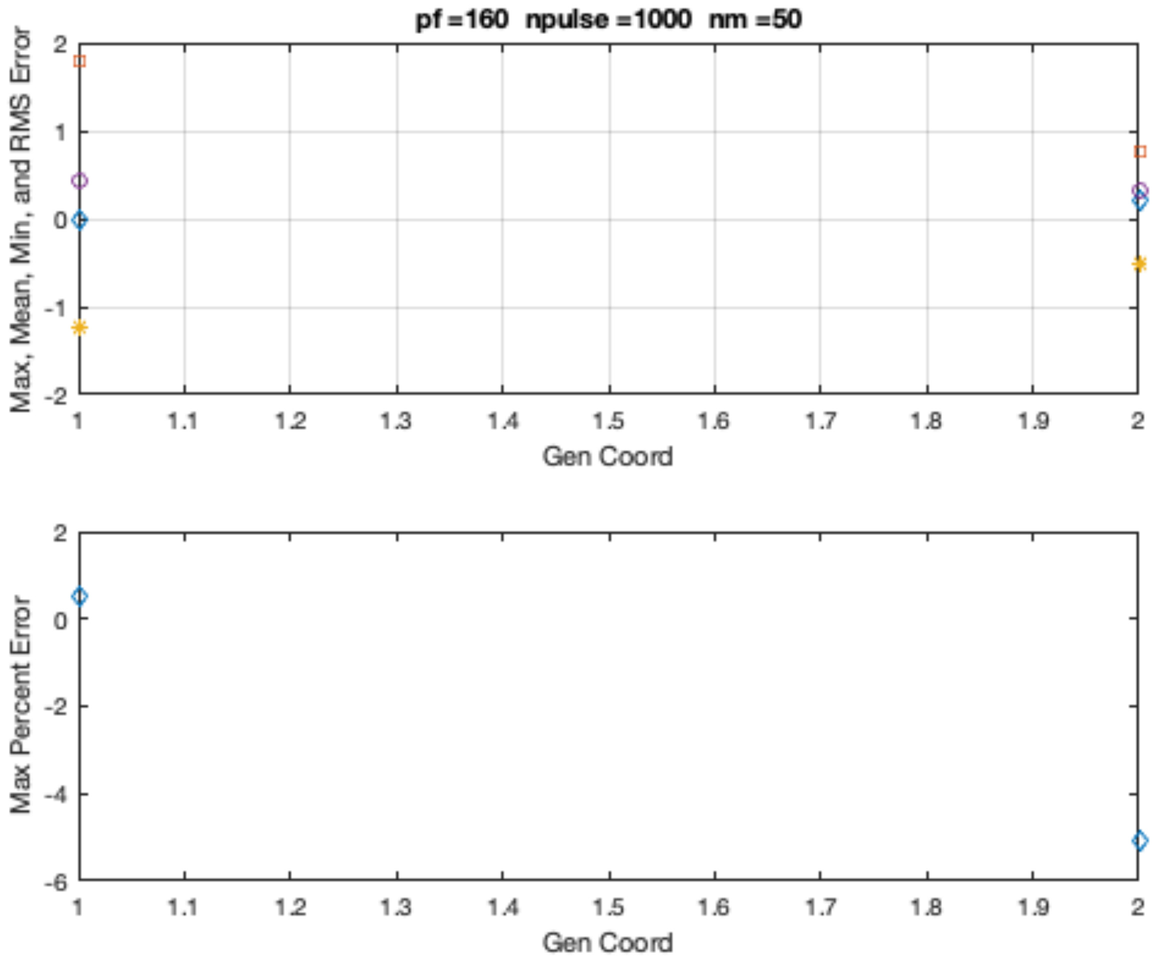
M8A0a – ROM/KESTREL GAFs

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

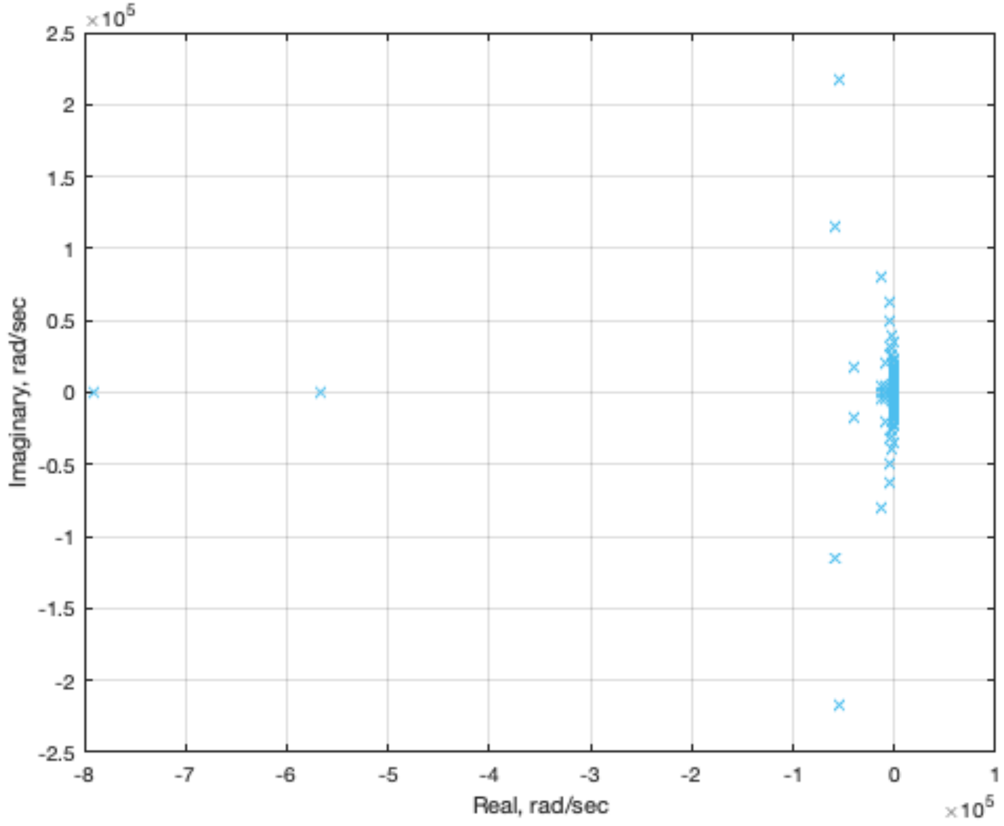




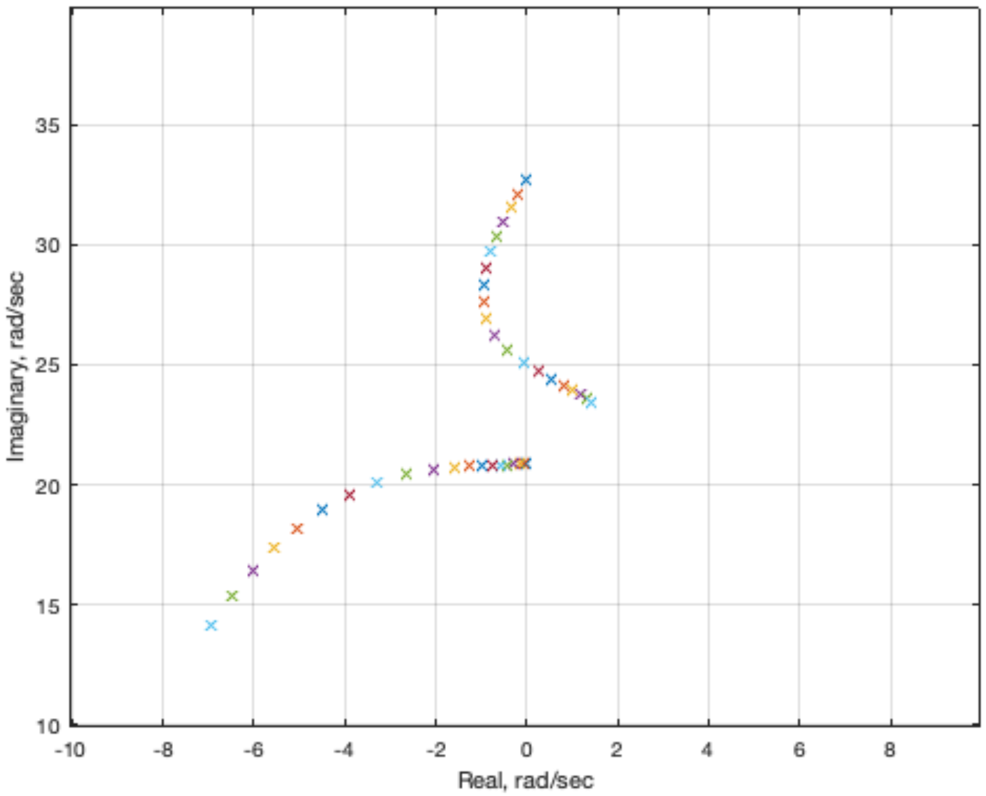
M8A0a – ROM/KESTREL GAFs Error



M8A0a – ROM/KESTREL Root Locus

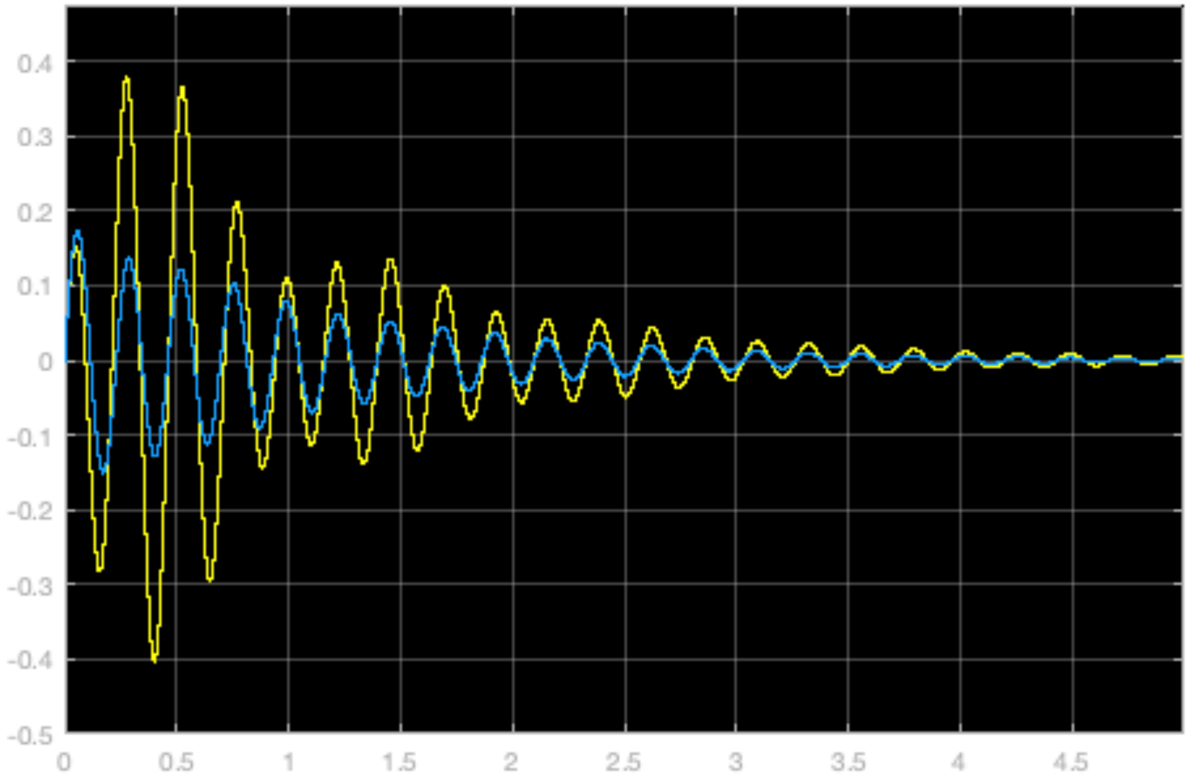


Zoom

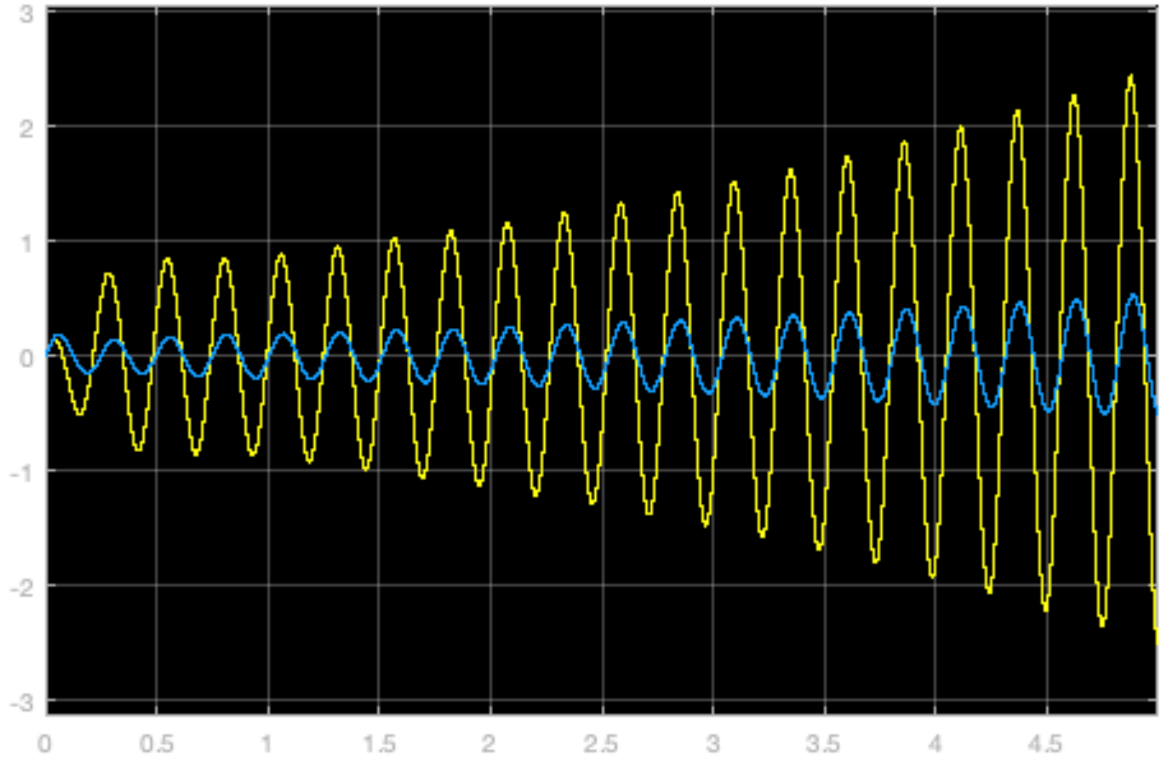


M8A0a – ROM Responses (SIMULINK)

Q = 0.9 psi

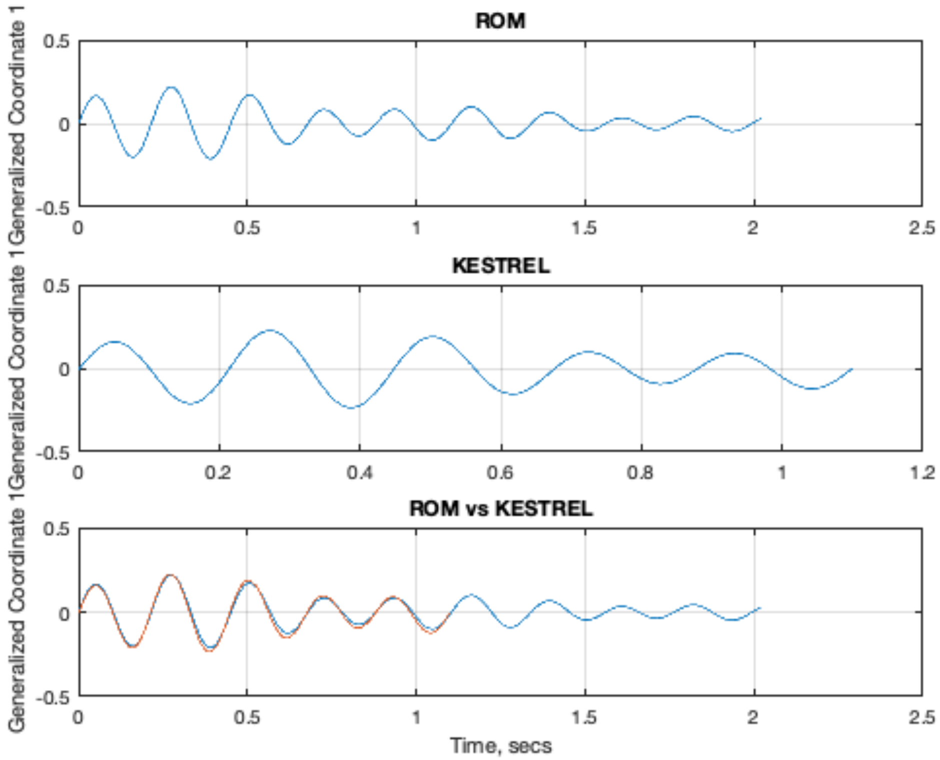


Q = 1.3 psi

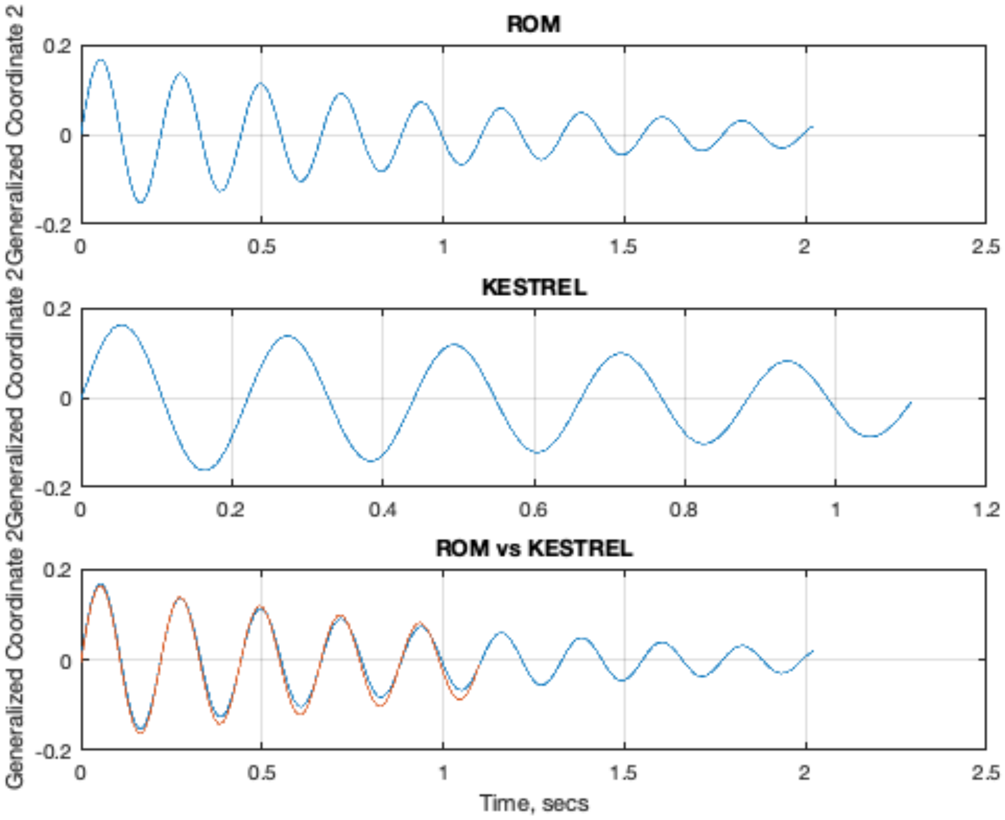


M8A0a – ROM/KESTREL Responses, Q=100 psf

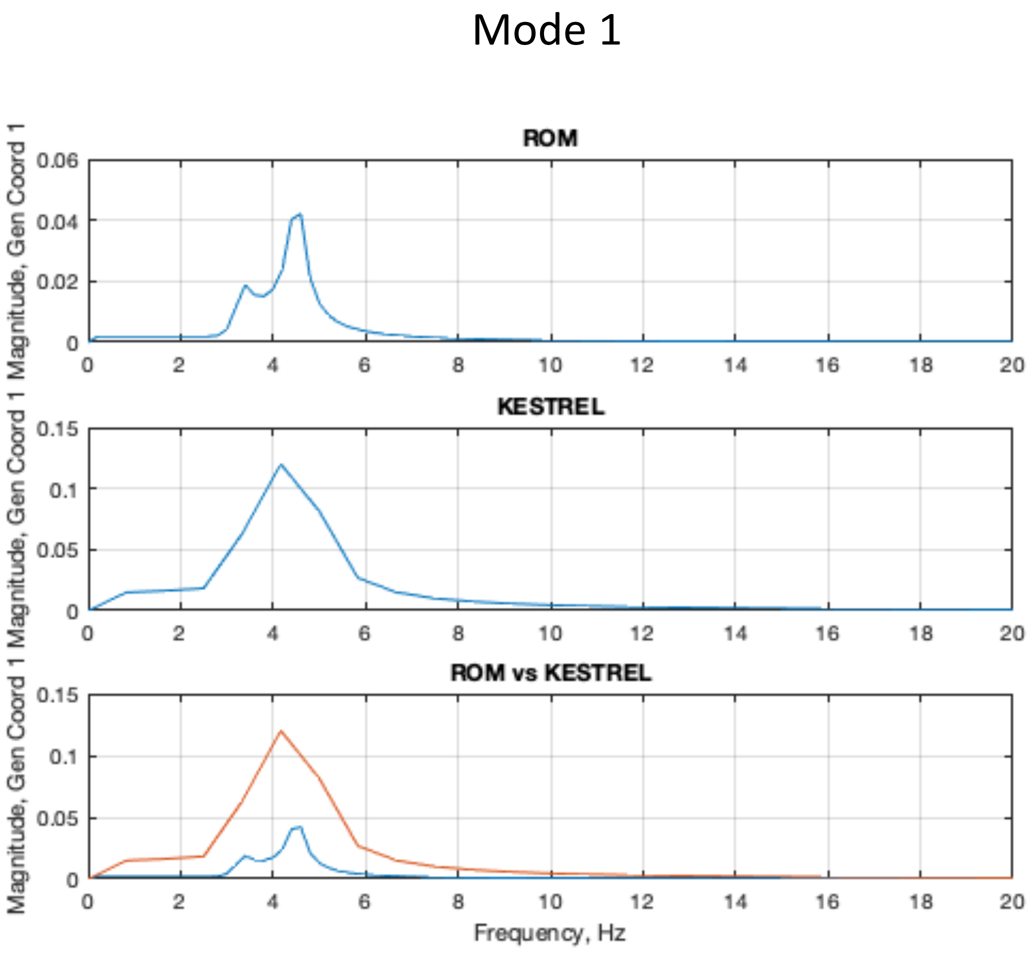
Mode 1

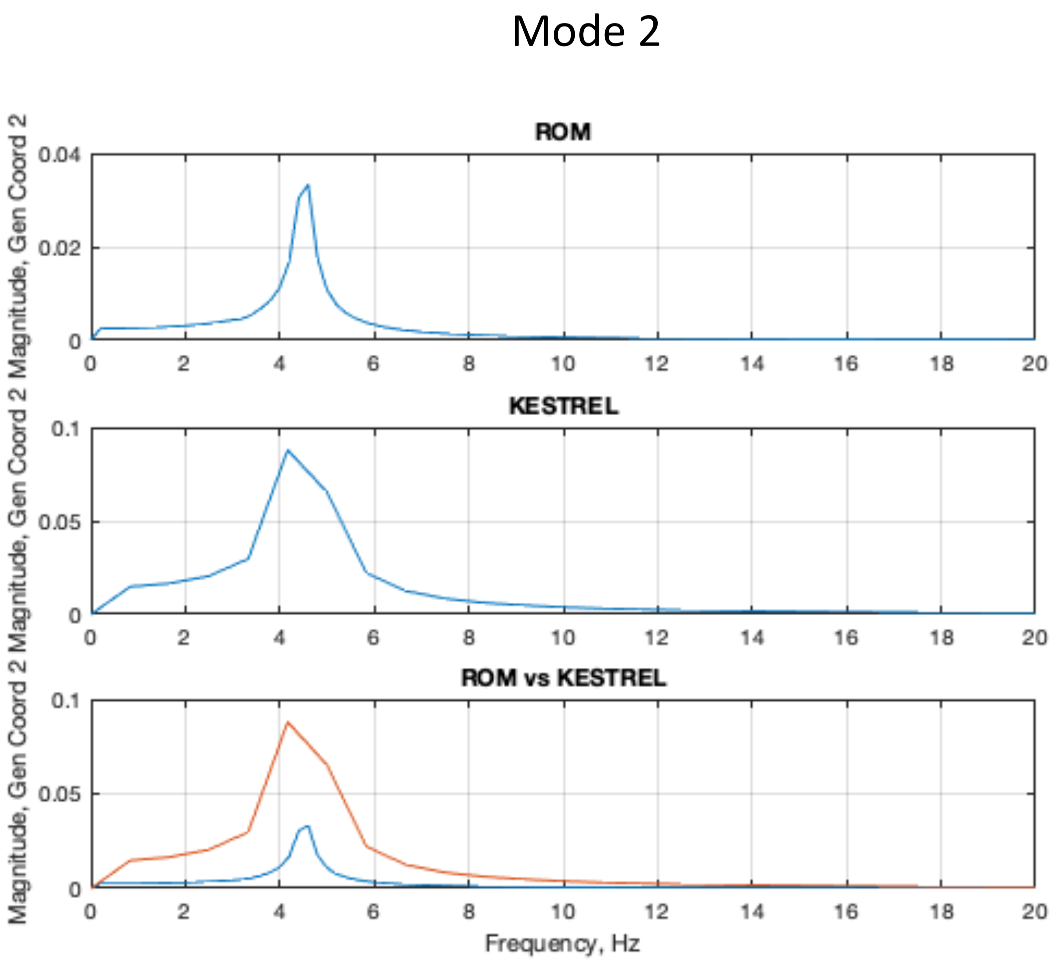


Mode 2



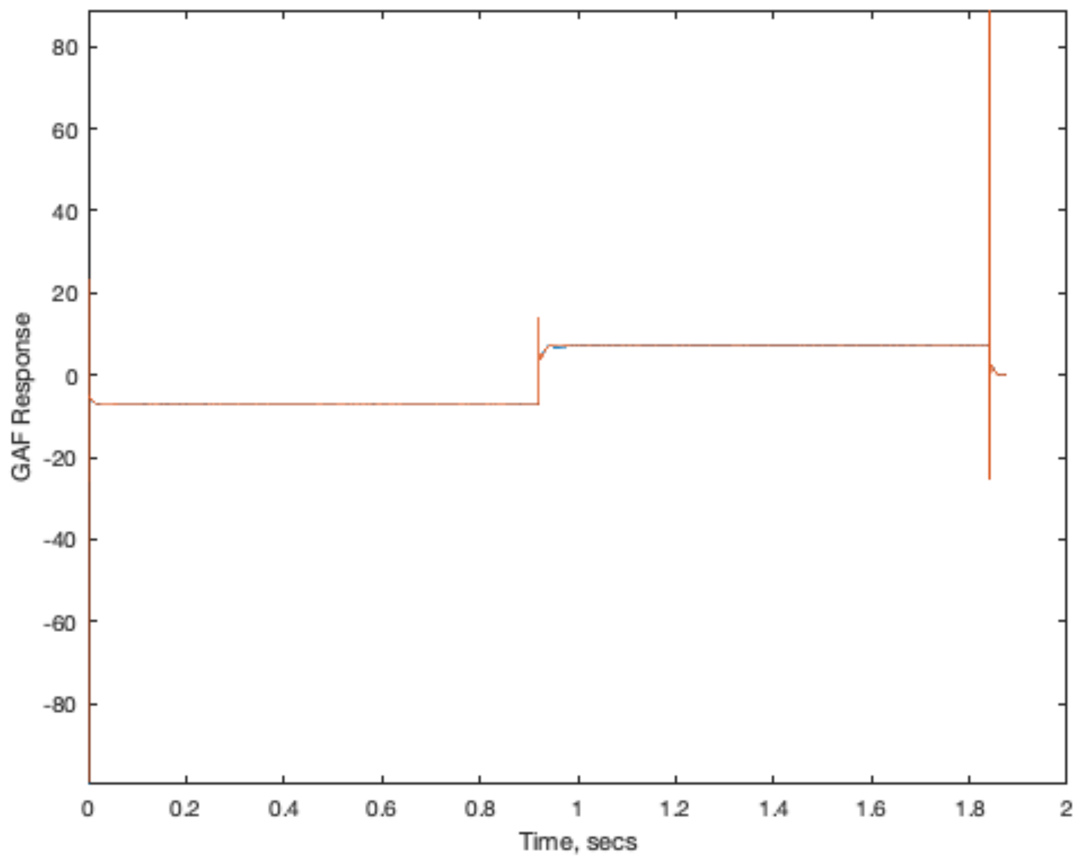
M8A0a – ROM/KESTREL Responses, Q=100 psf

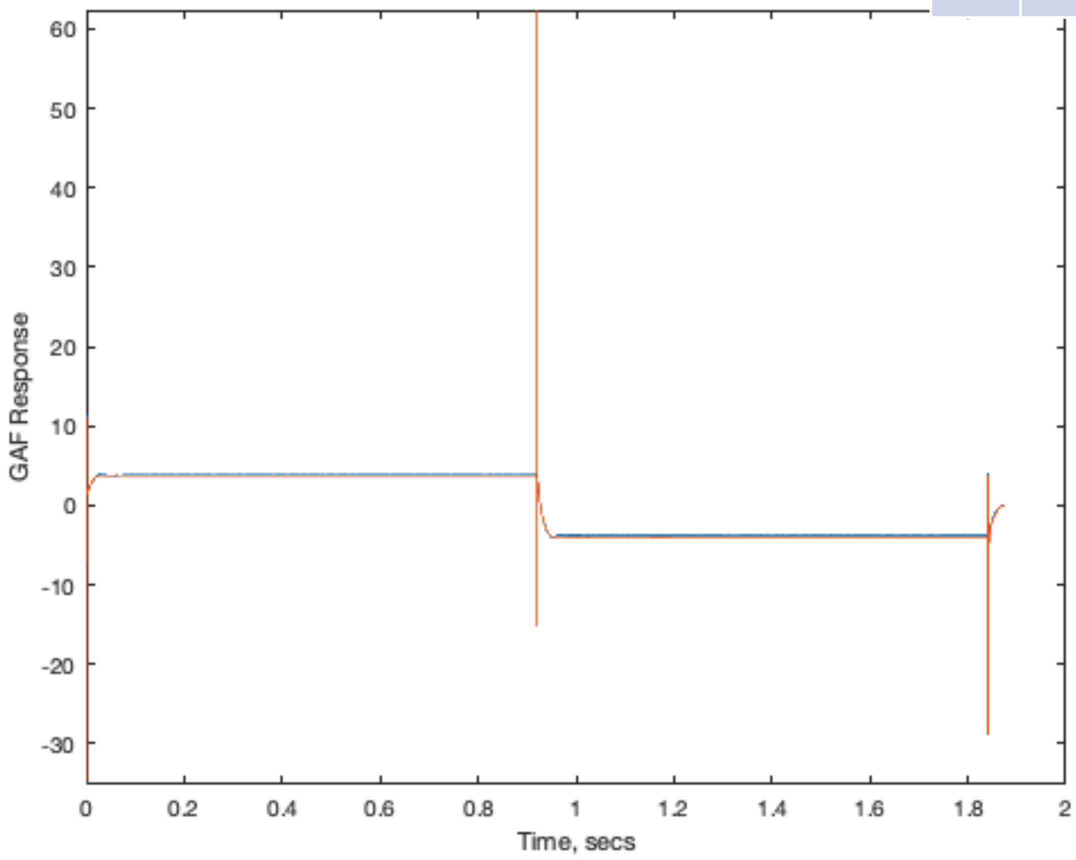




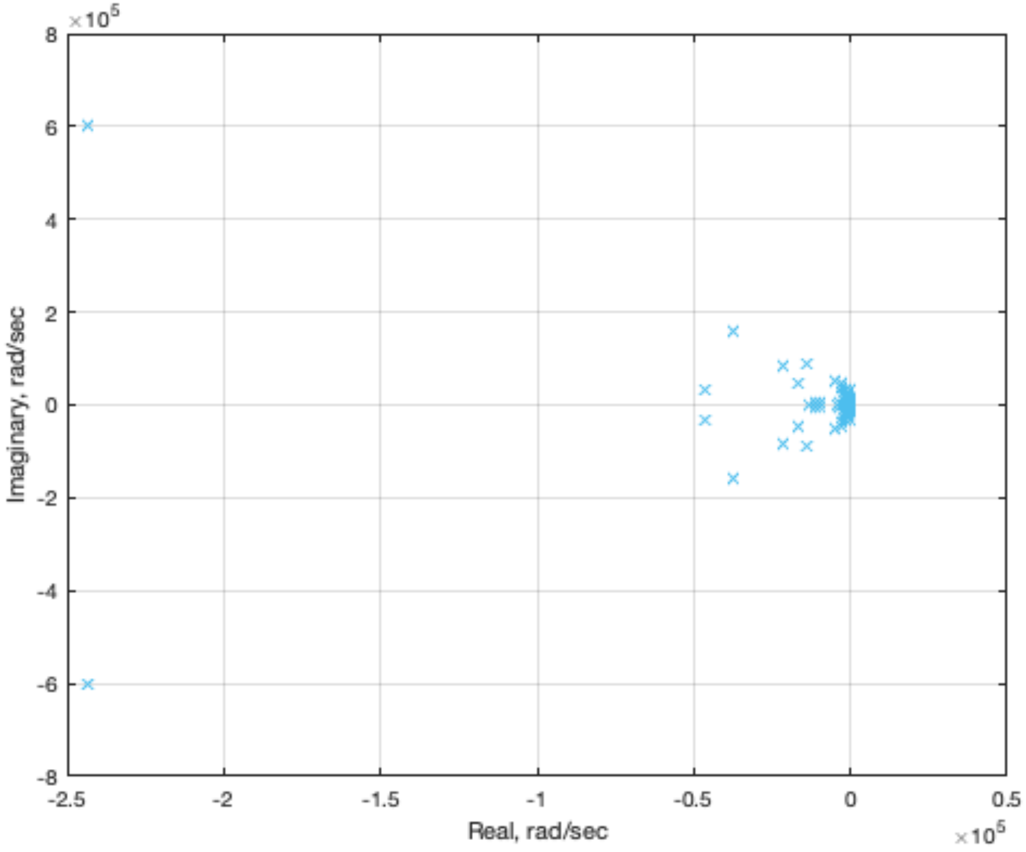
M8A0b – ROM/KESTREL GAFs

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

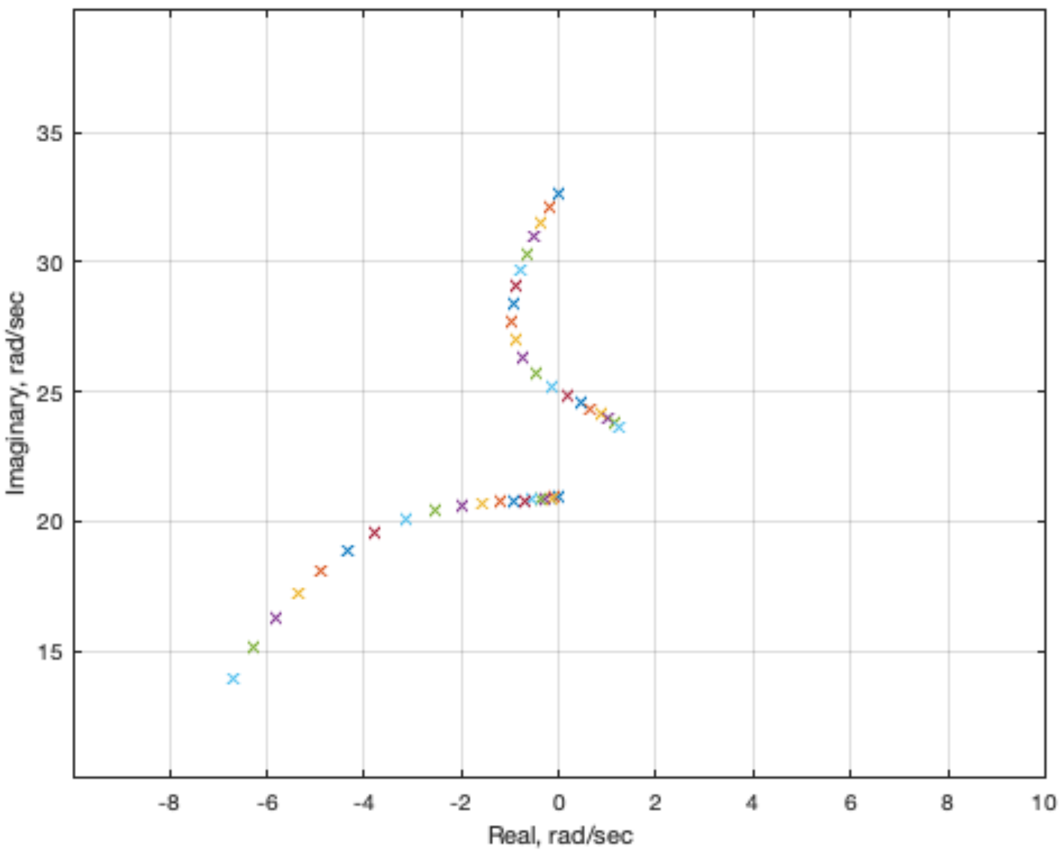




M8A0b – ROM/KESTREL Root Locus

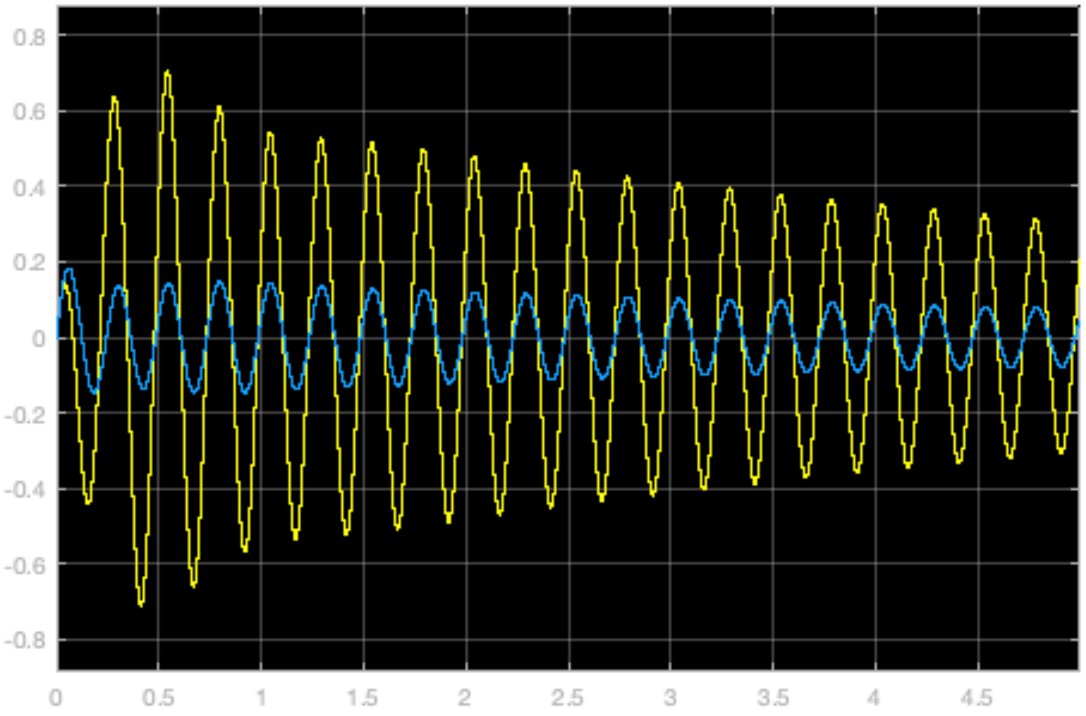


Zoom

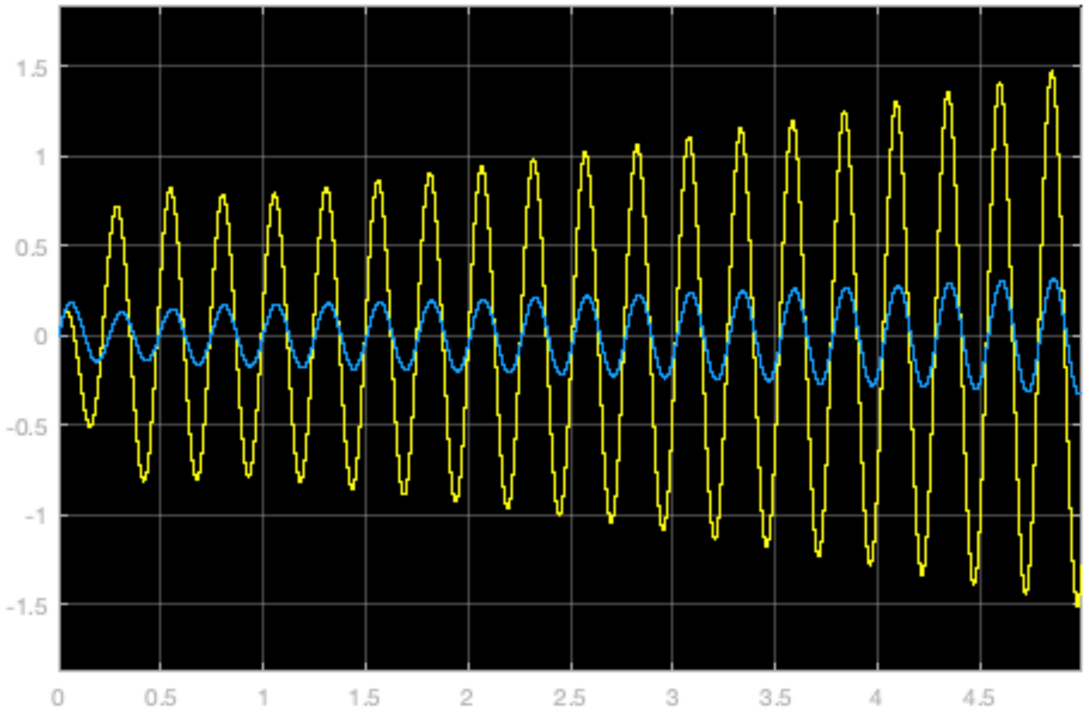


M8A0b – ROM Responses (SIMULINK)

Q = 1.2 psi

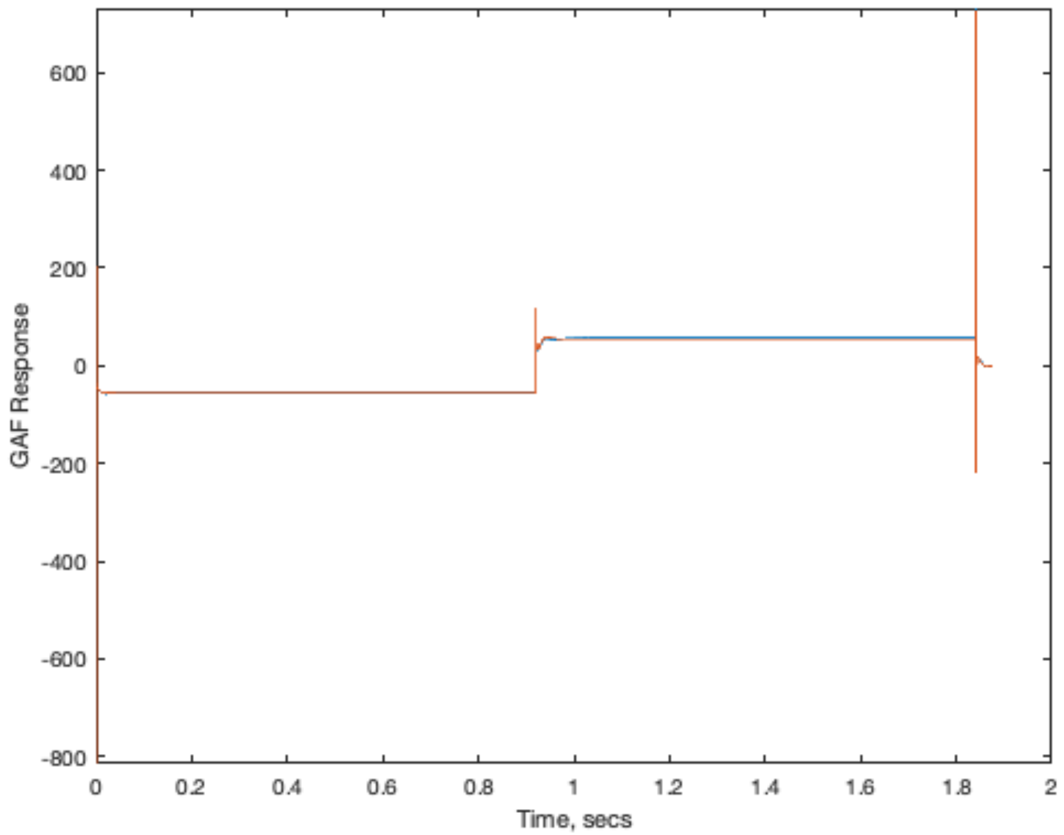


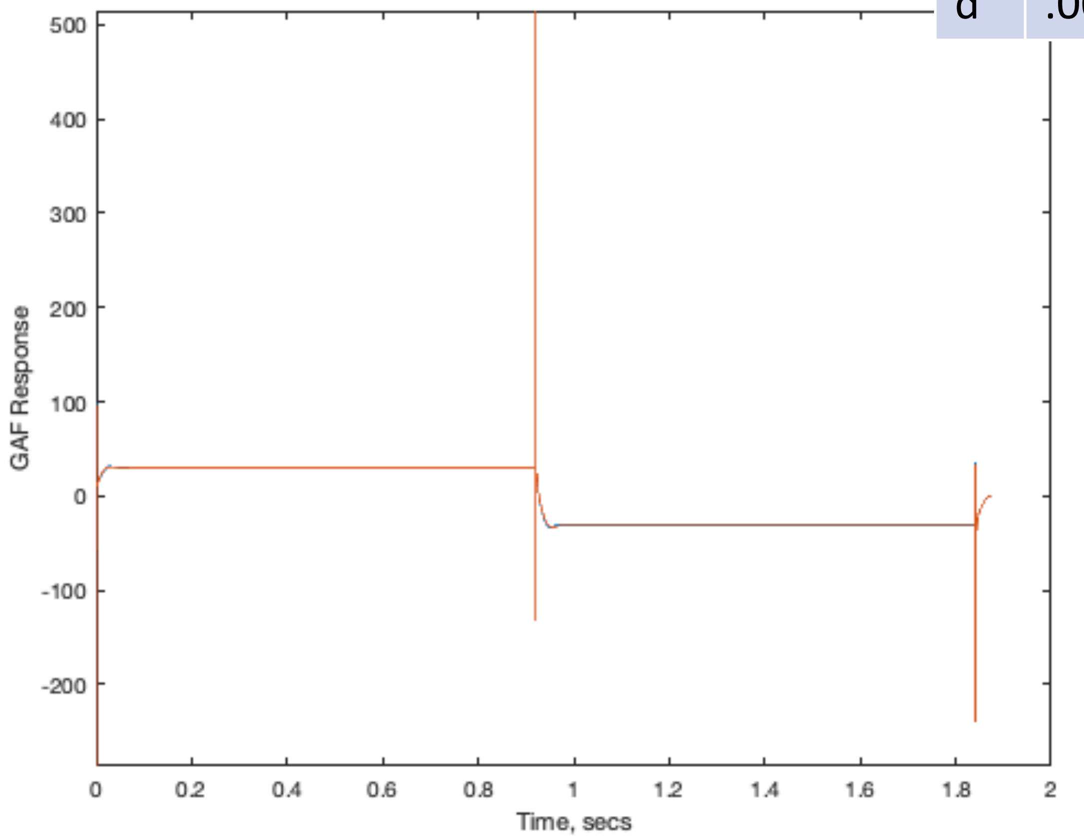
Q = 1.3 psi



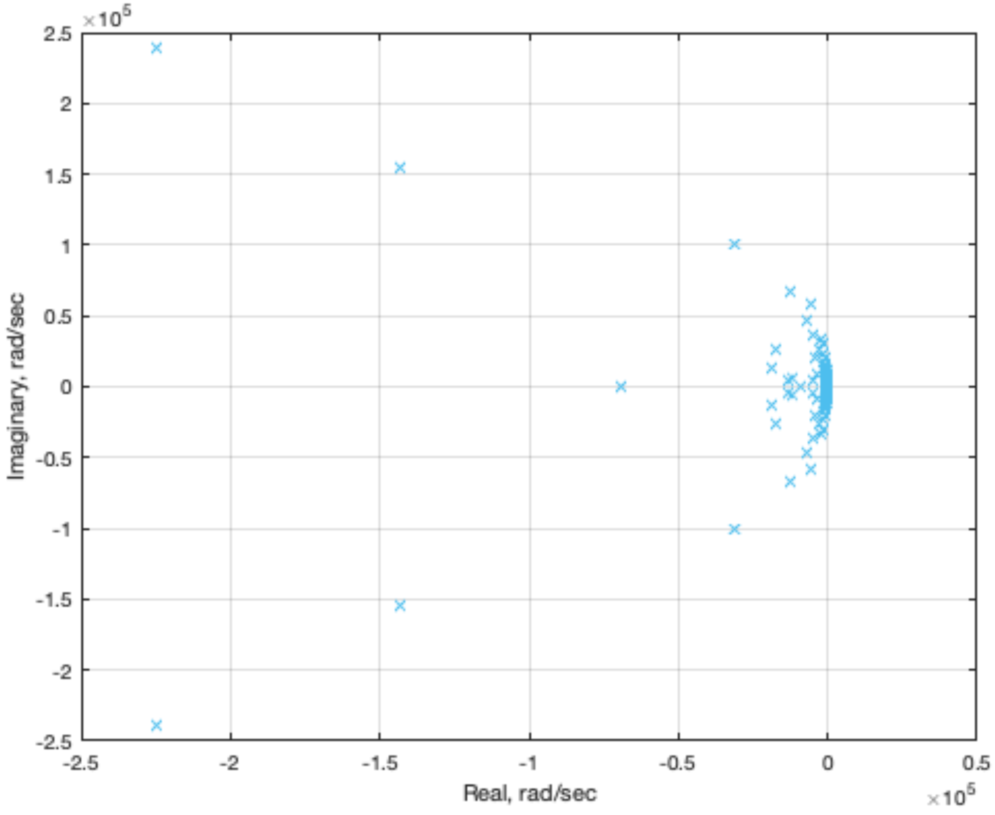
M8A0c – ROM/KESTREL GAFs

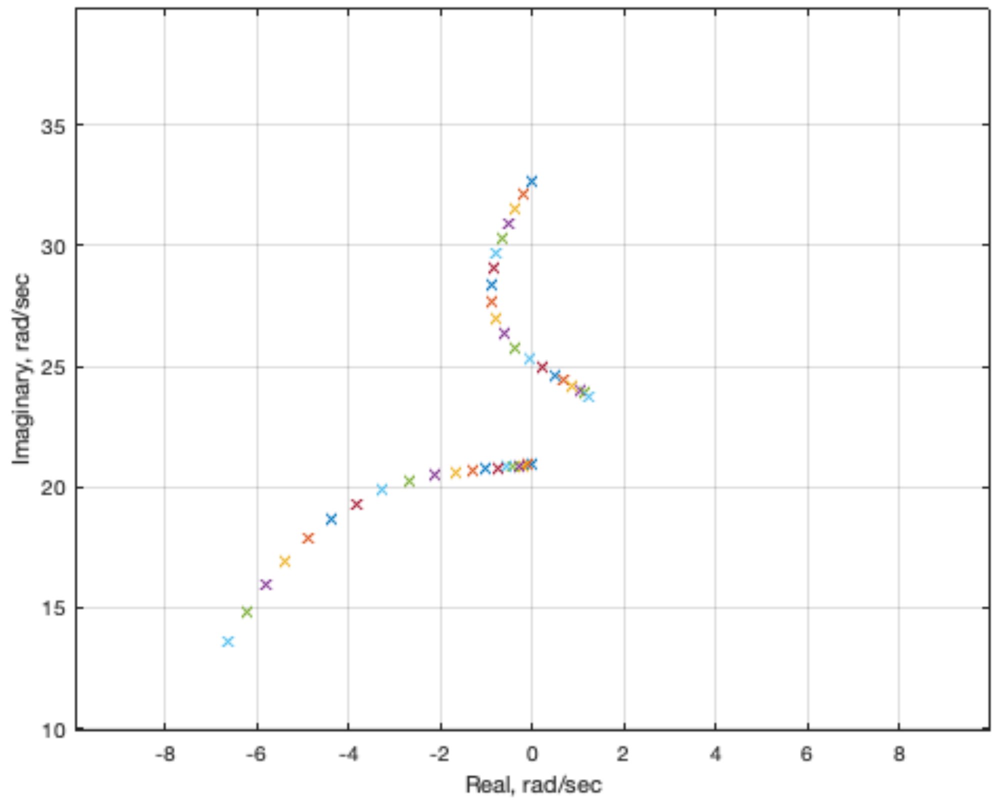
a	.04
b	.01
c	.08
d	.001





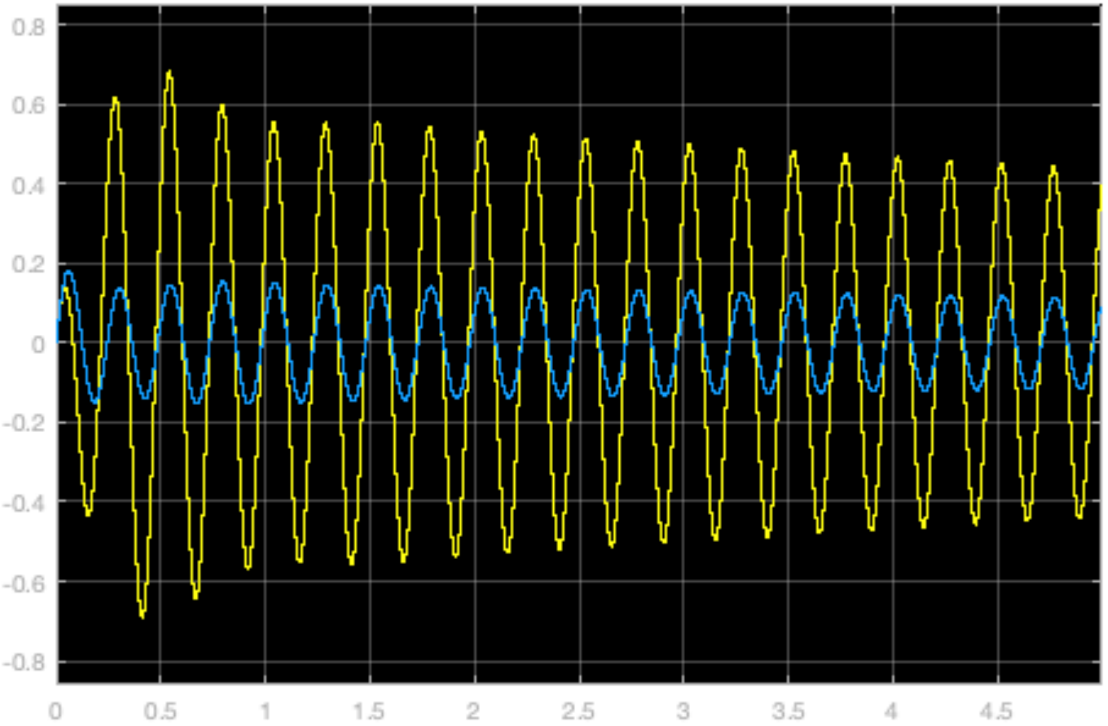
M8A0c – ROM/KESTREL GAFs Root Locus



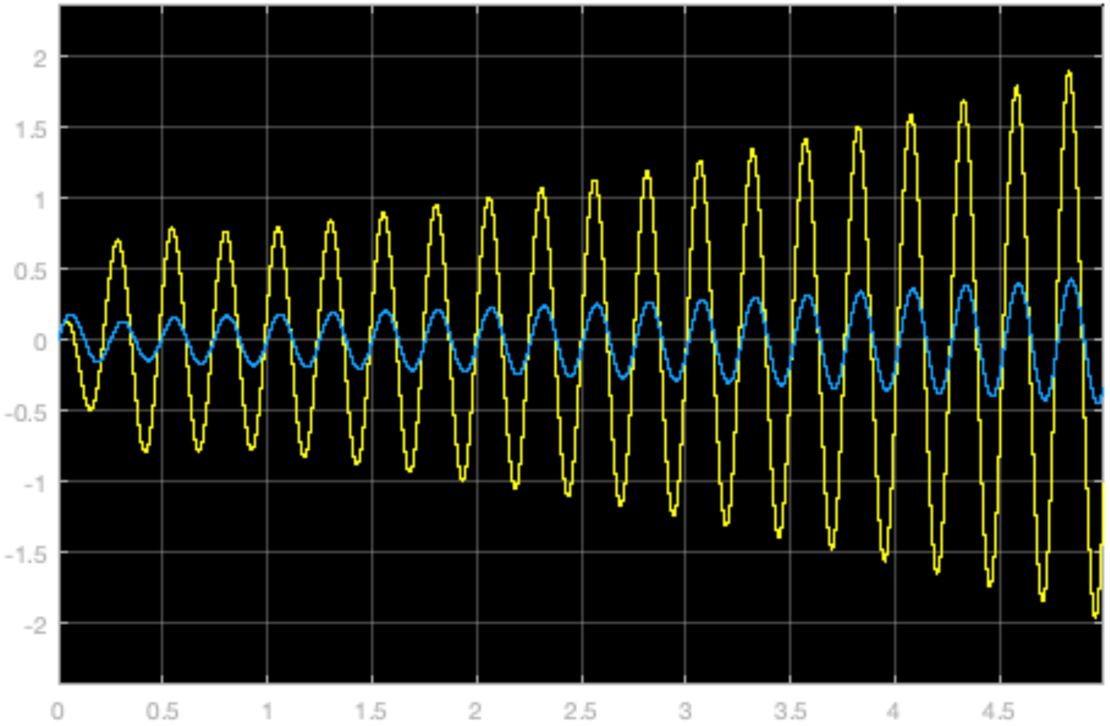


M8A0c – ROM Responses (SIMULINK)

Q = 1.2 psi

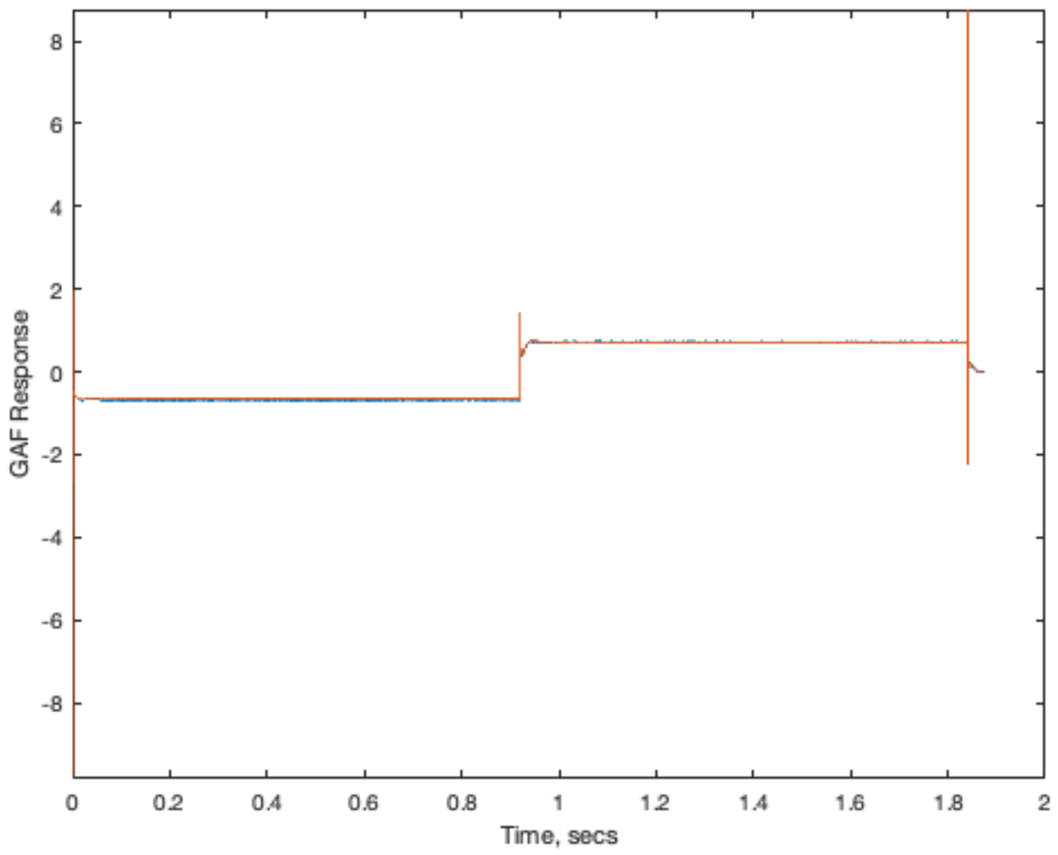


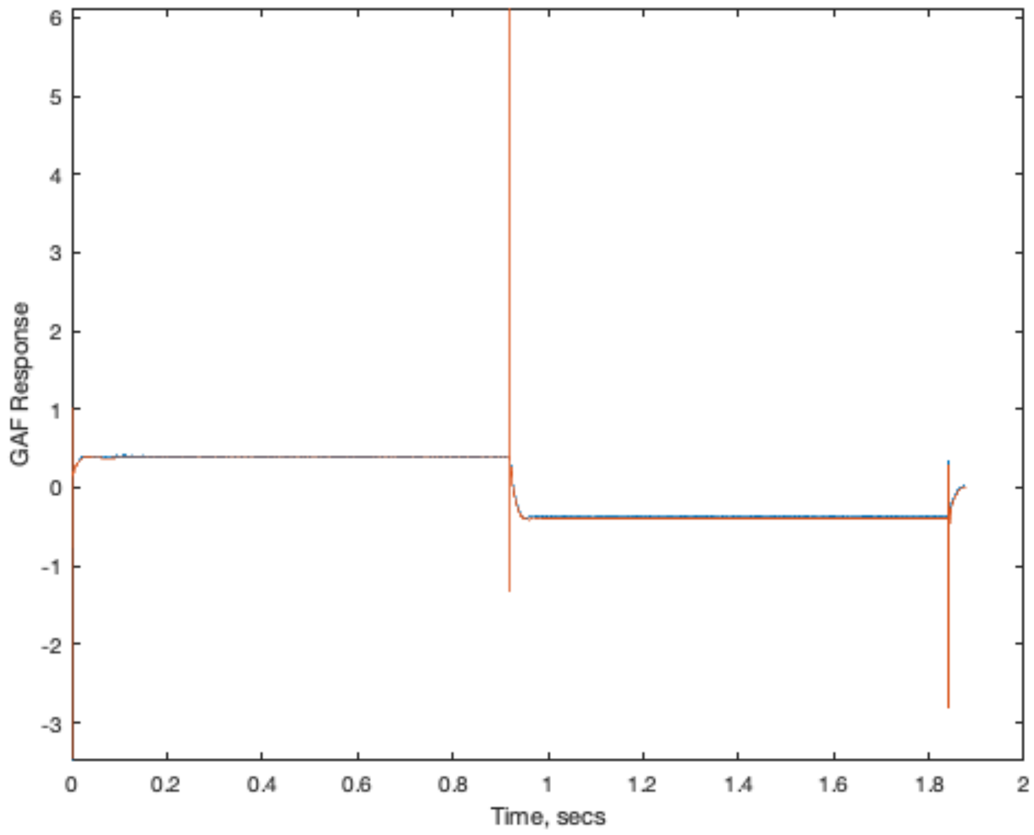
Q = 1.3 psi



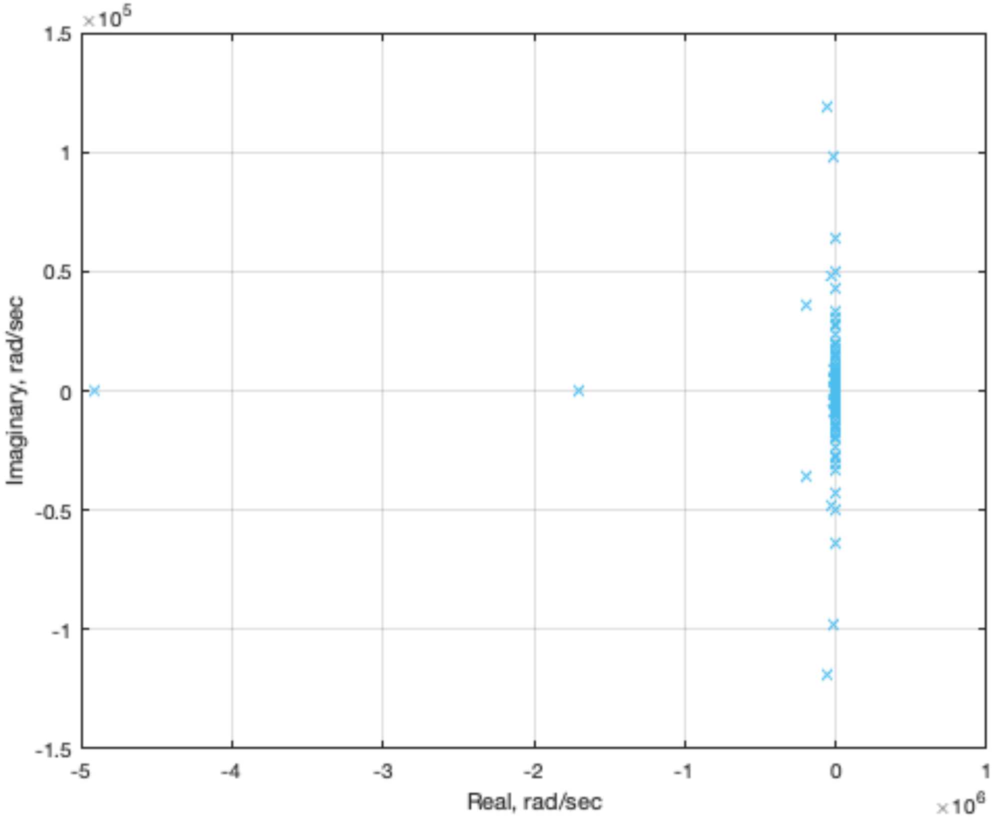
M8A0d – ROM/KESTREL GAFs

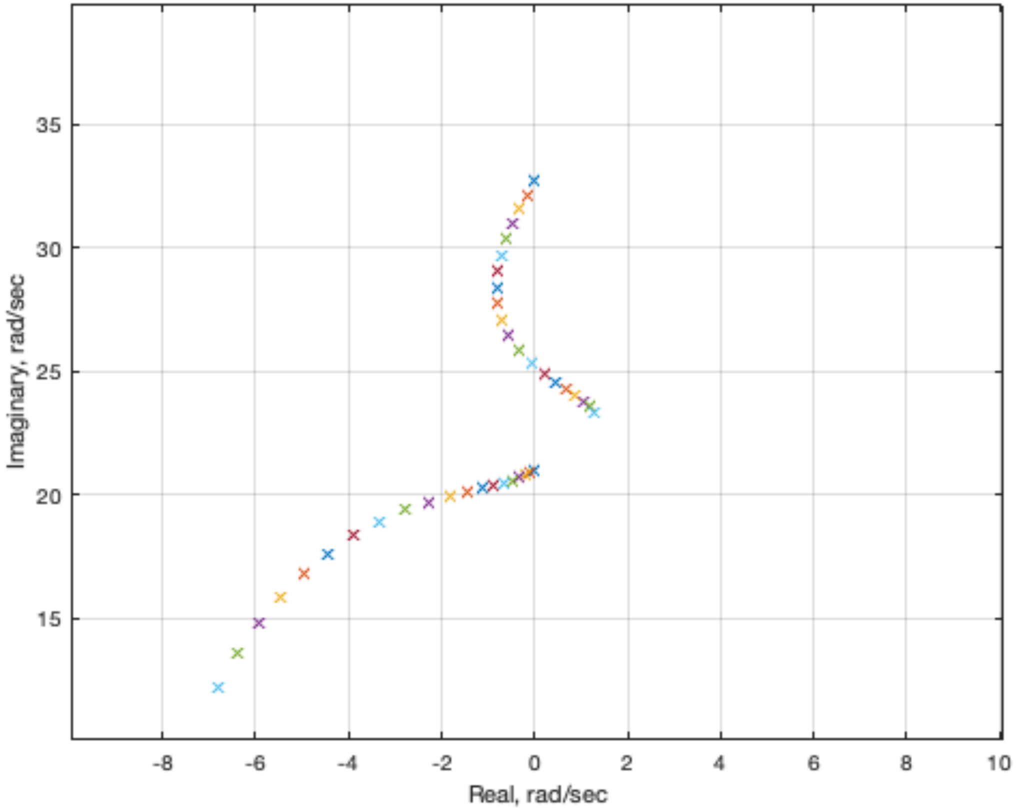
a	.04
b	.01
c	.08
d	.001





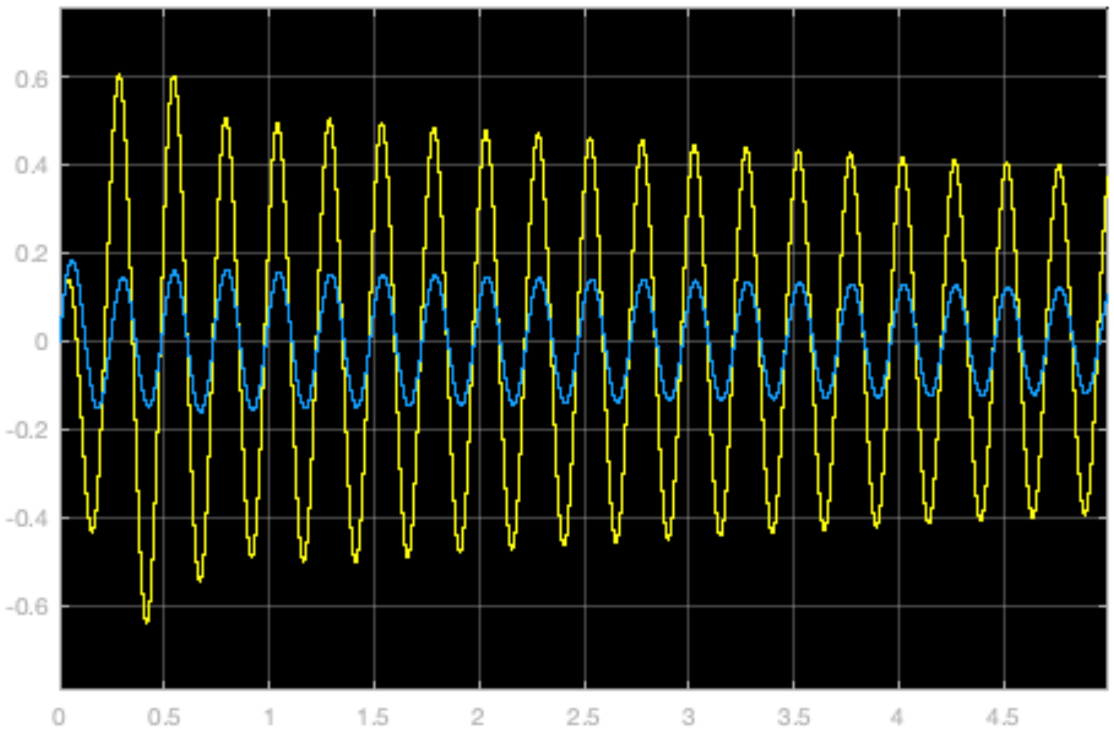
M8A0d – ROM/KESTREL Root Locus



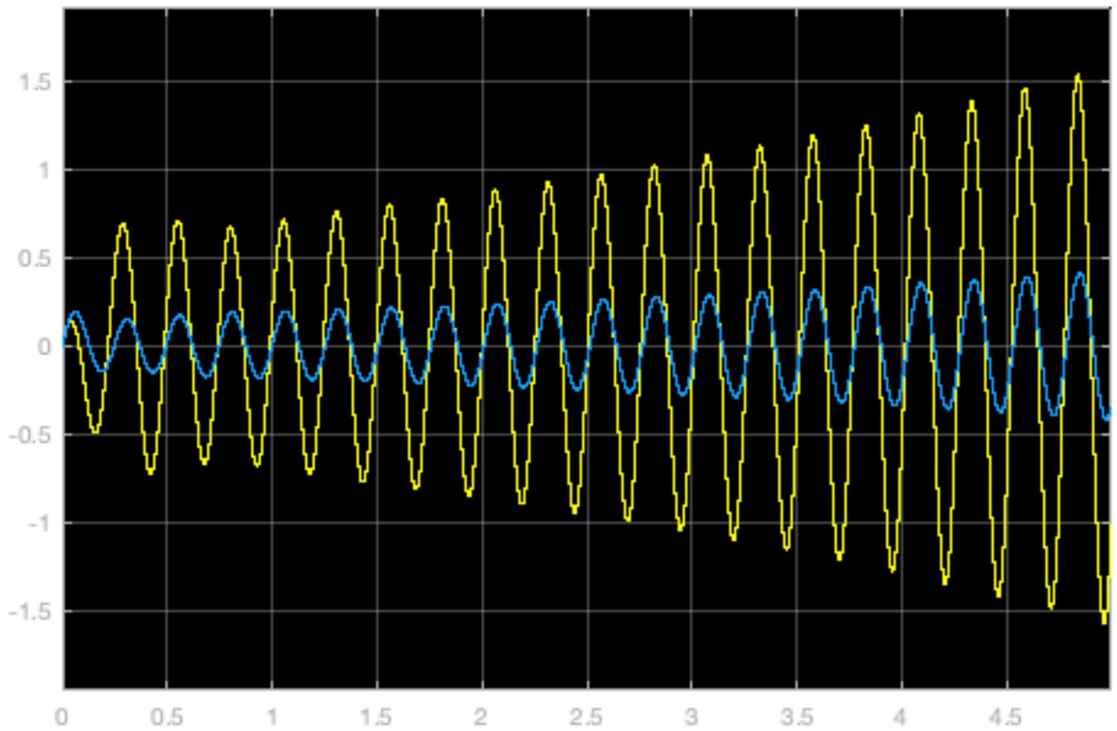


M8A0d – ROM Responses (SIMULINK)

Q = 1.2 psi

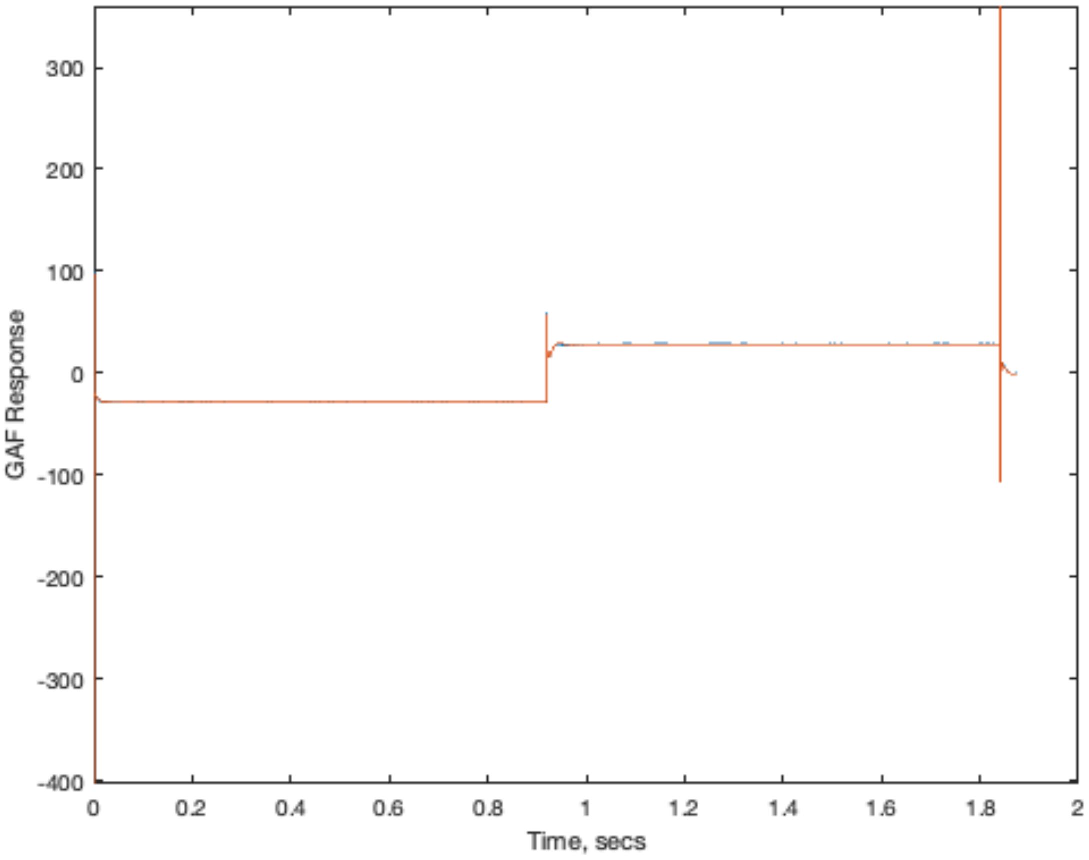


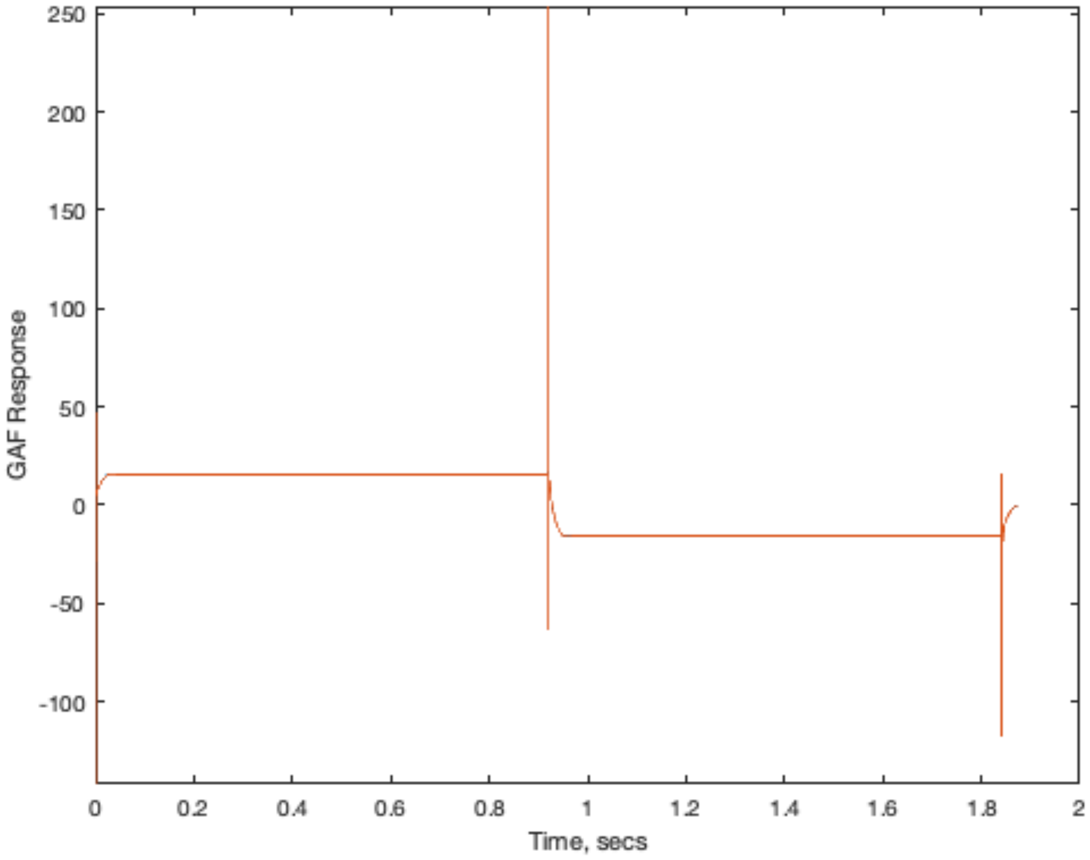
Q = 1.3 psi



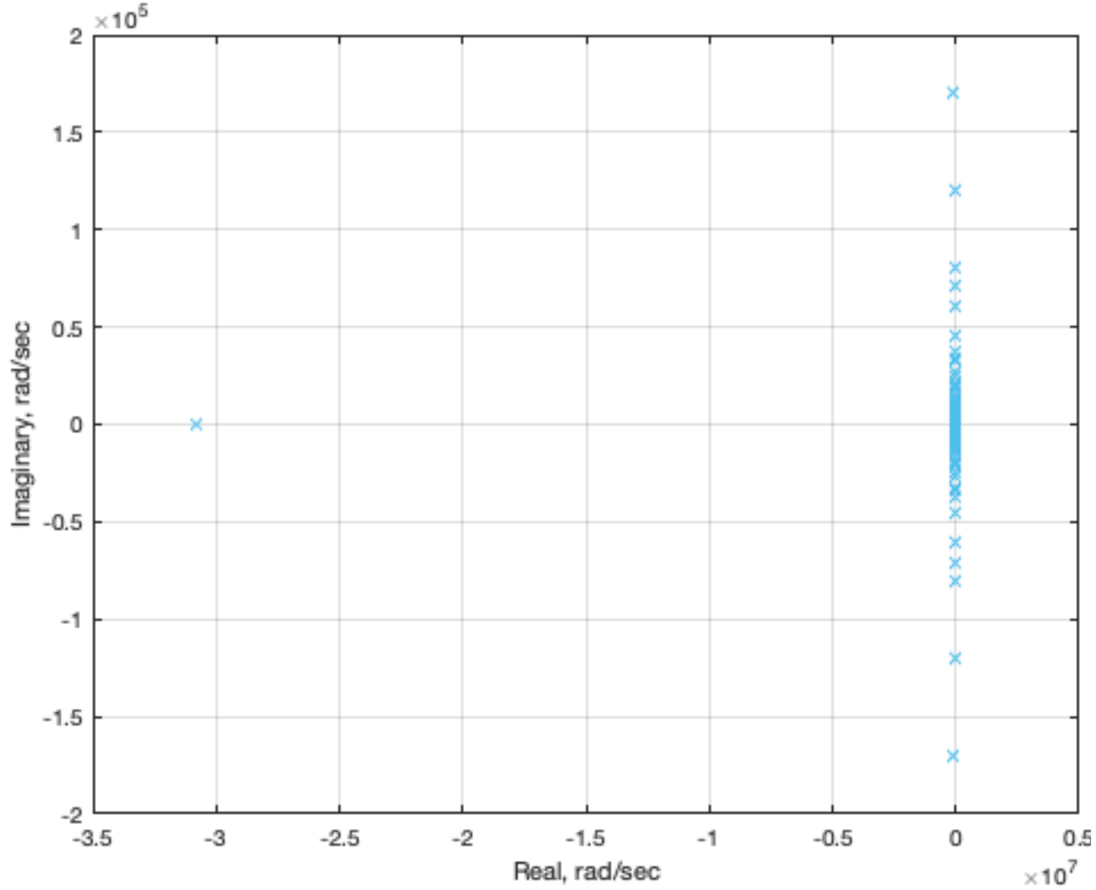
Alpha = 1 deg

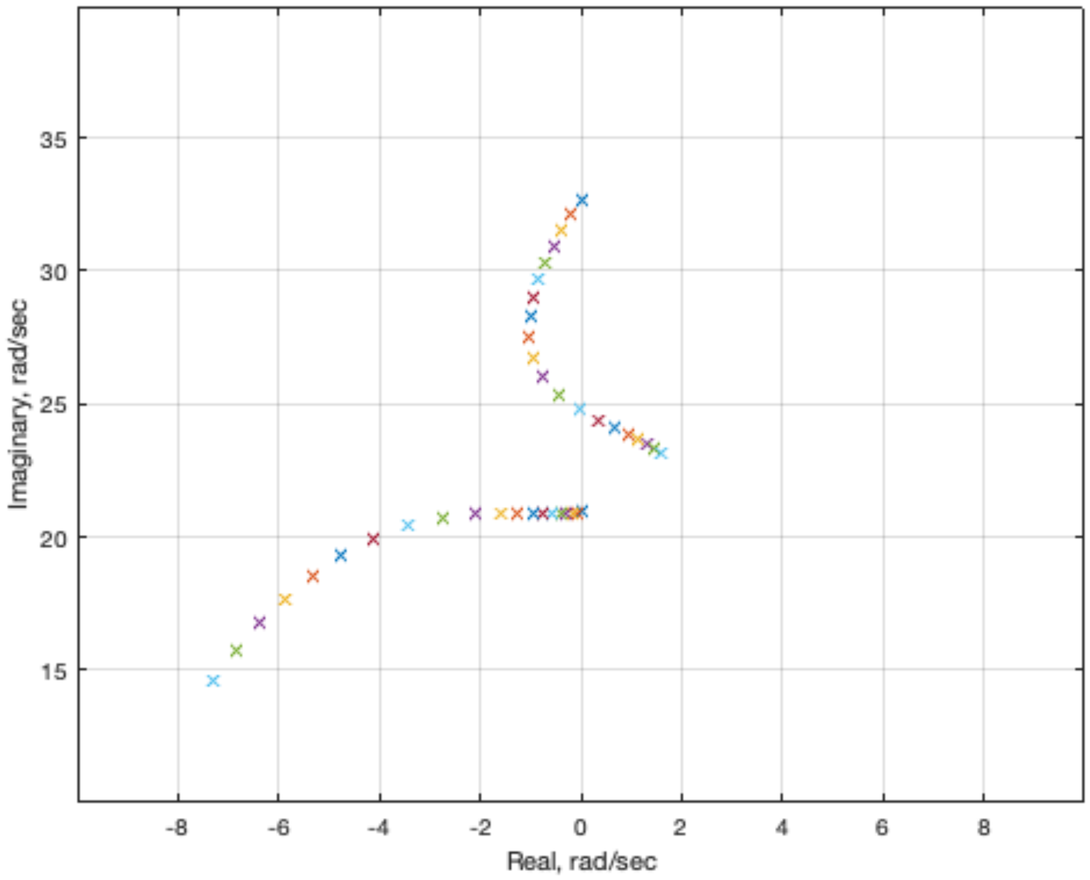
M8A1a – ROM/KESTREL GAFs





M8A1a – ROM/KESTREL Root Locus

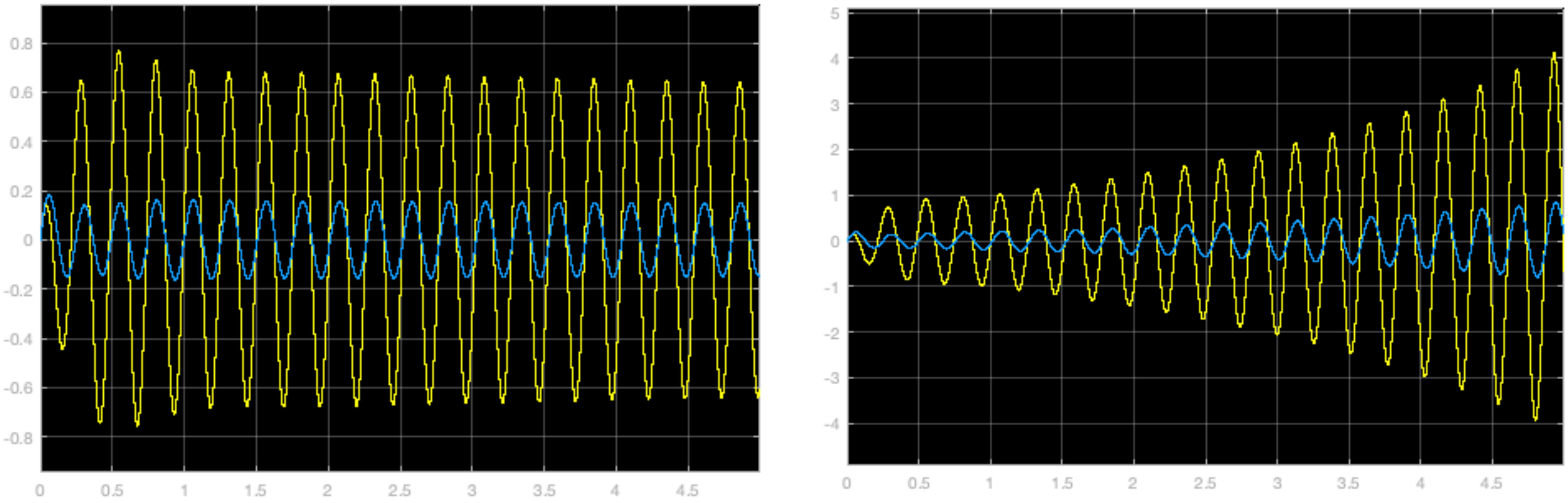




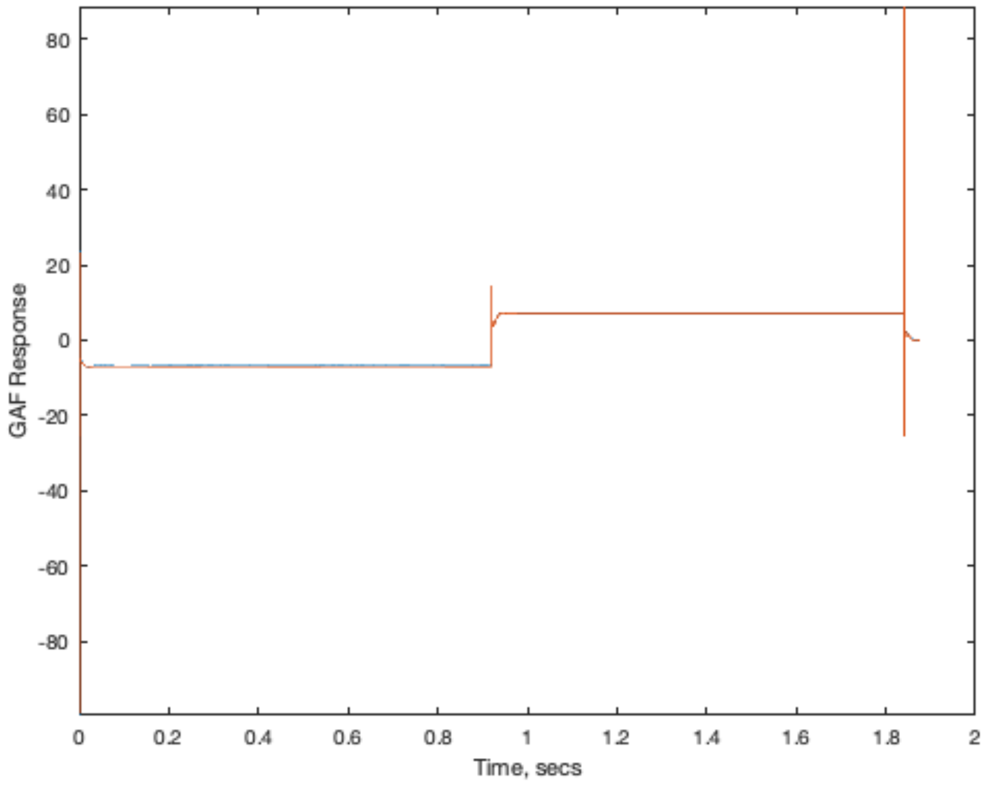
M8A1a – ROM Responses

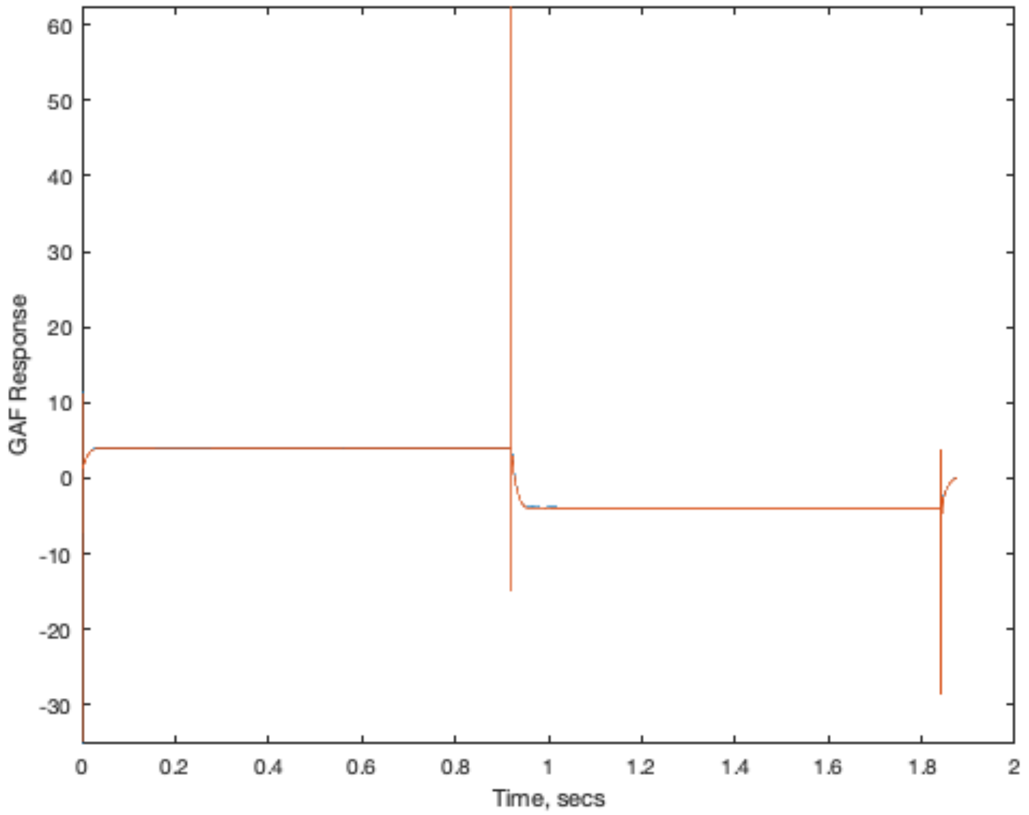
Q = 1.2 psi

Q = 1.3 psi

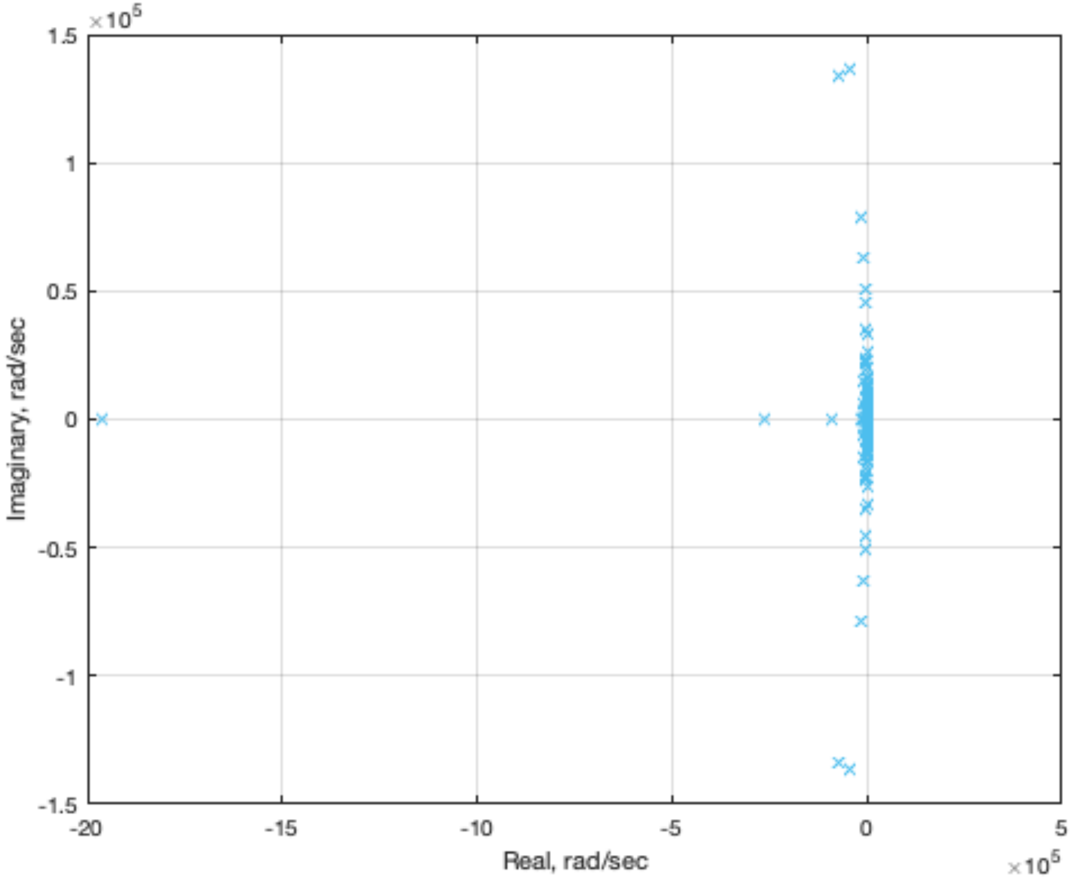


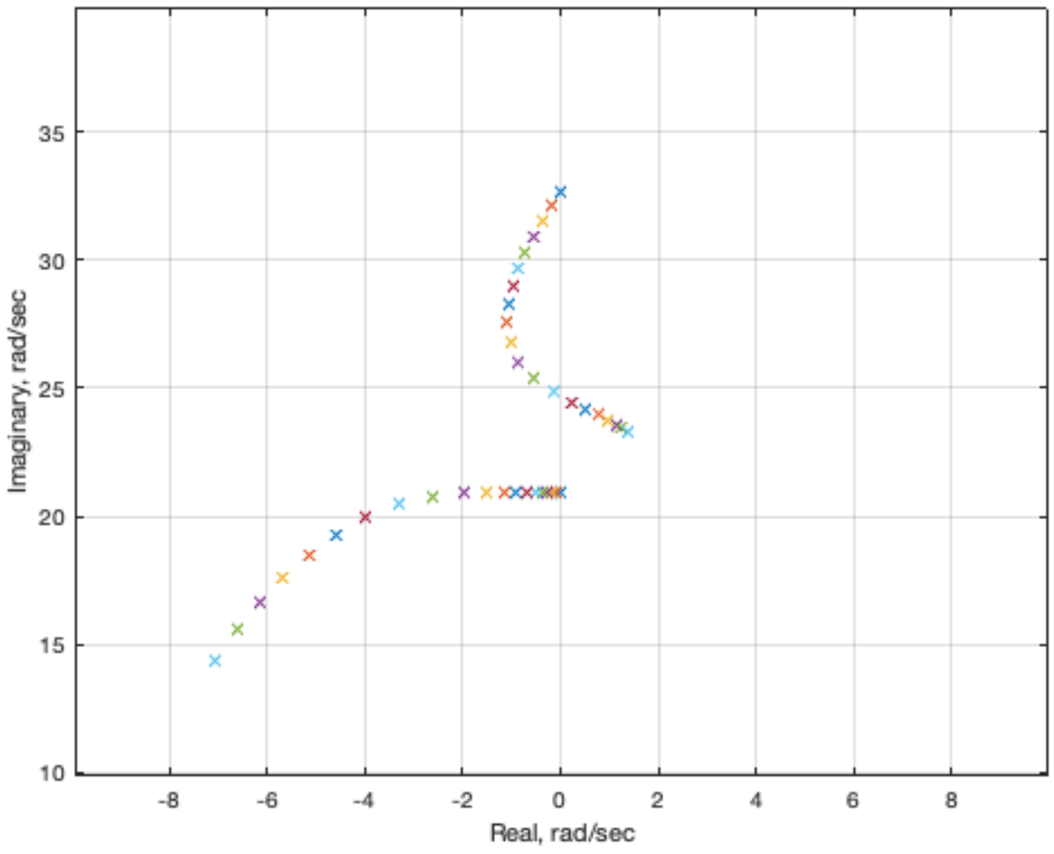
M8A1b – ROM/KESTREL GAFs





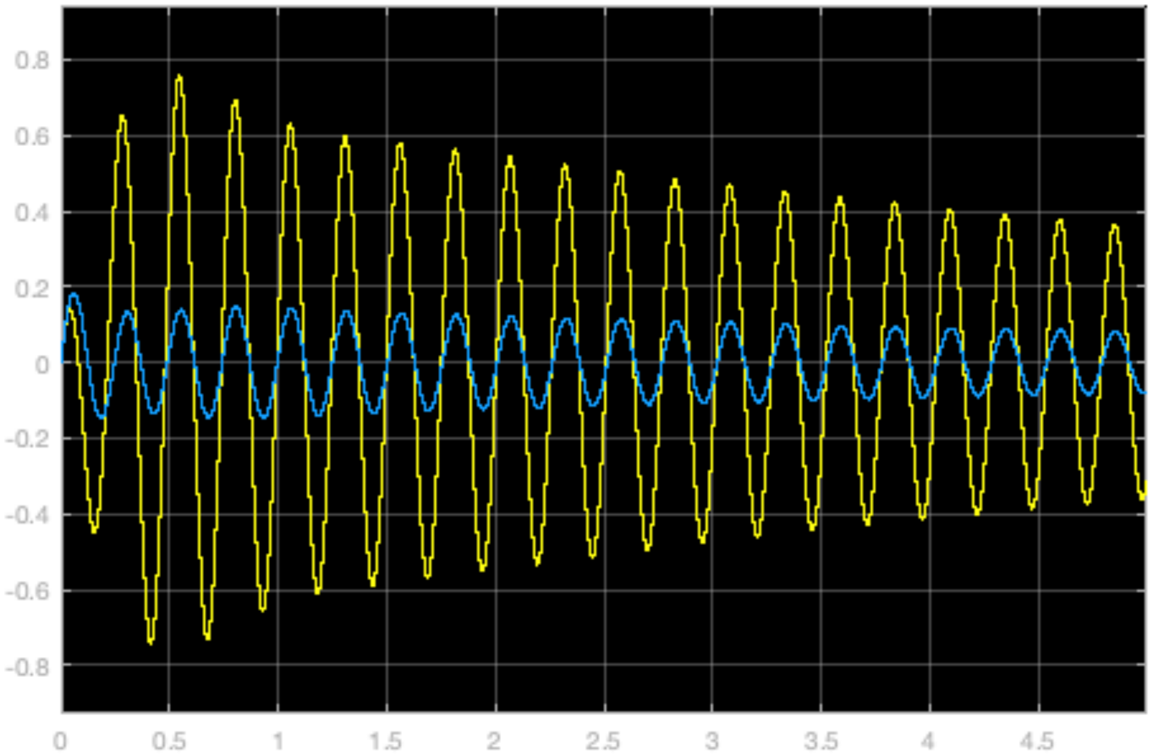
M8A1b – ROM/KESTREL Root Locus



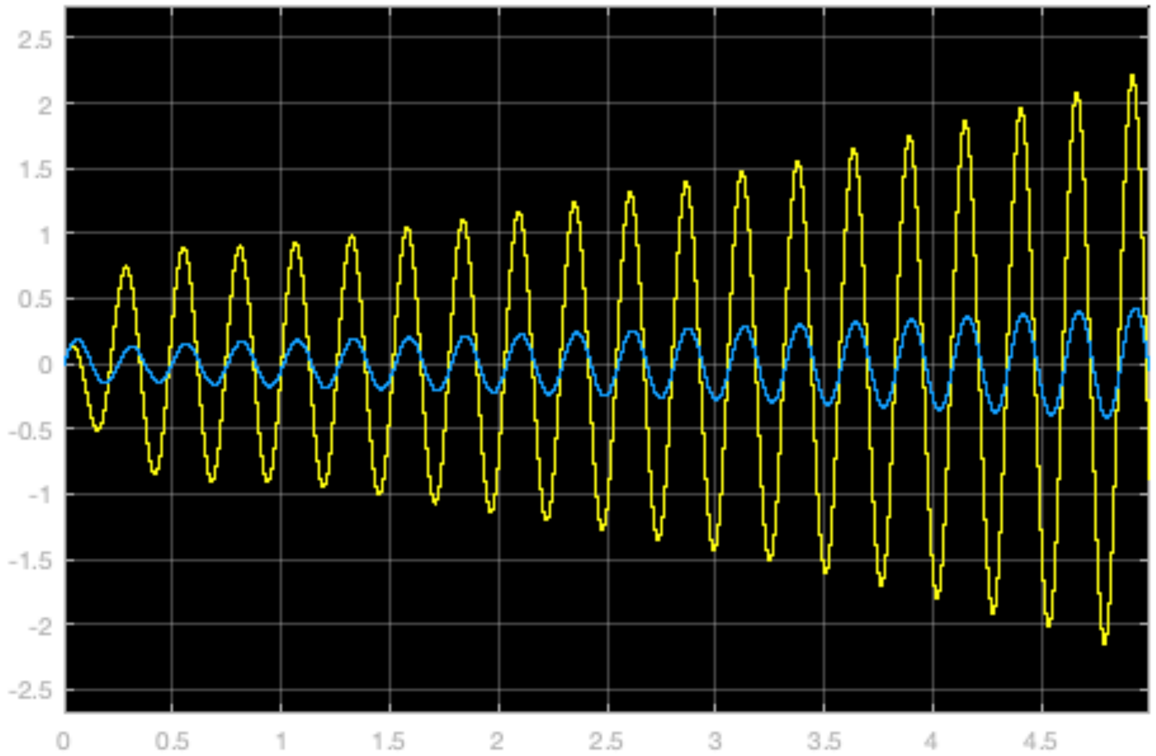


M8A1b – ROM Responses

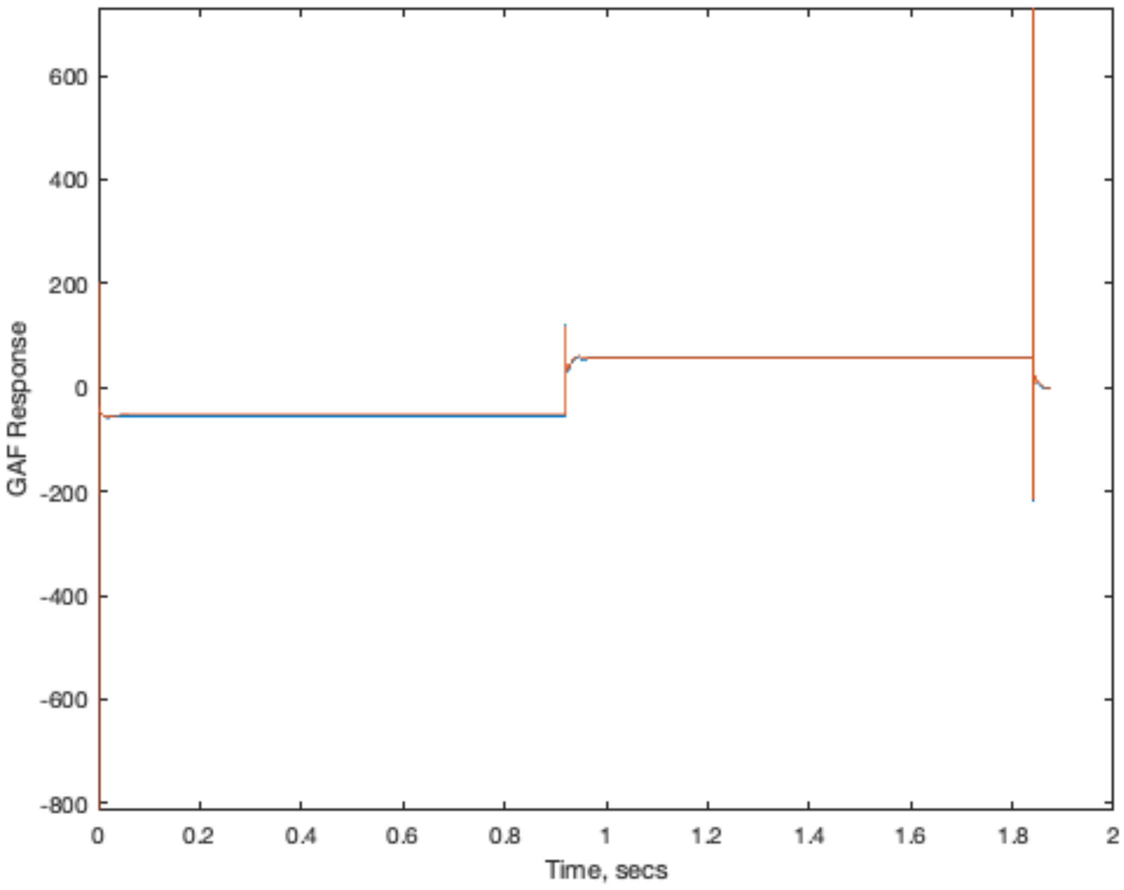
Q = 1.2 psi

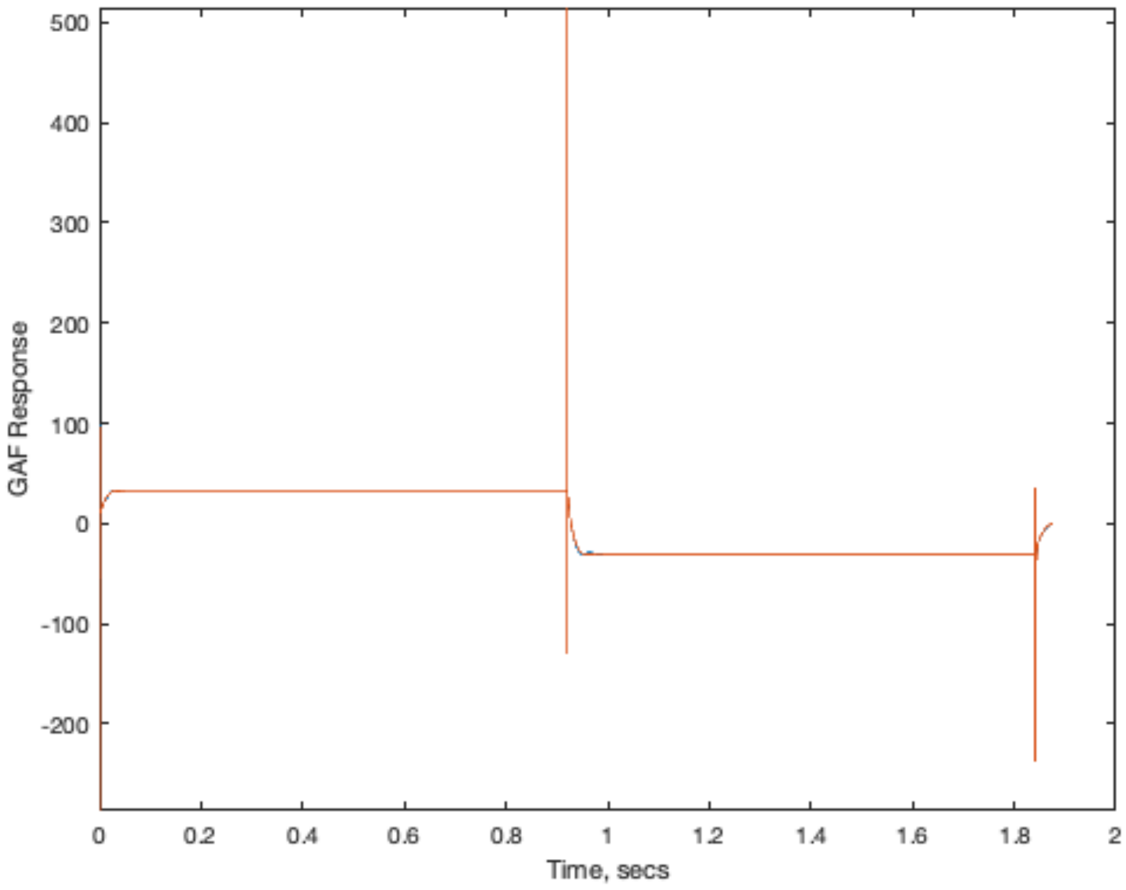


Q = 1.3 psi

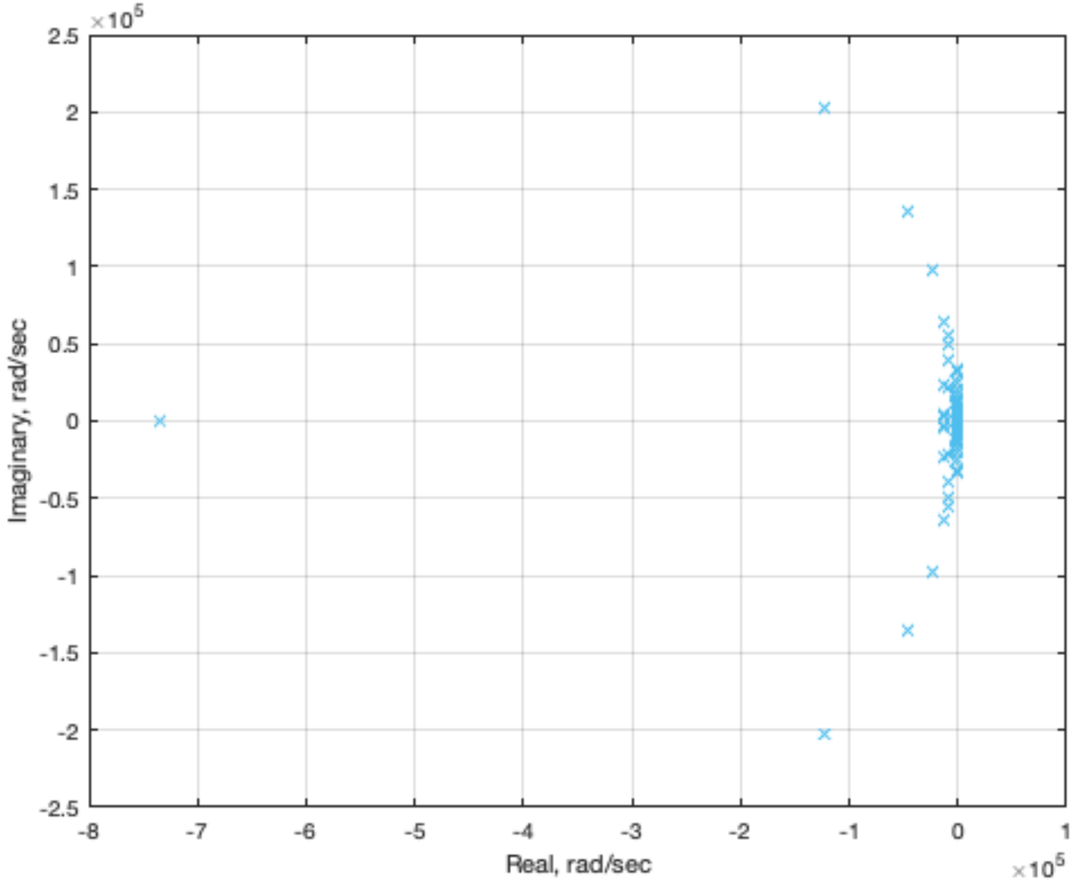


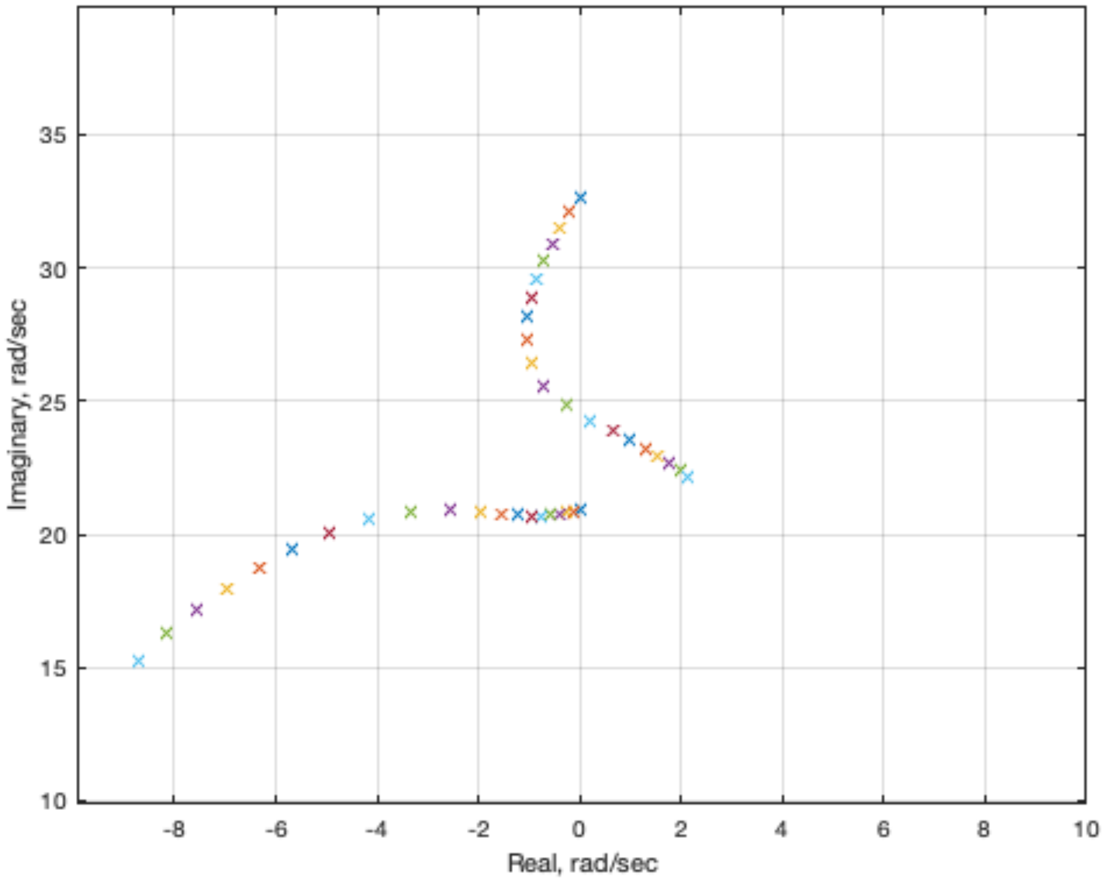
M8A1c – ROM/KESTREL GAFs





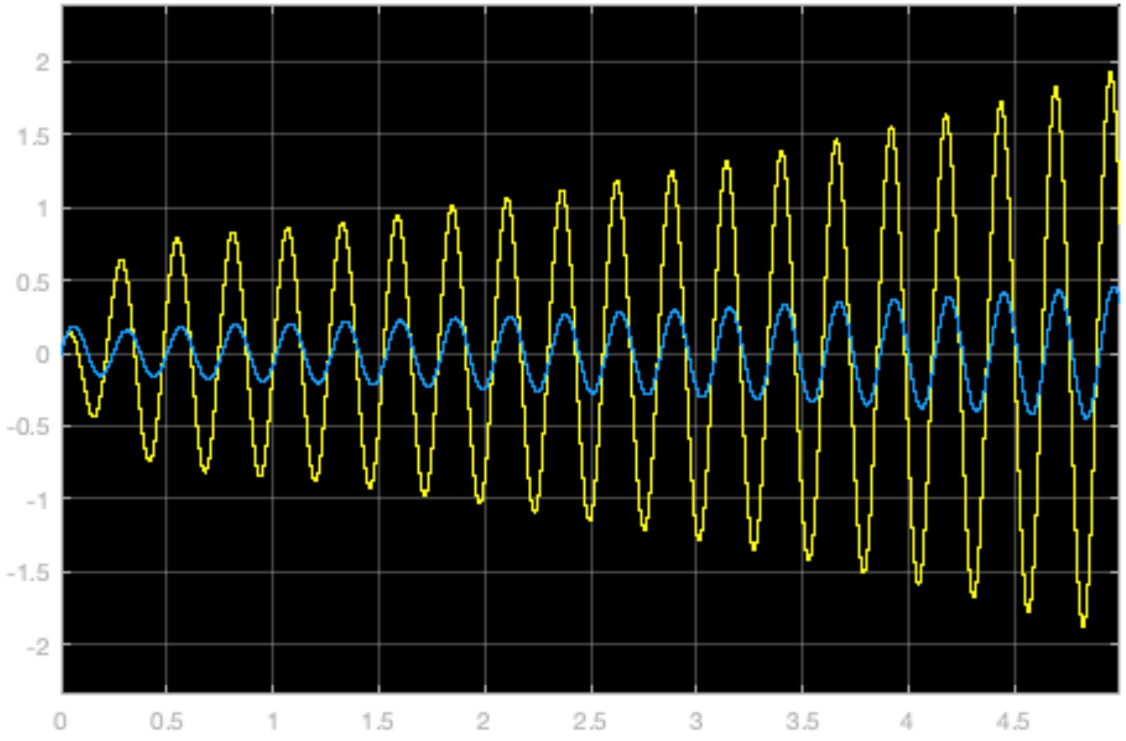
M8A1c – ROM/KESTREL Root Locus



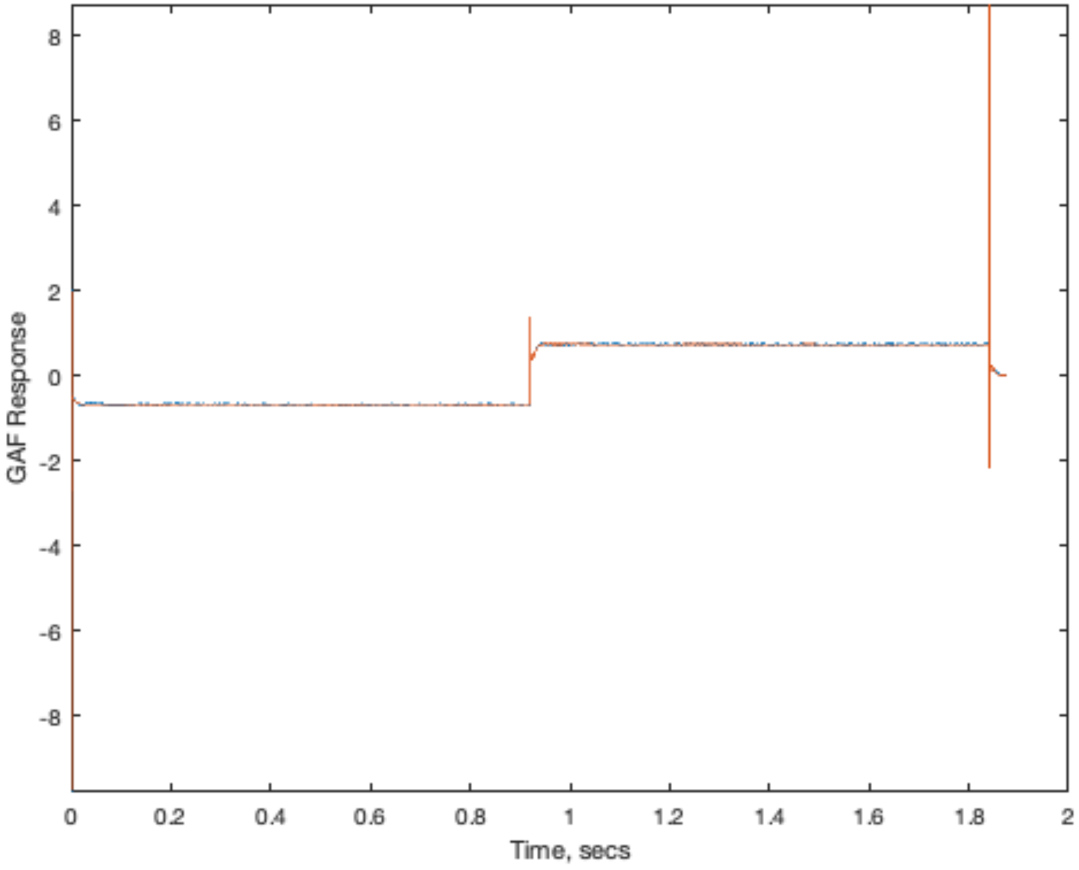


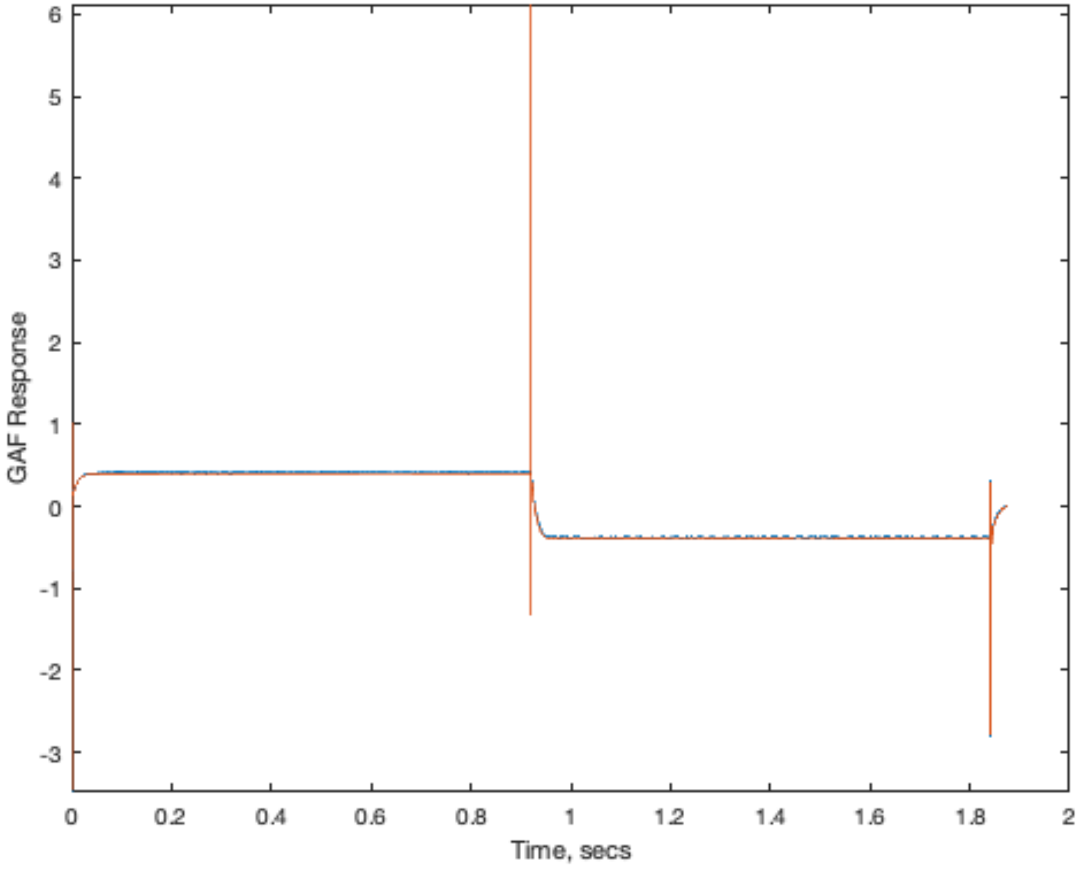
M8A1c – ROM Responses

Q = 1.2 psi

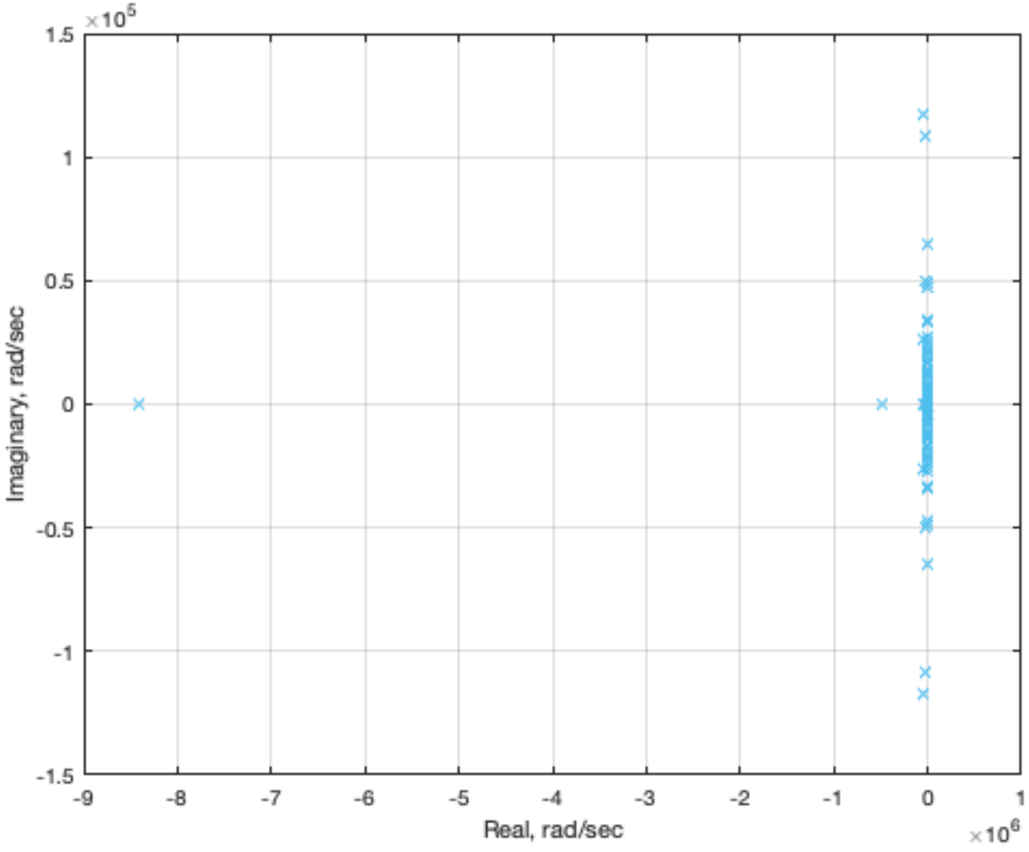


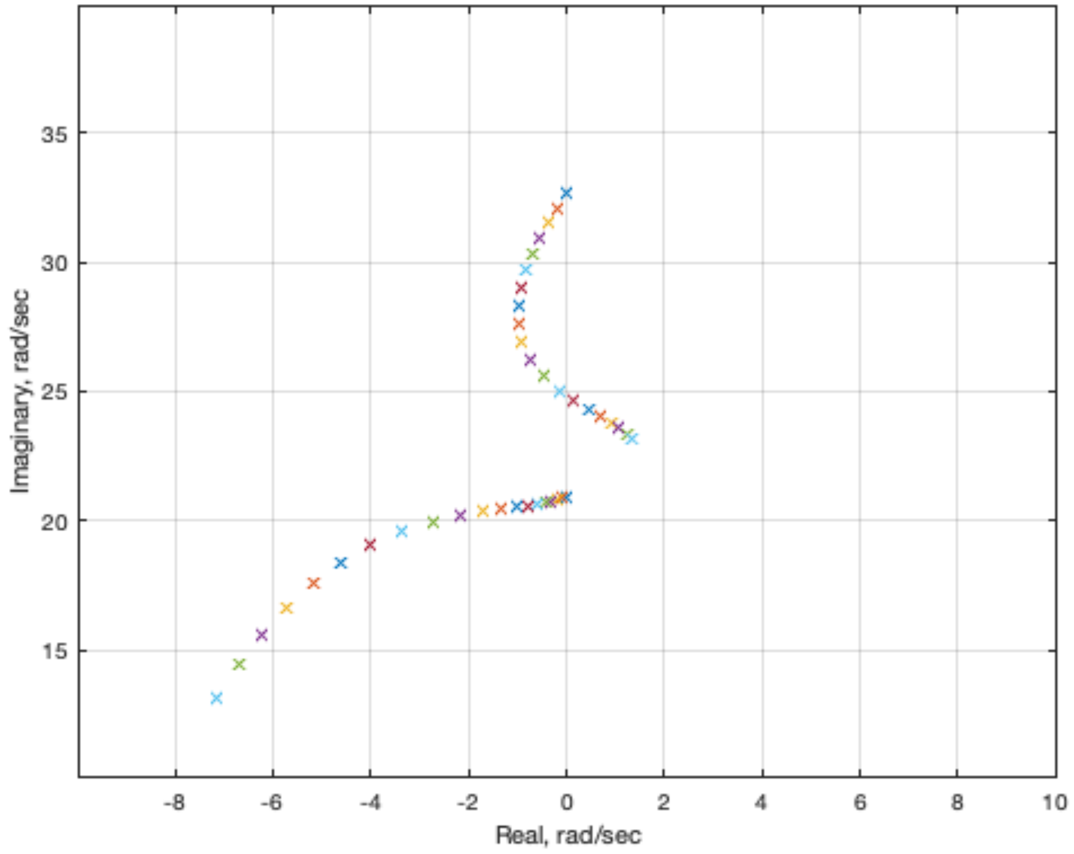
M8A1d – ROM/KESTREL GAFs





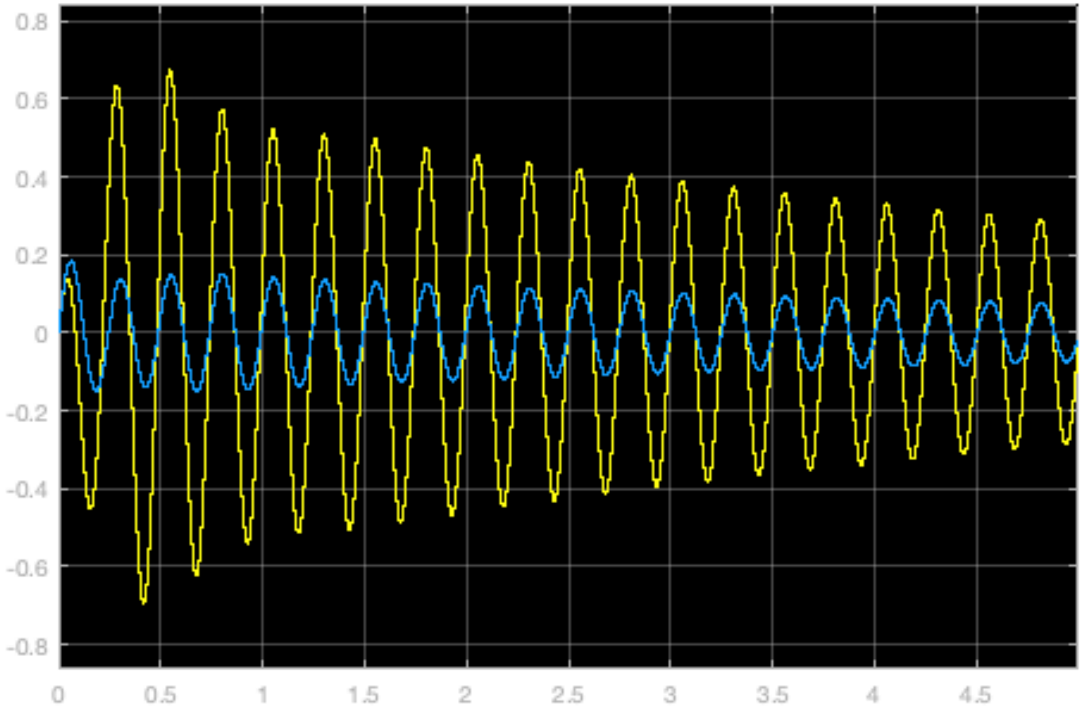
M8A1d – ROM/KESTREL Root Locus



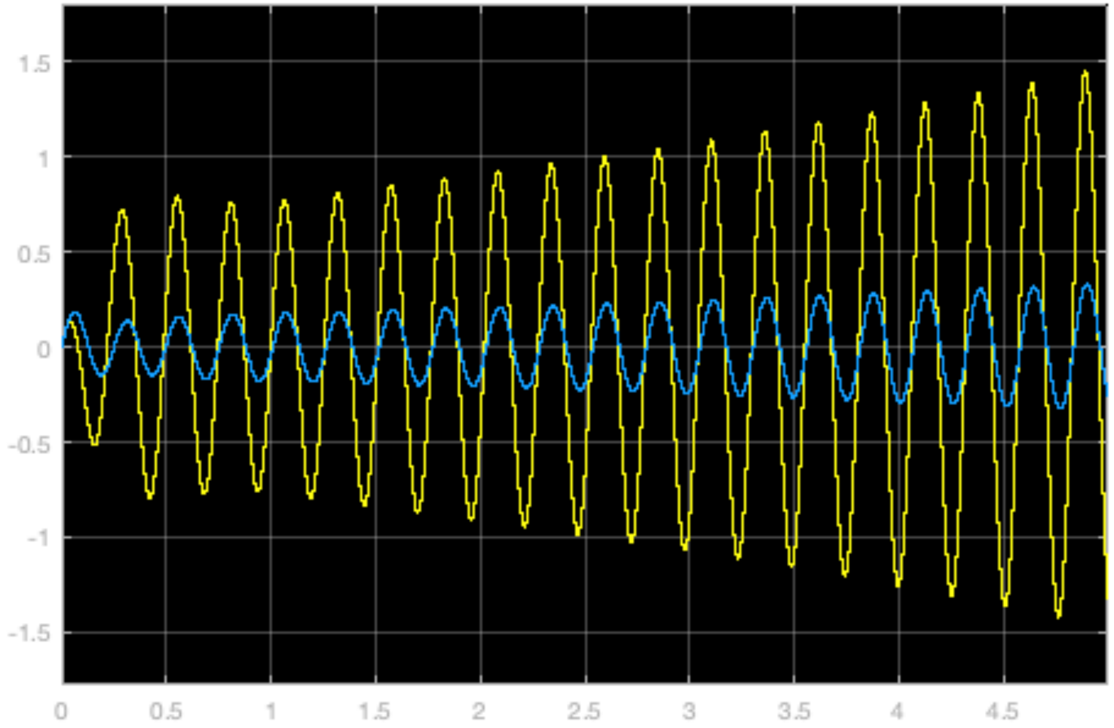


M8A1d – ROM Responses

Q = 1.2 psi

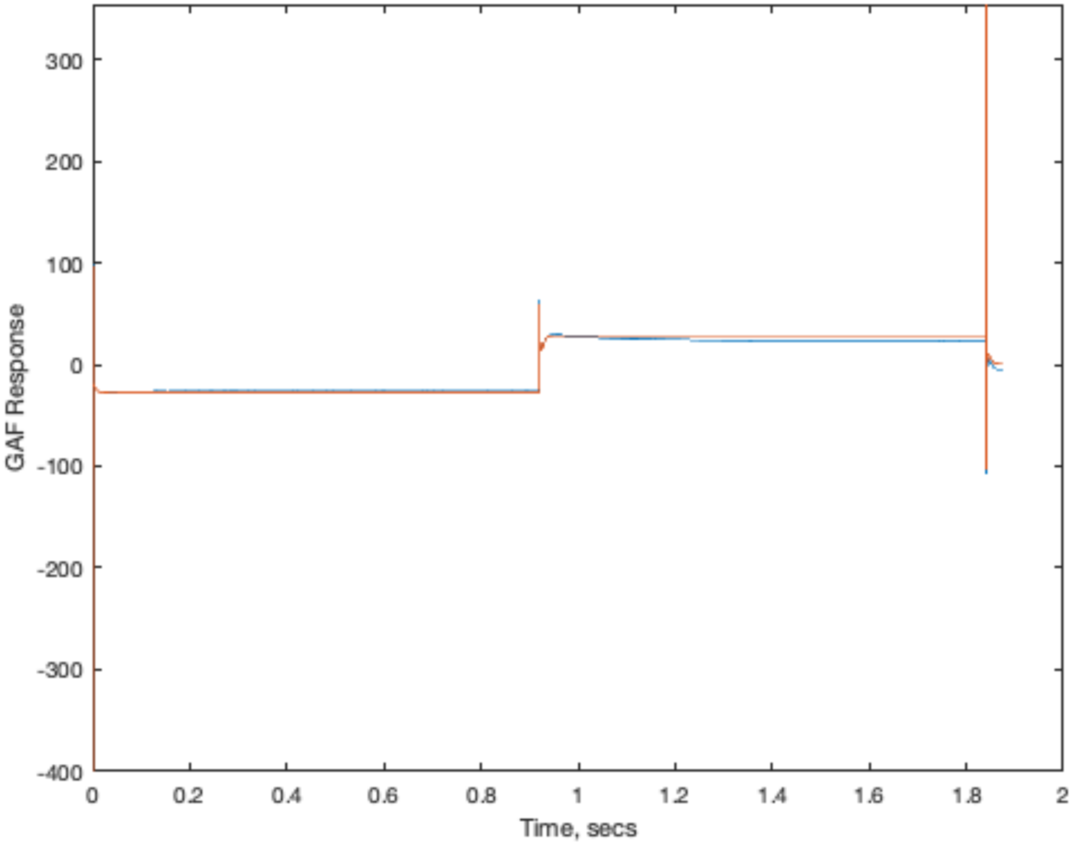


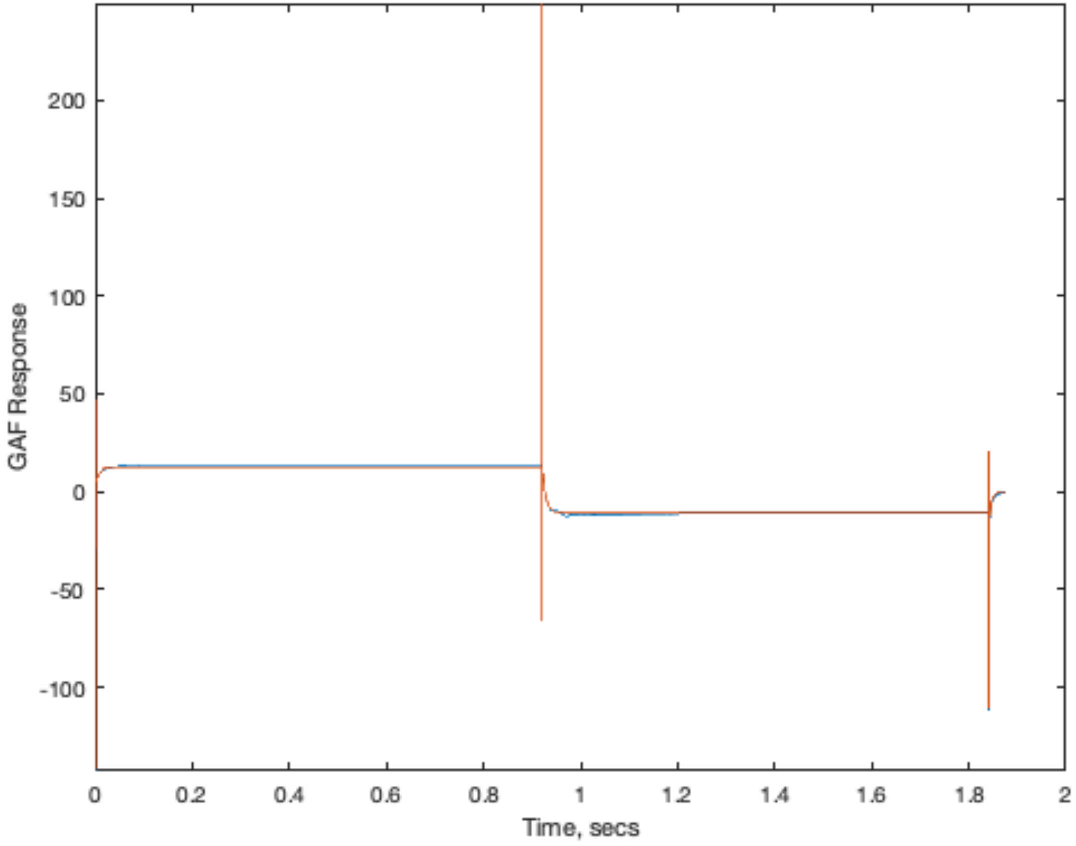
Q = 1.3 psi



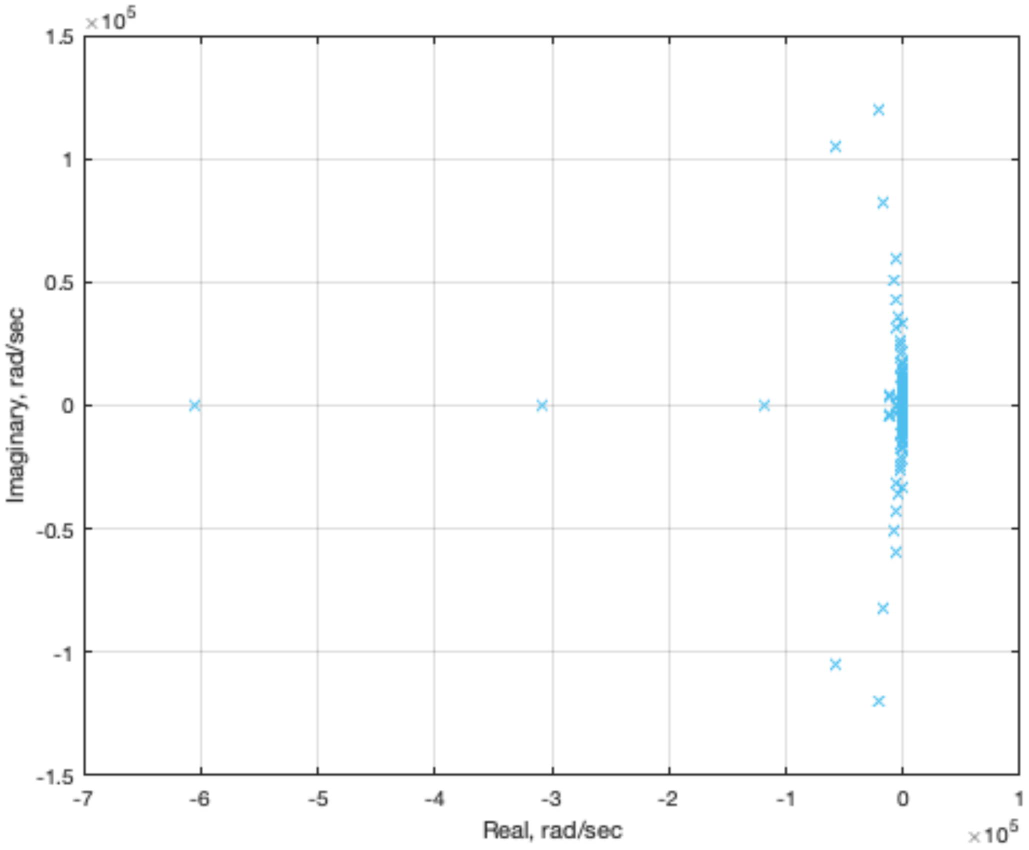
Alpha = 3 deg

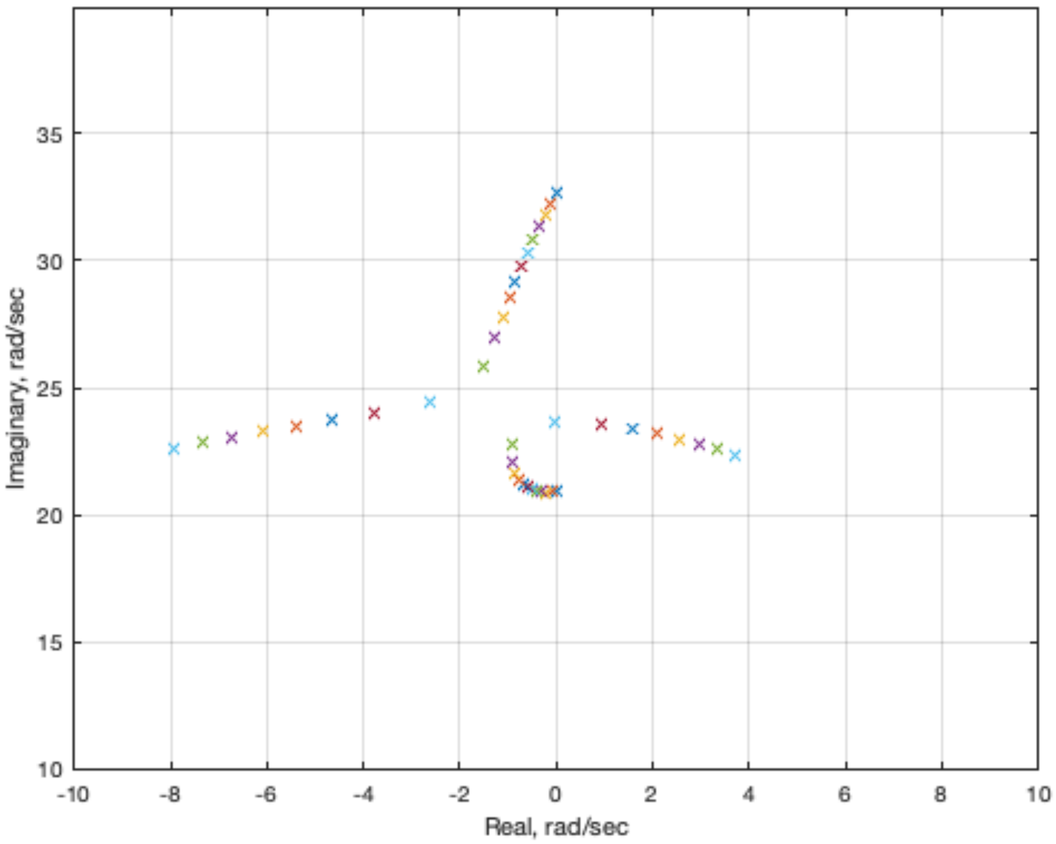
M8A3a – ROM/KESTREL GAFs





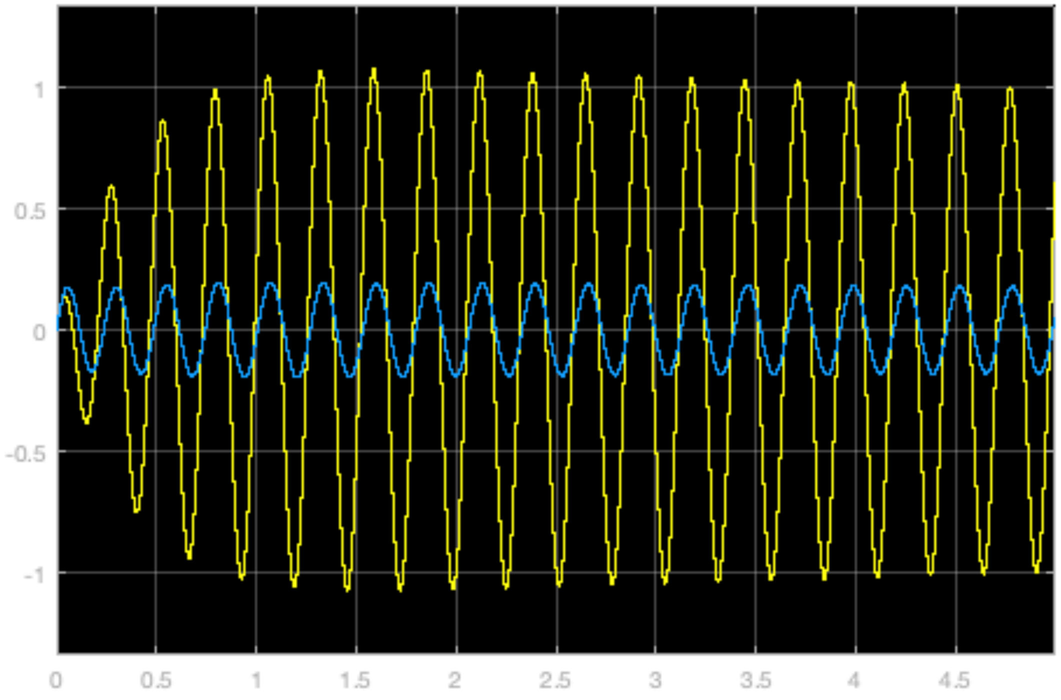
M8A3a – ROM/KESTREL Root Locus



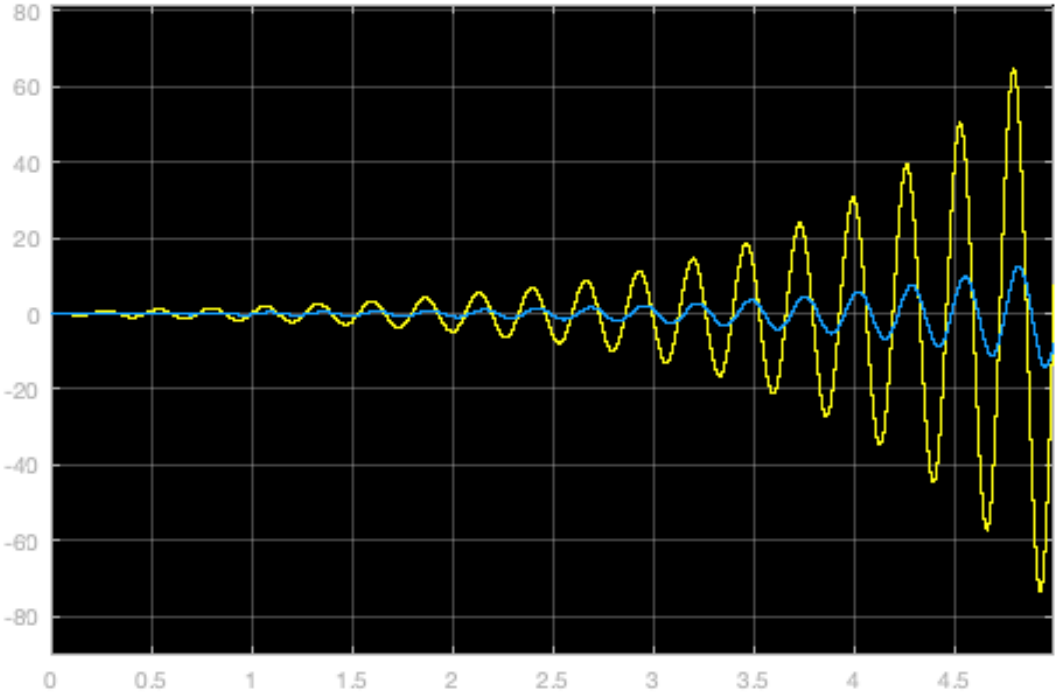


M8A3a – ROM Responses

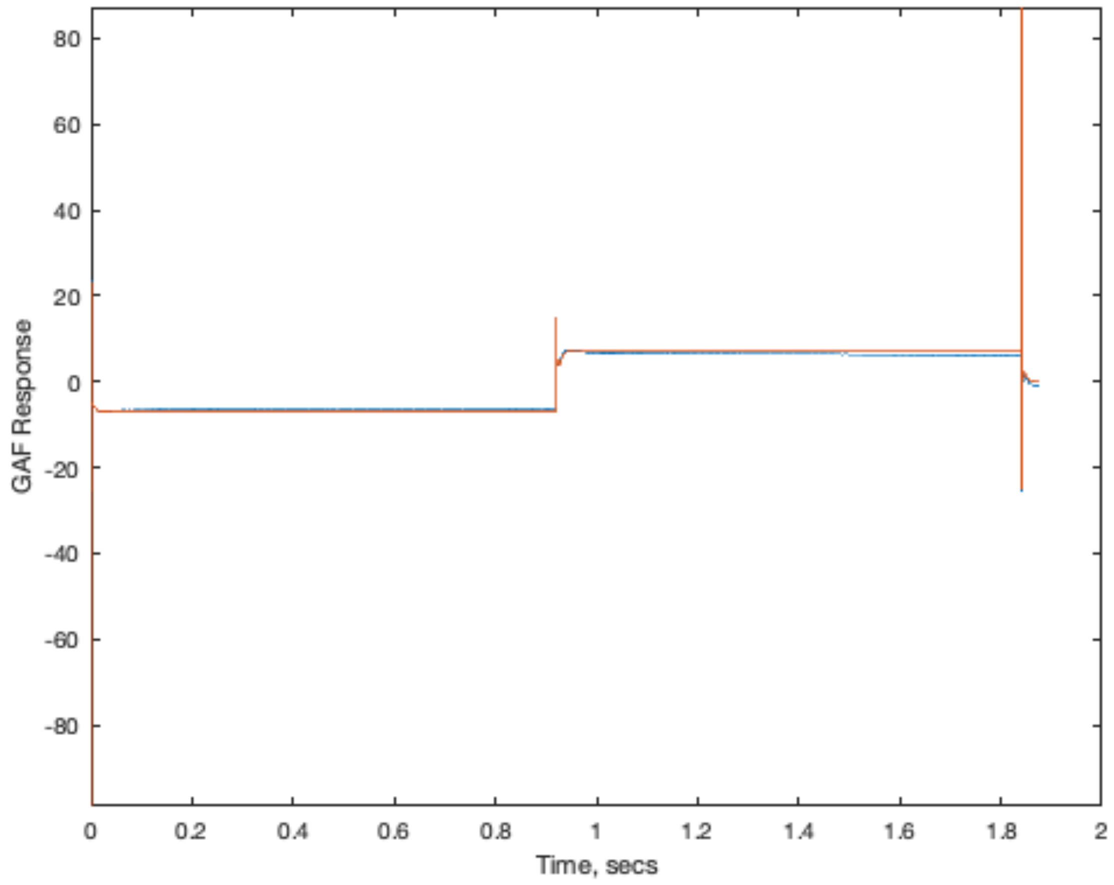
Q = 1.2 psi

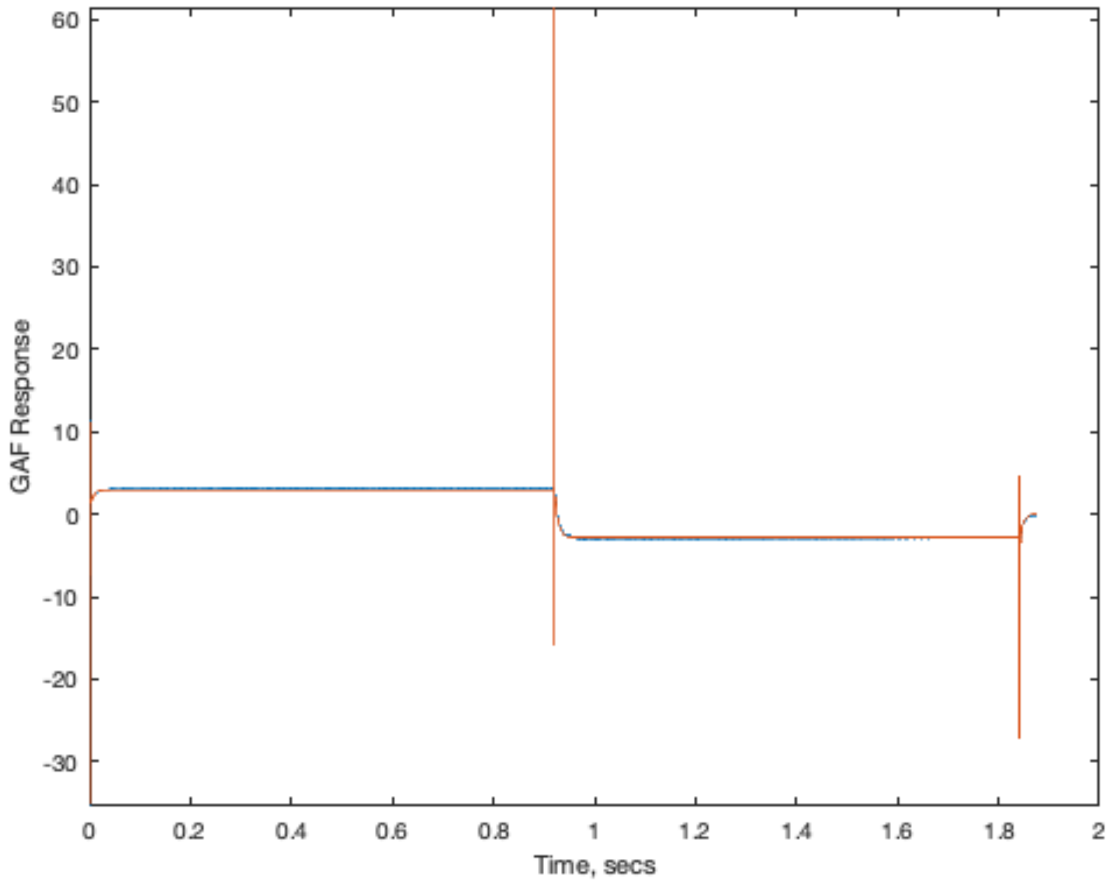


Q = 1.3 psi

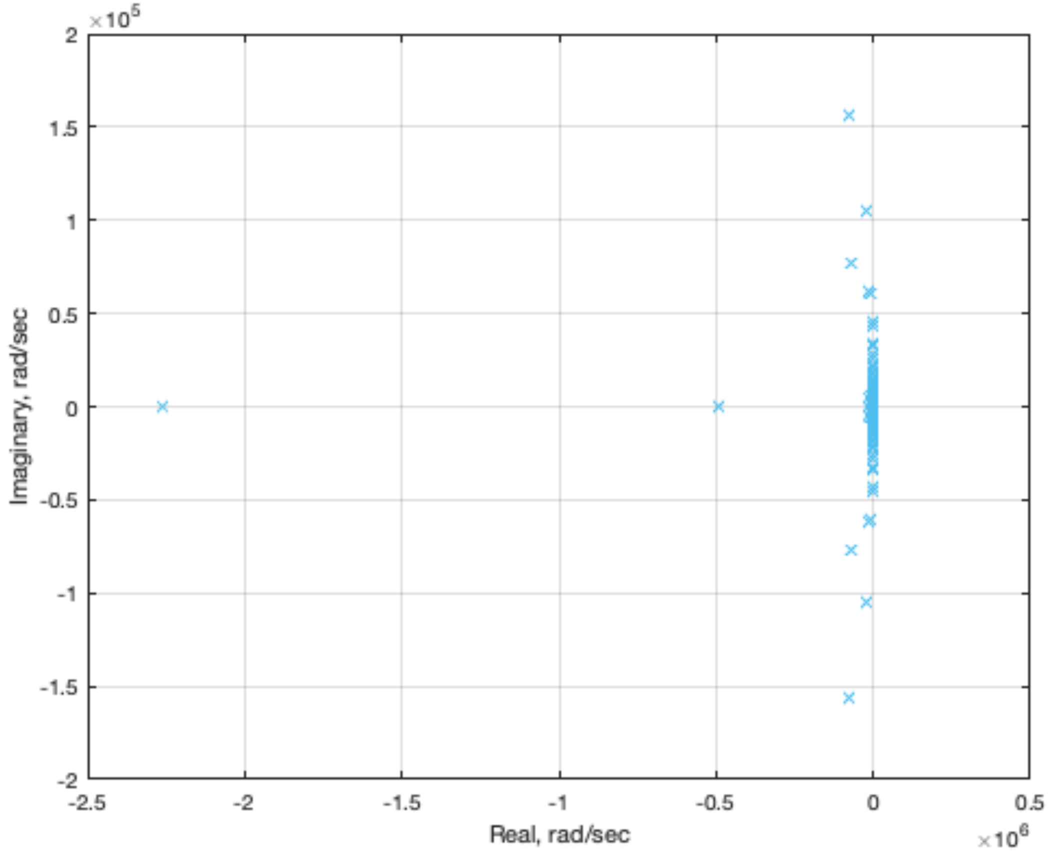


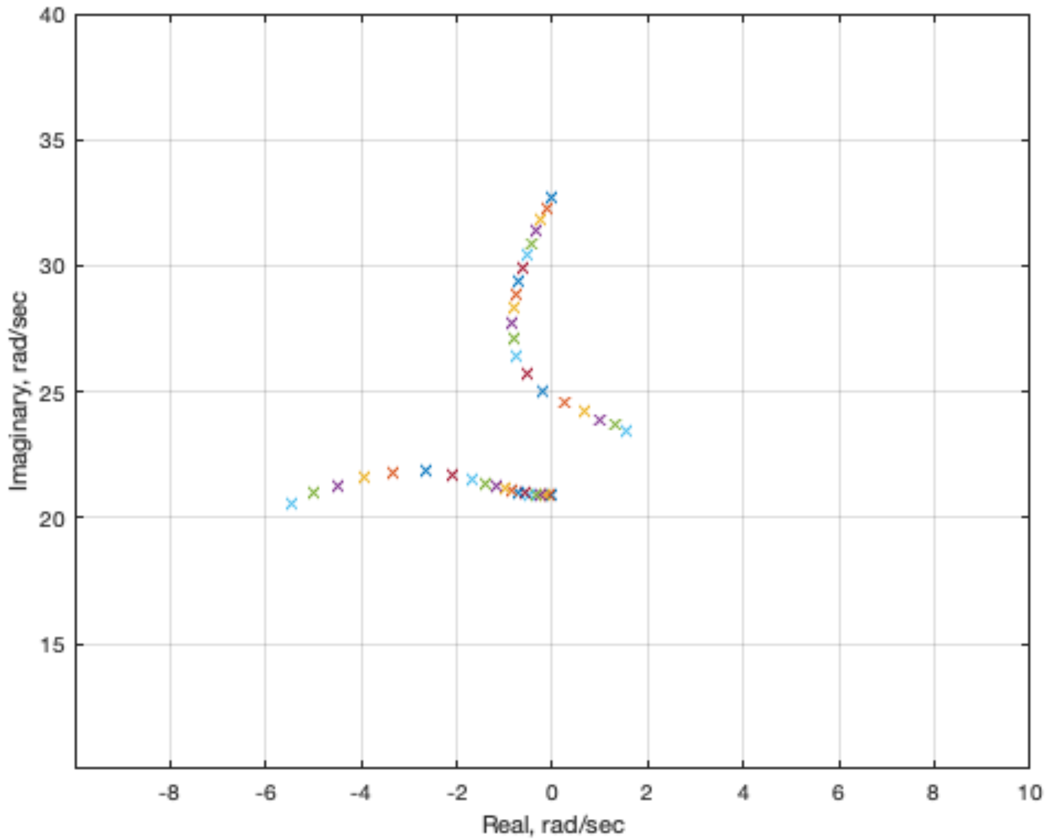
M8A3b – ROM/KESTREL GAFs





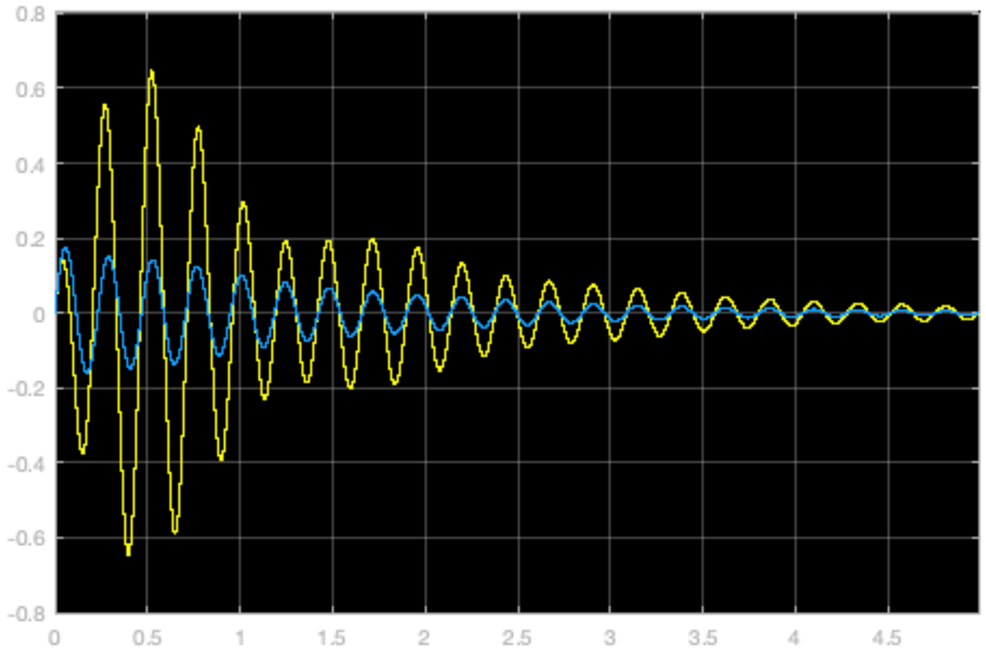
M8A3b – ROM/KESTREL Root Locus



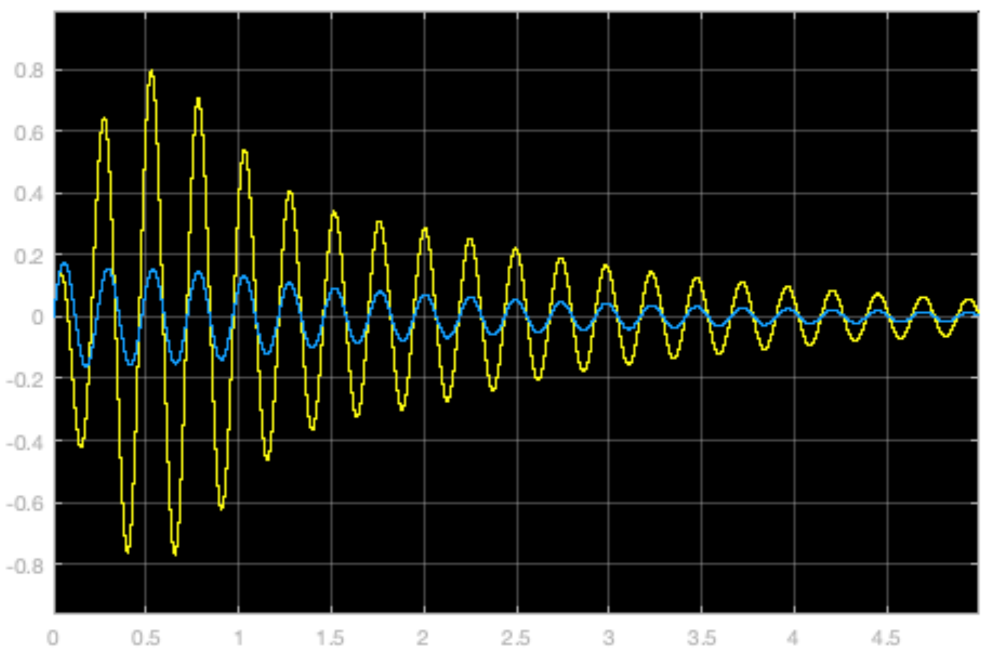


M8A3b – ROM Responses

Q = 1.2 psi

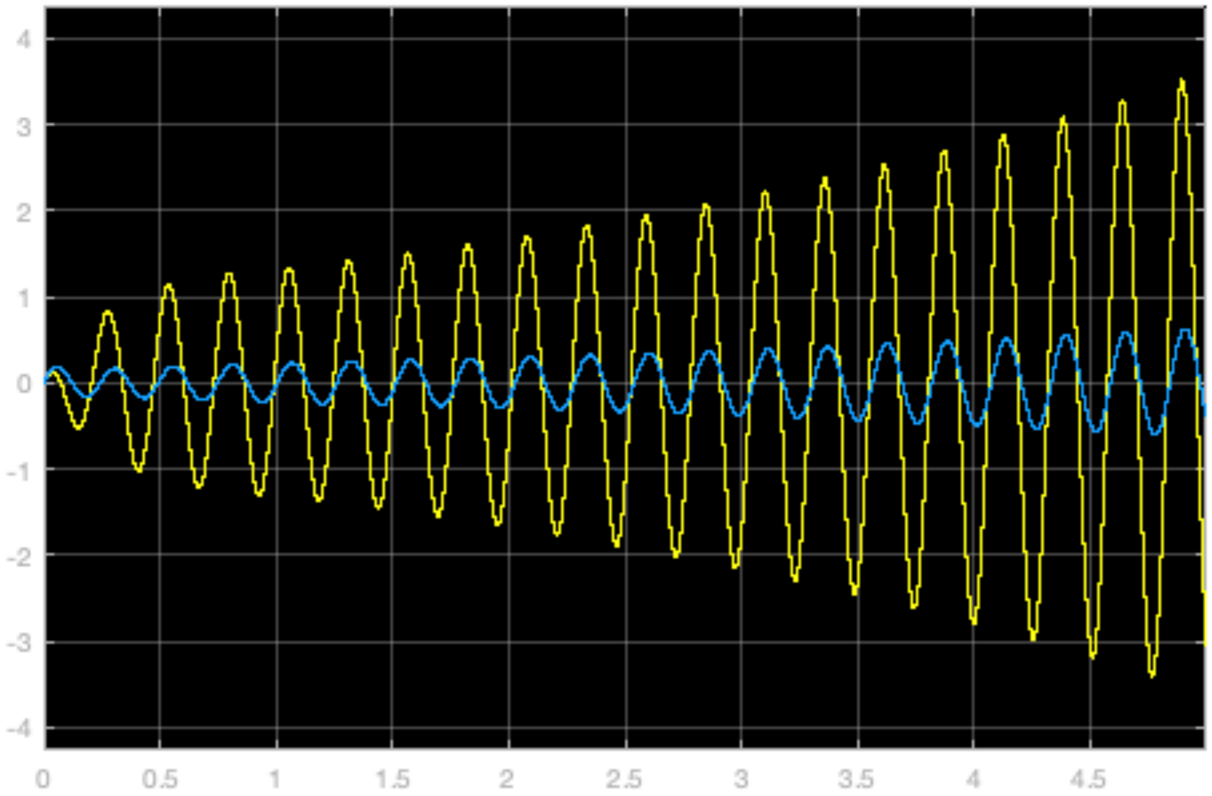


Q = 1.3 psi

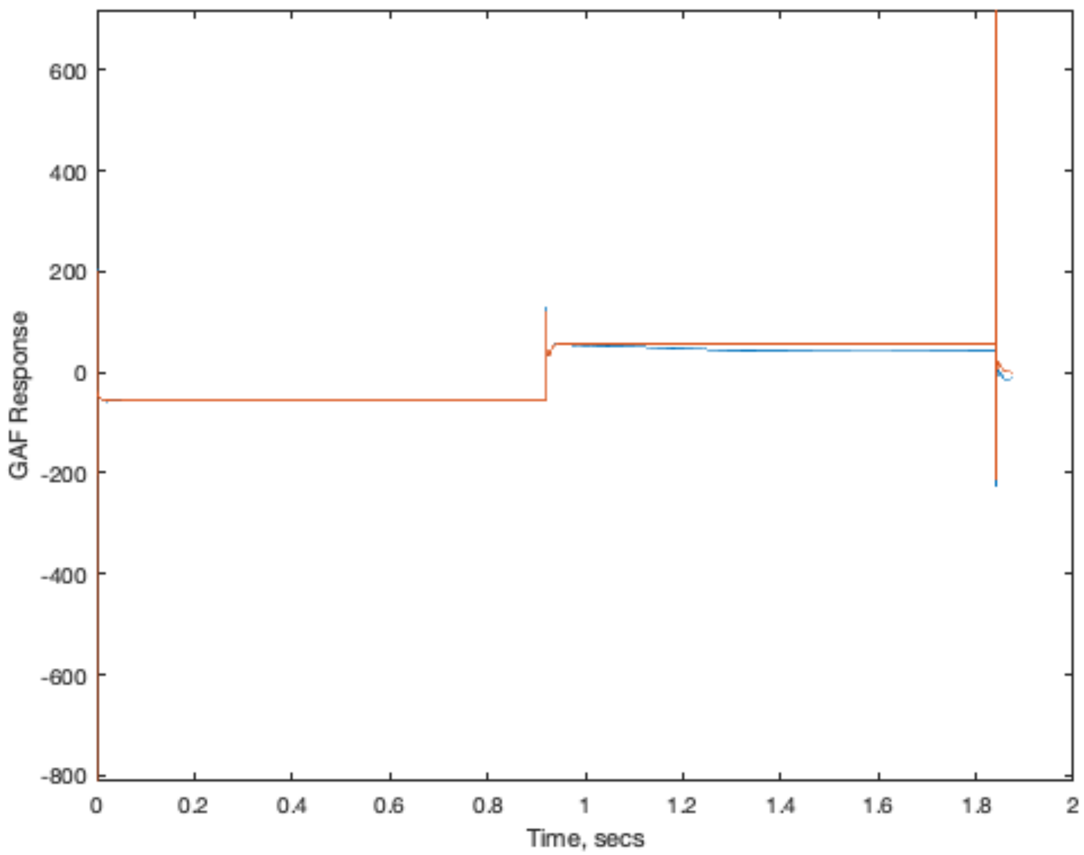


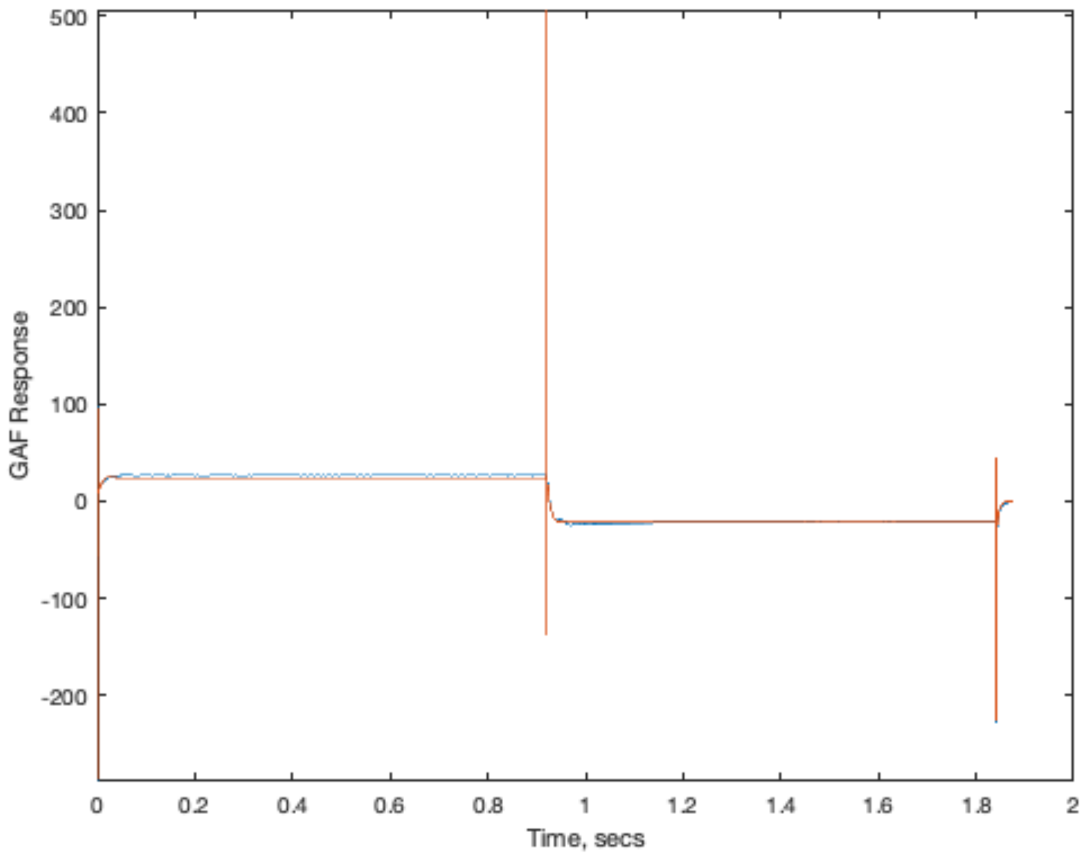
M8A3b – ROM Responses

Q = 1.5 psi

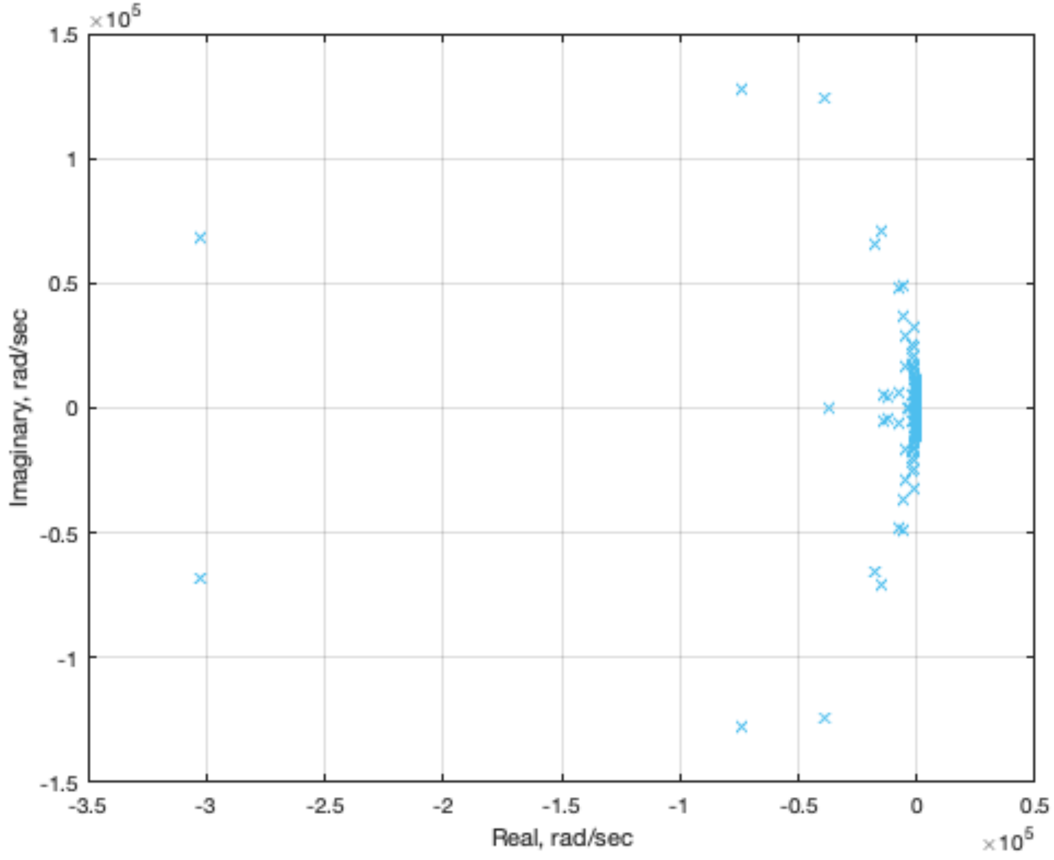


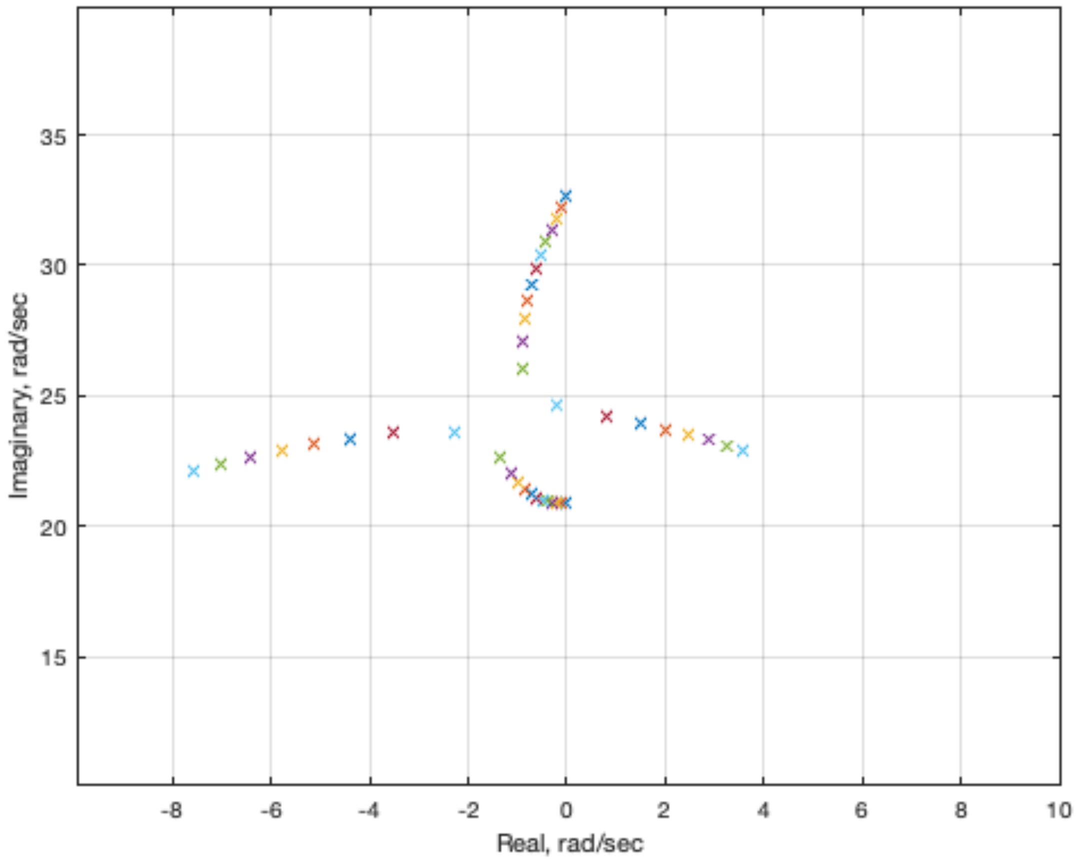
M8A3c – ROM/KESTREL GAFs





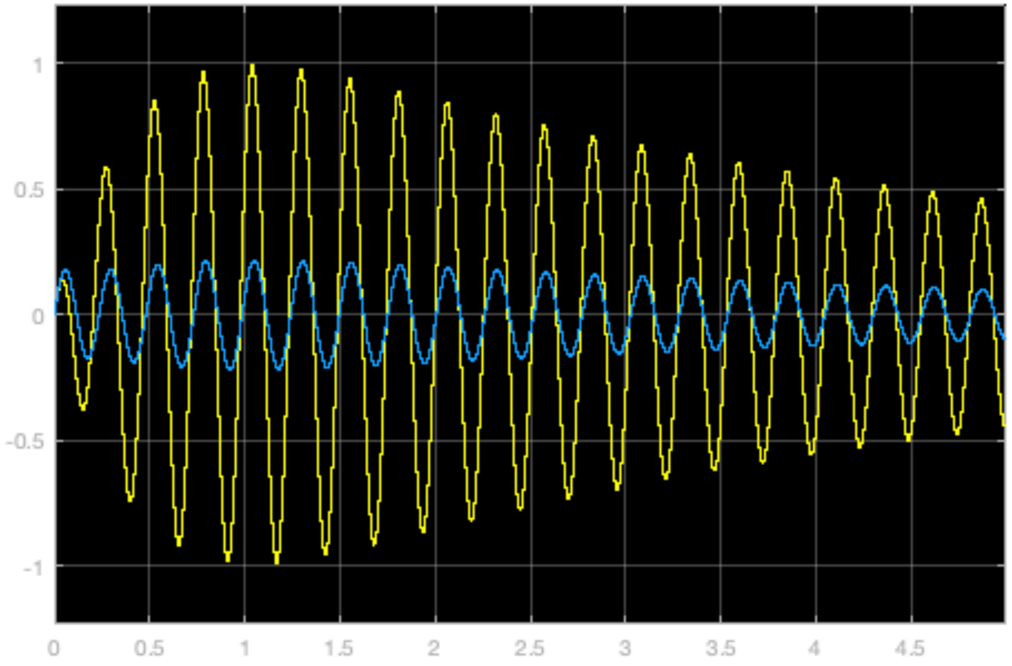
M8A3c – ROM/KESTREL Root Locus



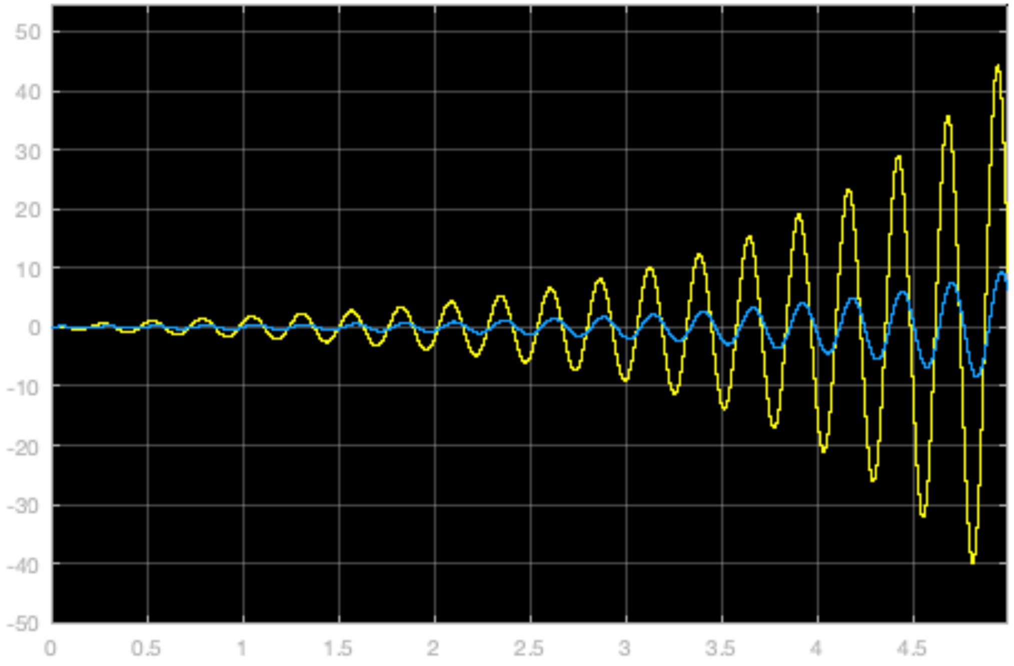


M8A3c – ROM Responses

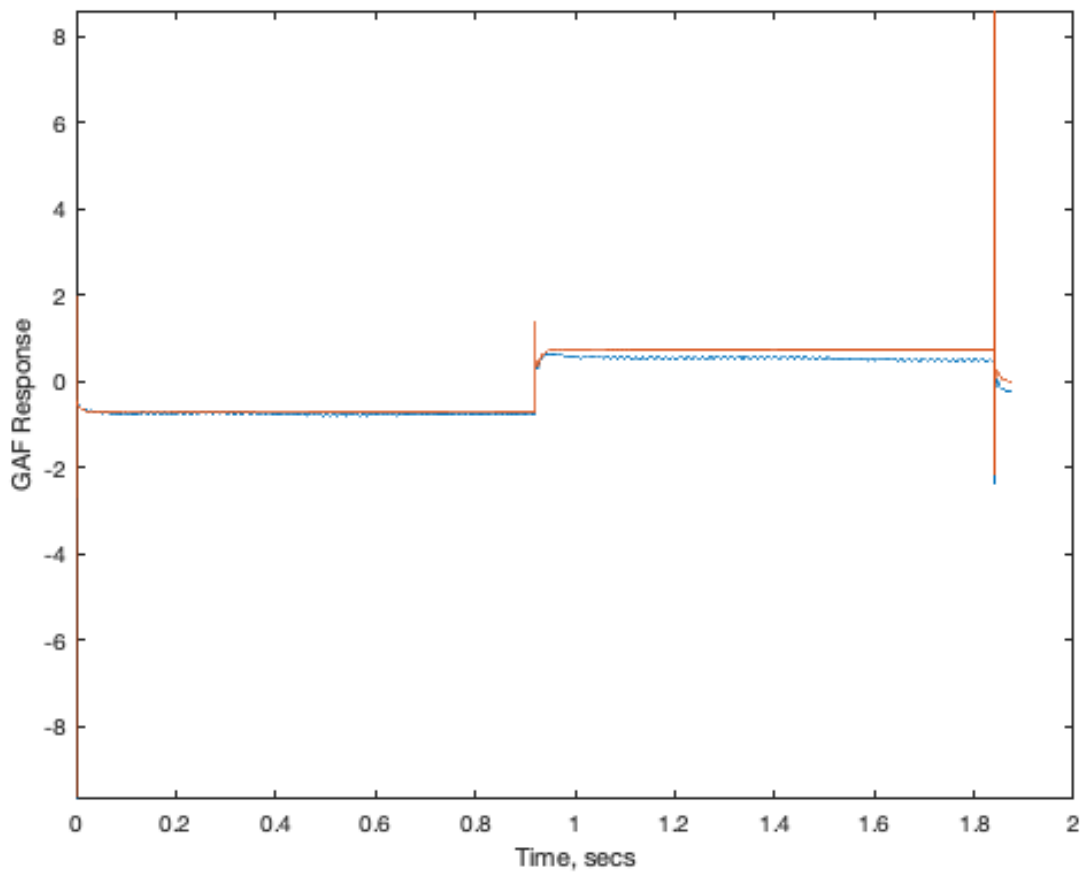
Q = 1.2 psi

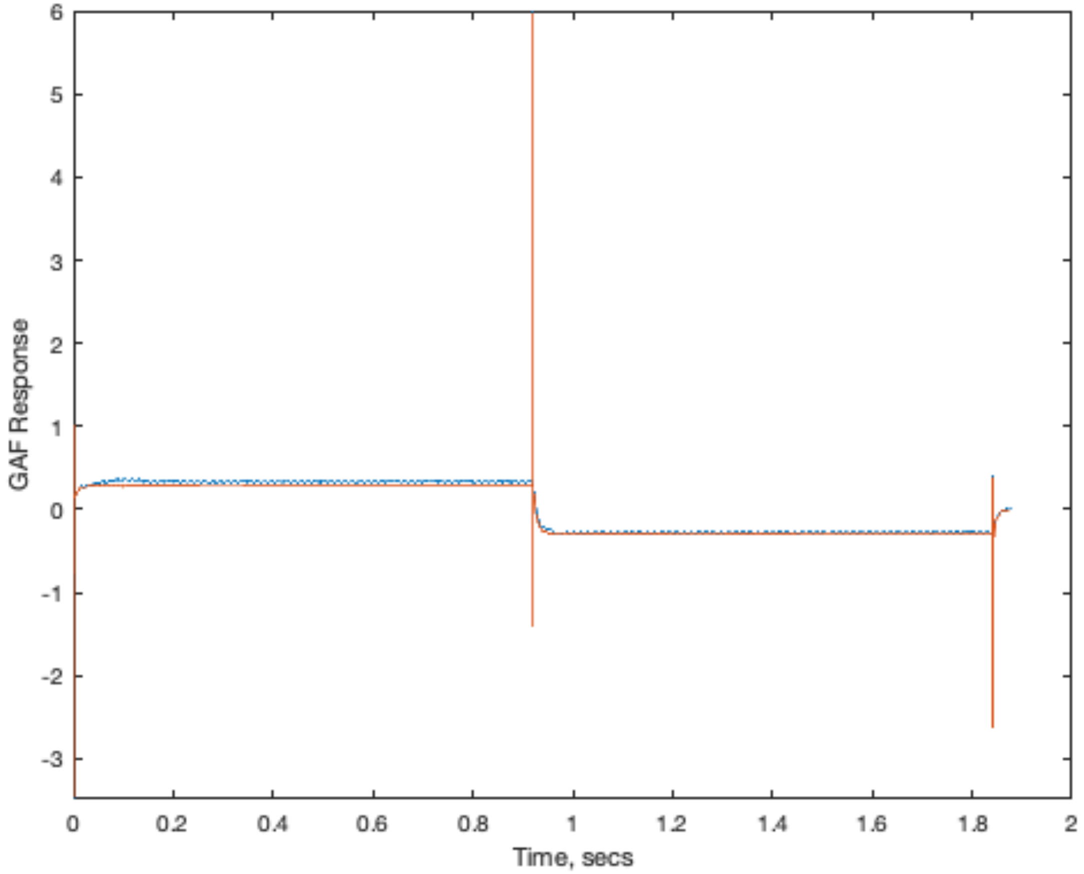


Q = 1.3 psi

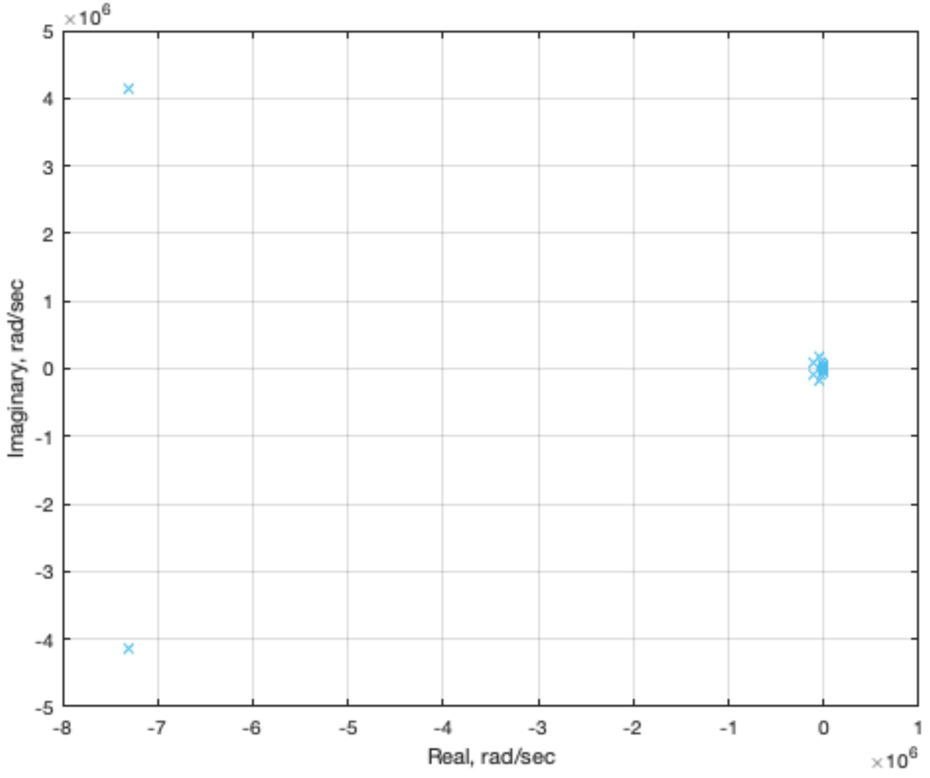


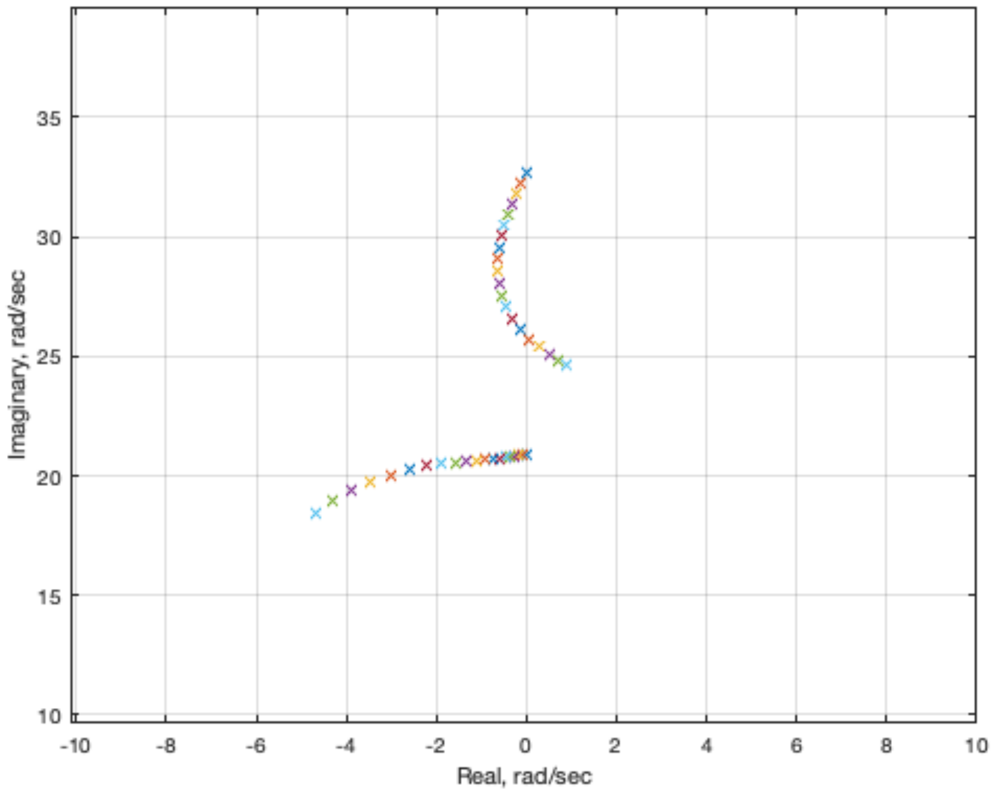
M8A3d – ROM/KESTREL GAFs





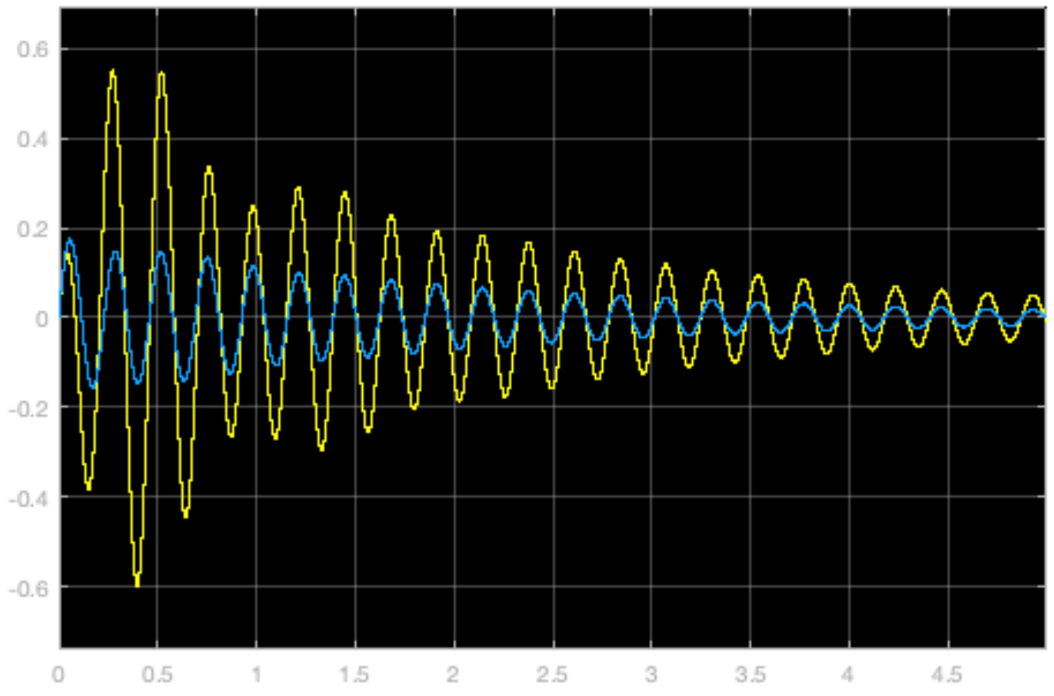
M8A3d – ROM/KESTREL Root Locus



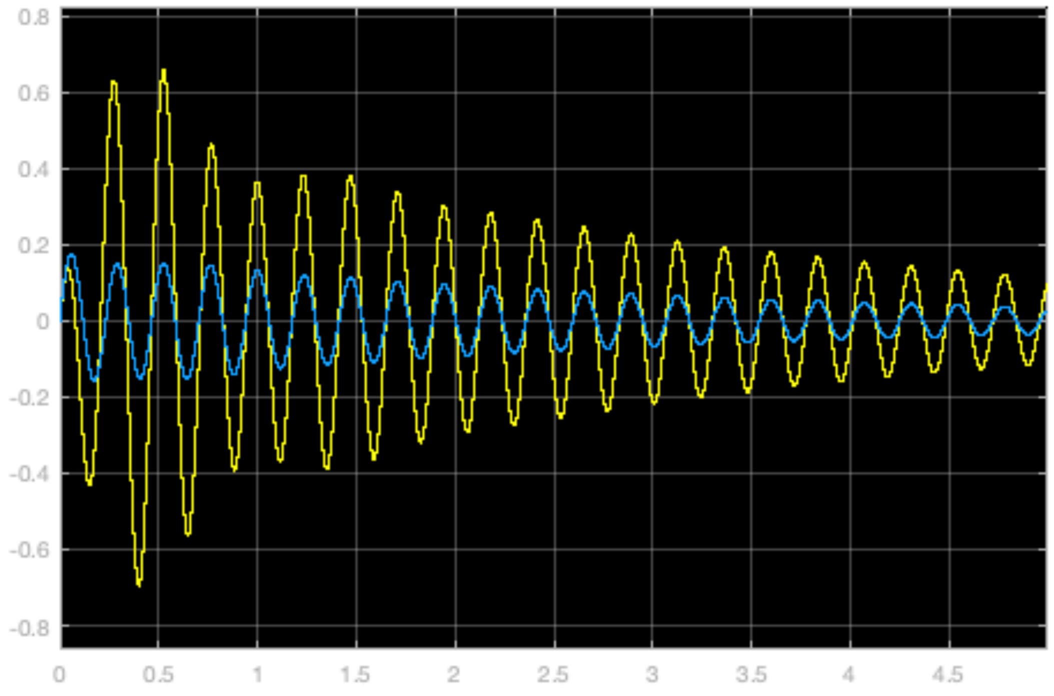


M8A3d – ROM Responses

Q = 1.2 psi

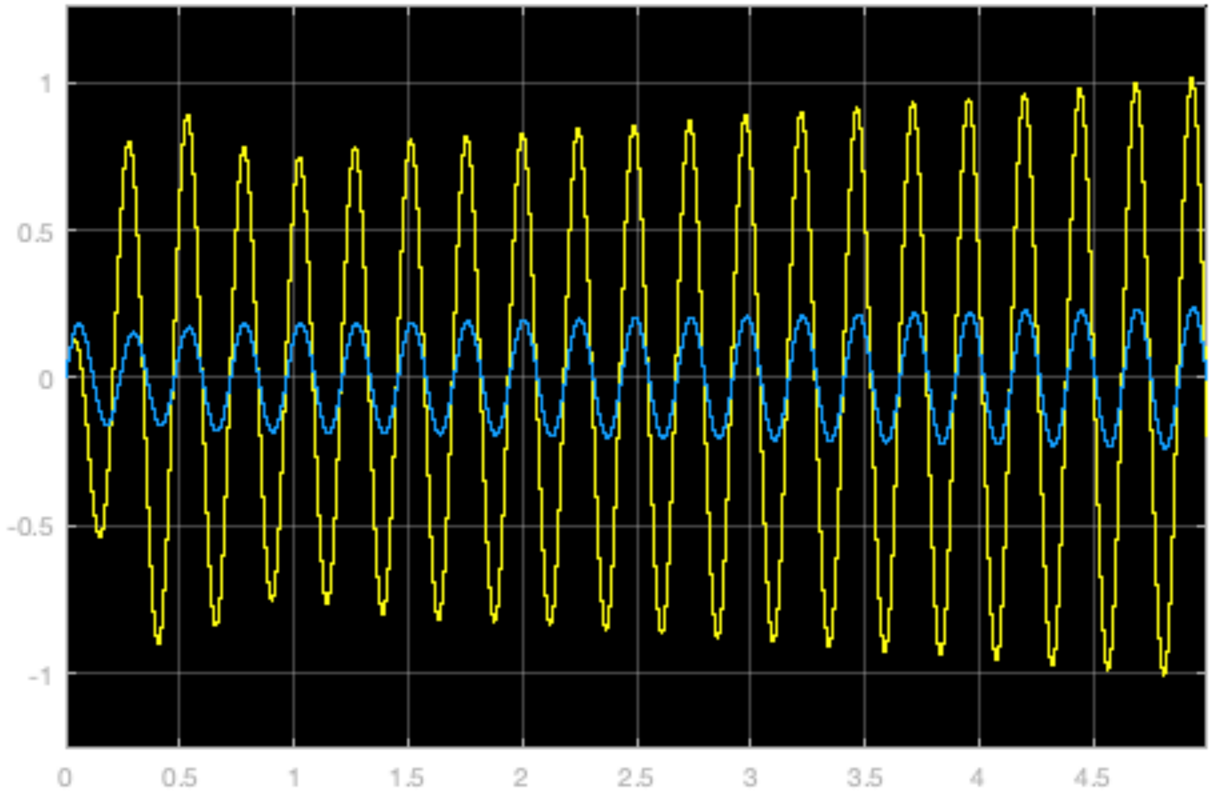


Q = 1.3 psi



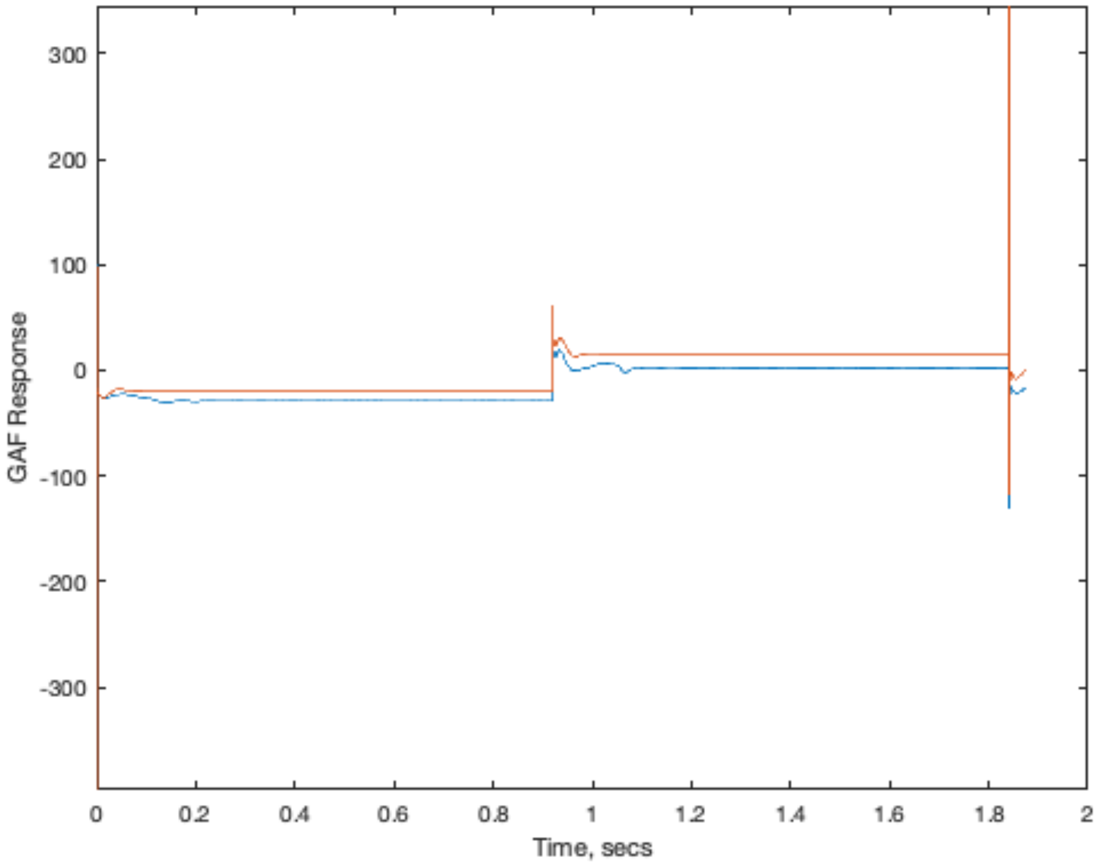
M8A3d – ROM Responses

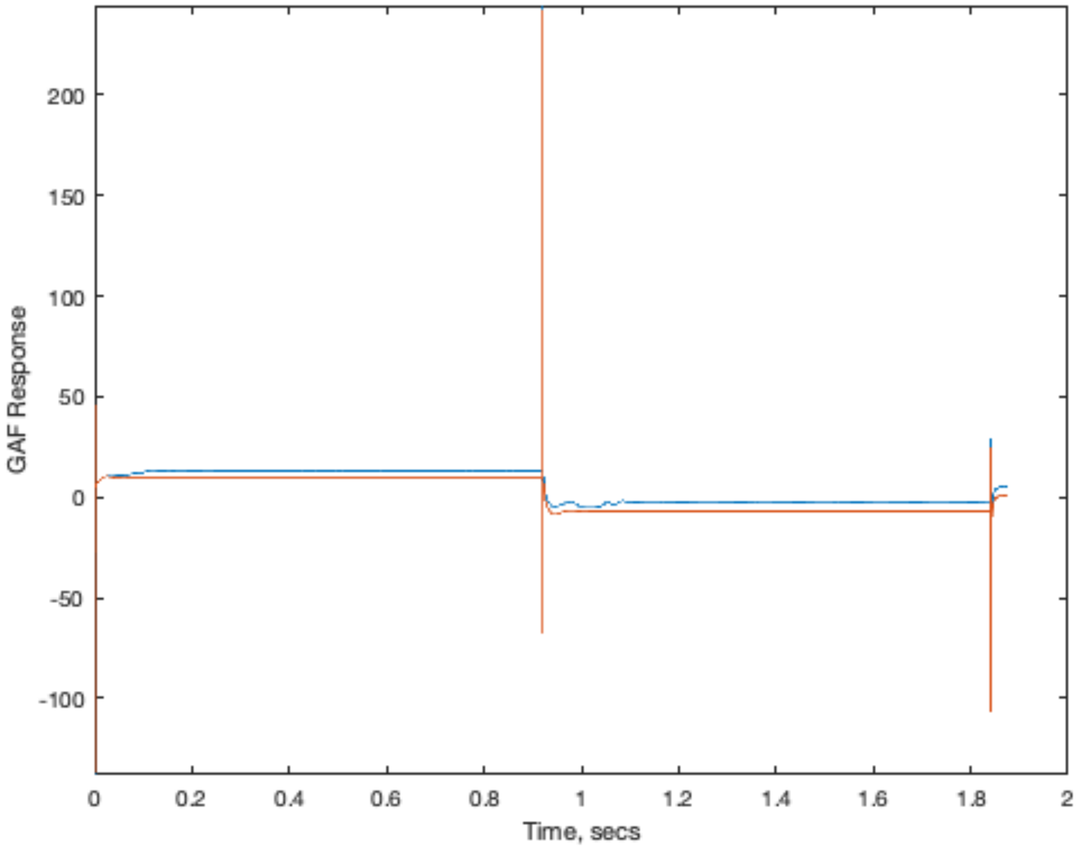
Q = 1.5 psi



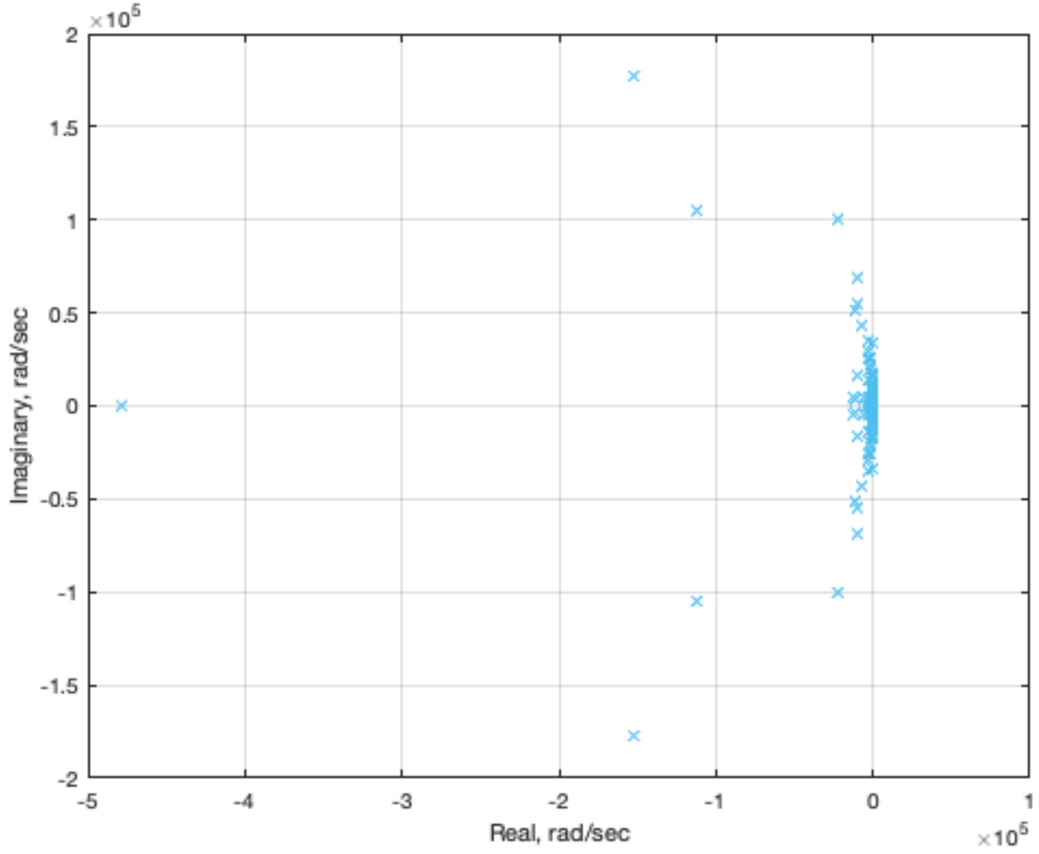
Alpha = 5 deg

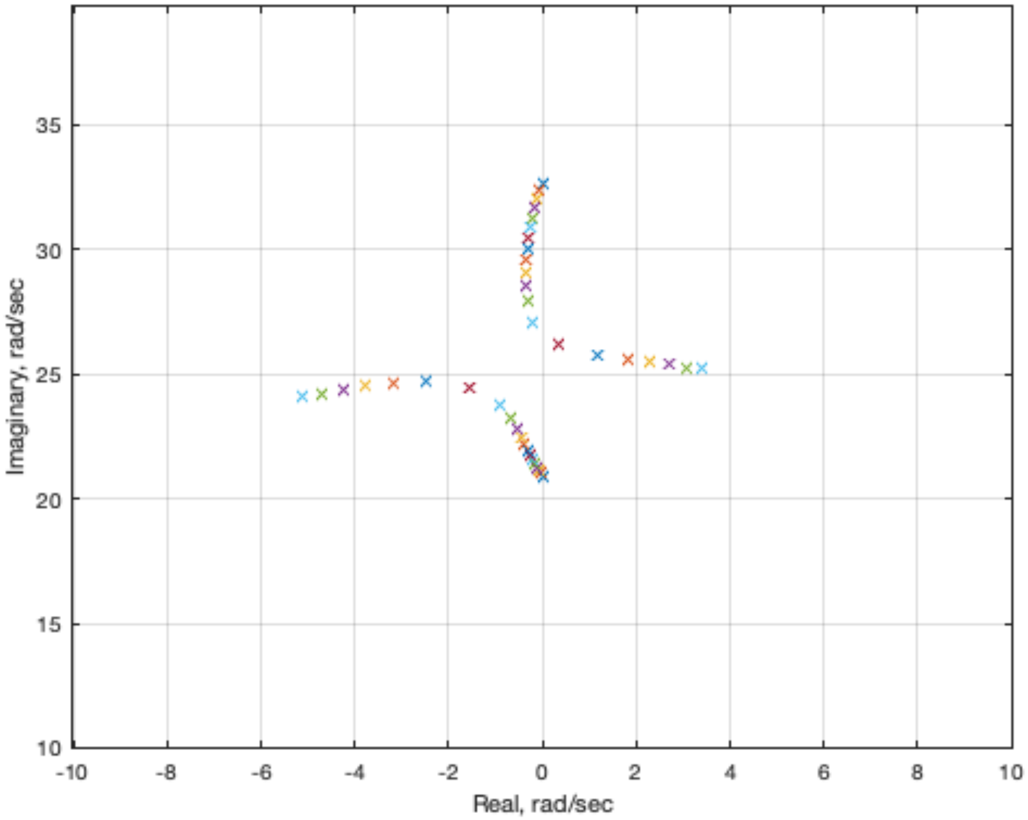
M8A5a – ROM/KESTREL GAFs





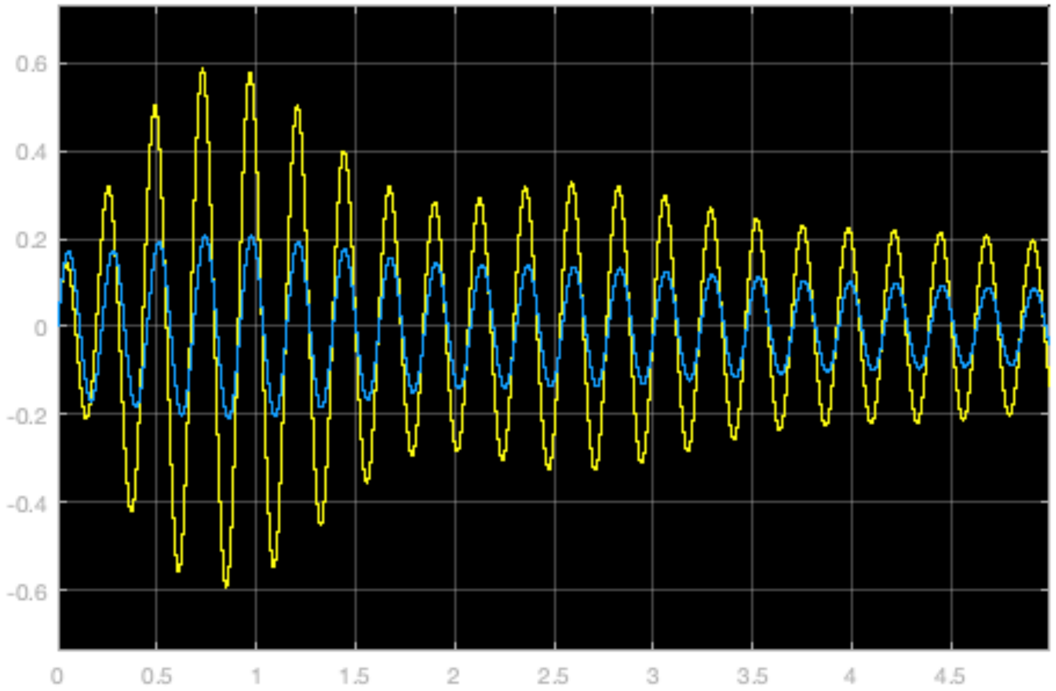
M8A5a – ROM/KESTREL Root Locus



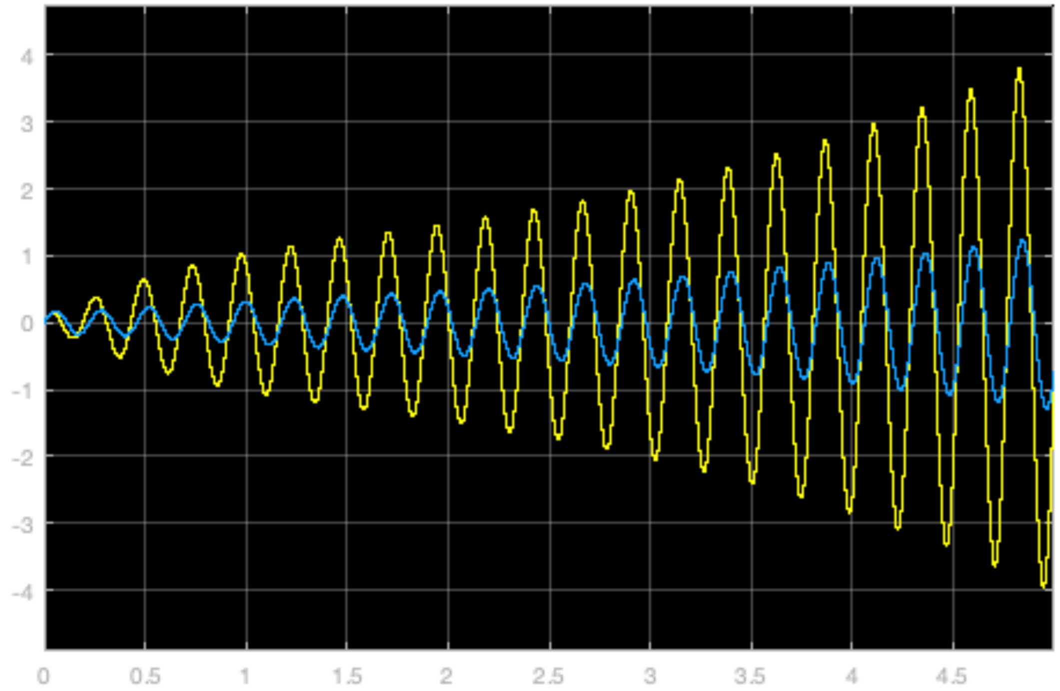


M8A5a – ROM Responses

Q = 1.2 psi



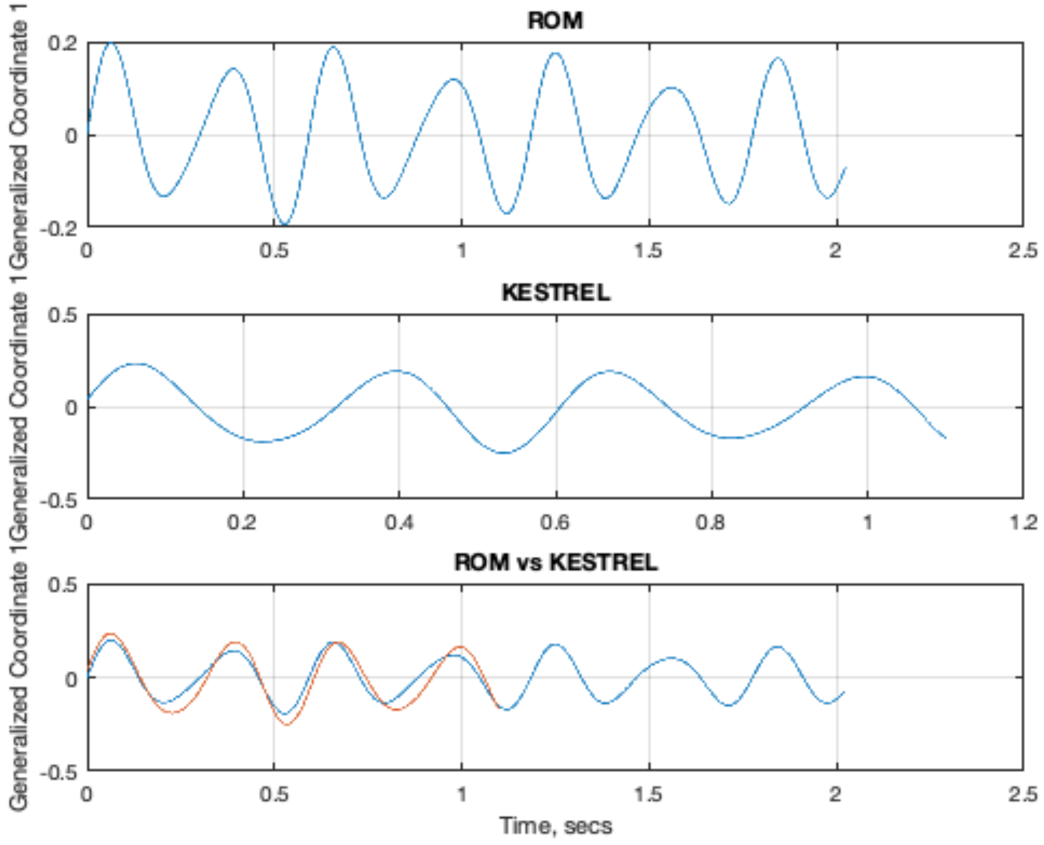
Q = 1.3 psi



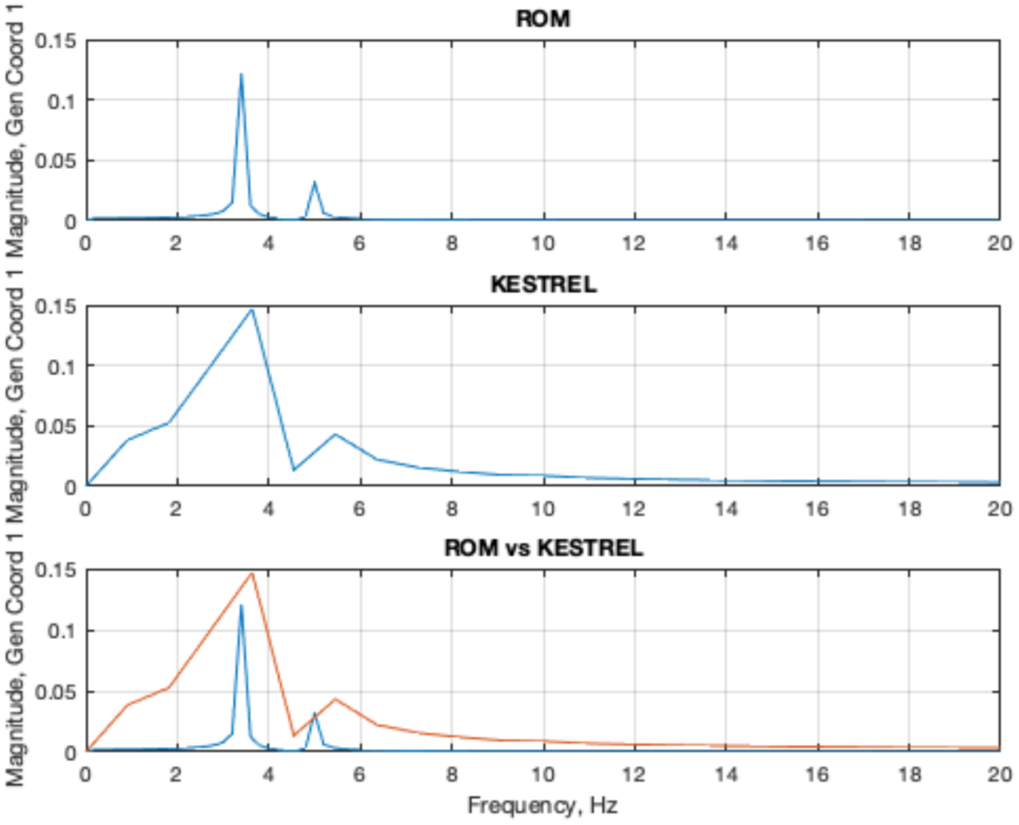
M8A5a – ROM and KESTREL Responses

Q = 50 psf, Mode 1

Time



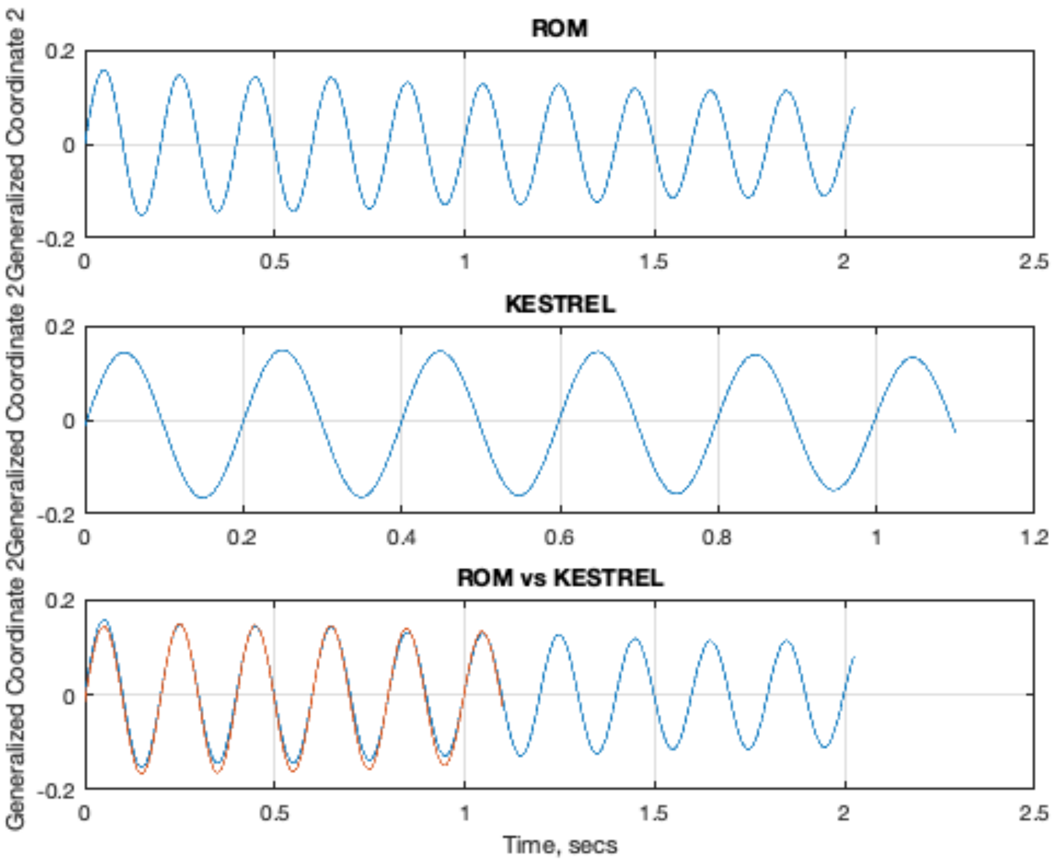
Frequency



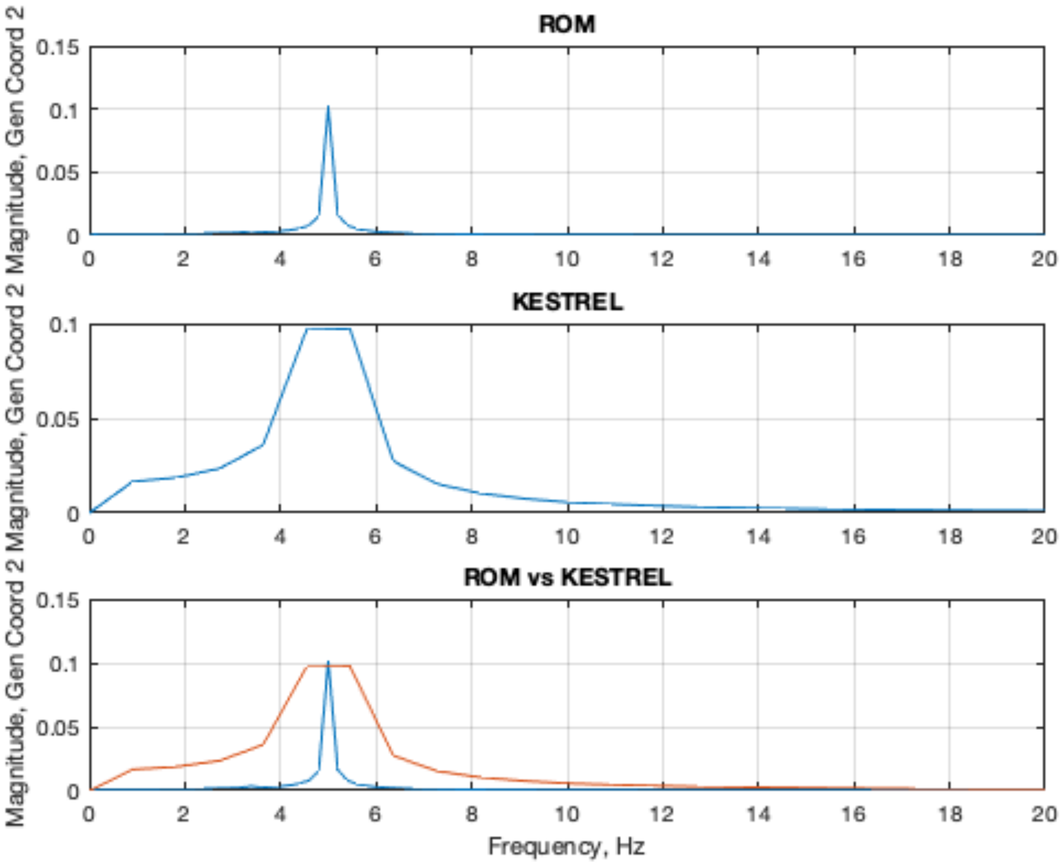
M8A5a – ROM and KESTREL Responses

Q = 50 psf, Mode 2

Time



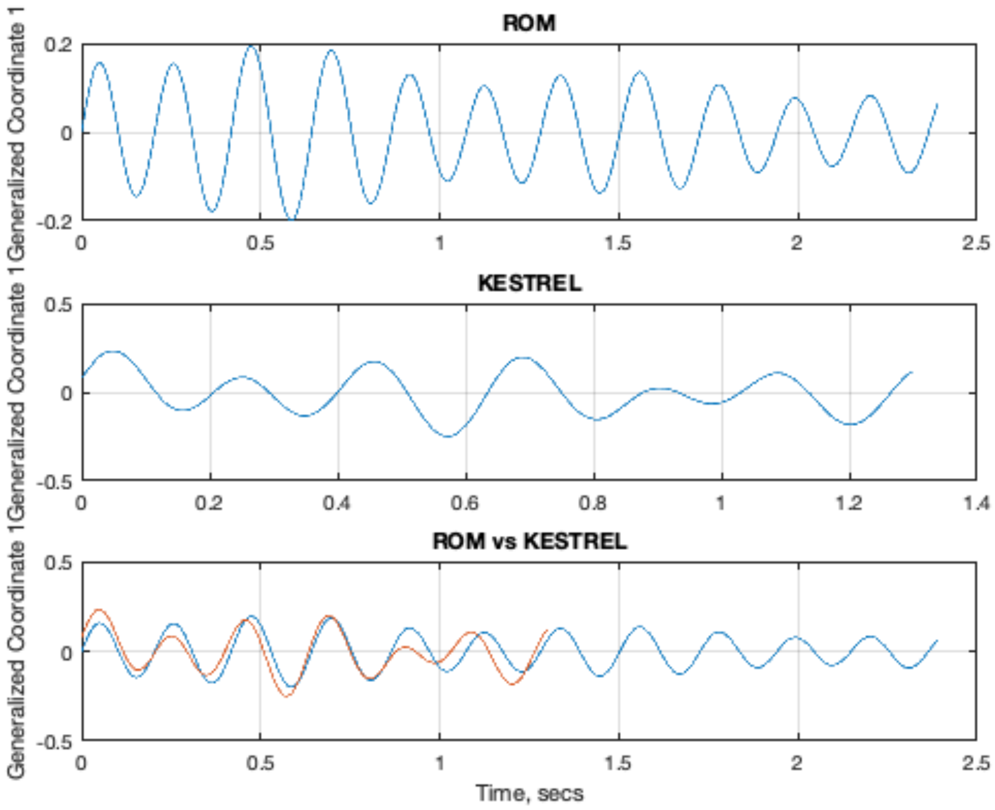
Frequency



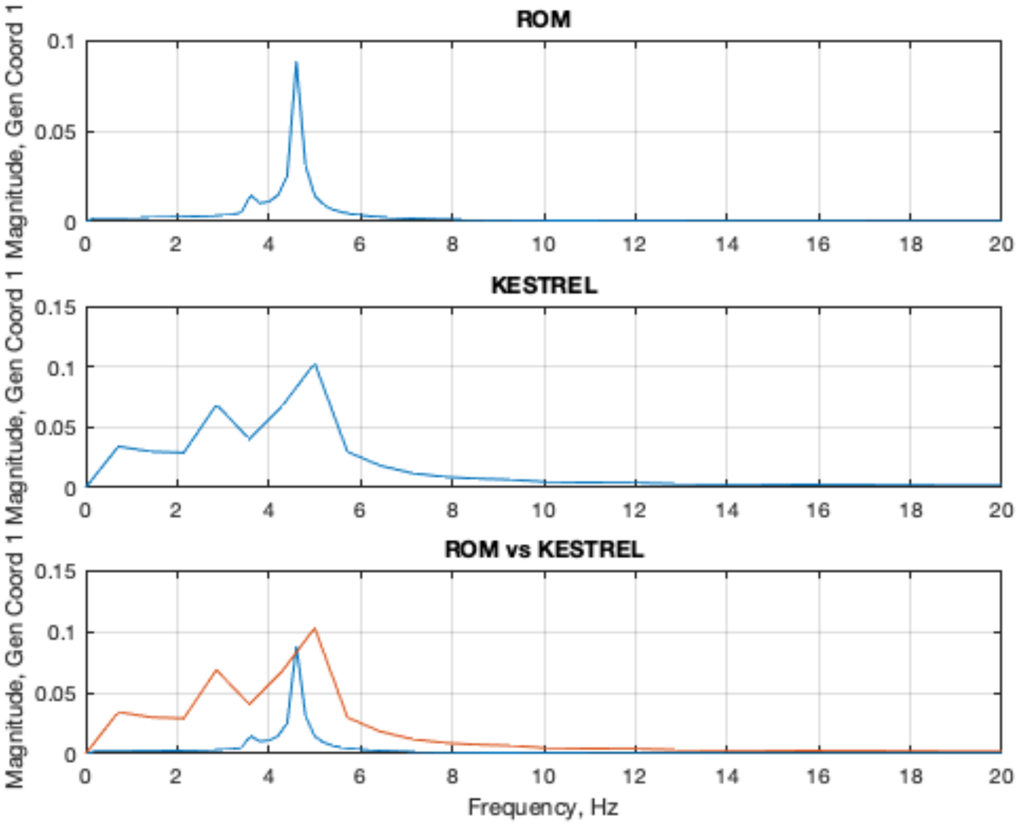
M8A5a – ROM and KESTREL Responses

Q = 130 psf, Mode 1

Time



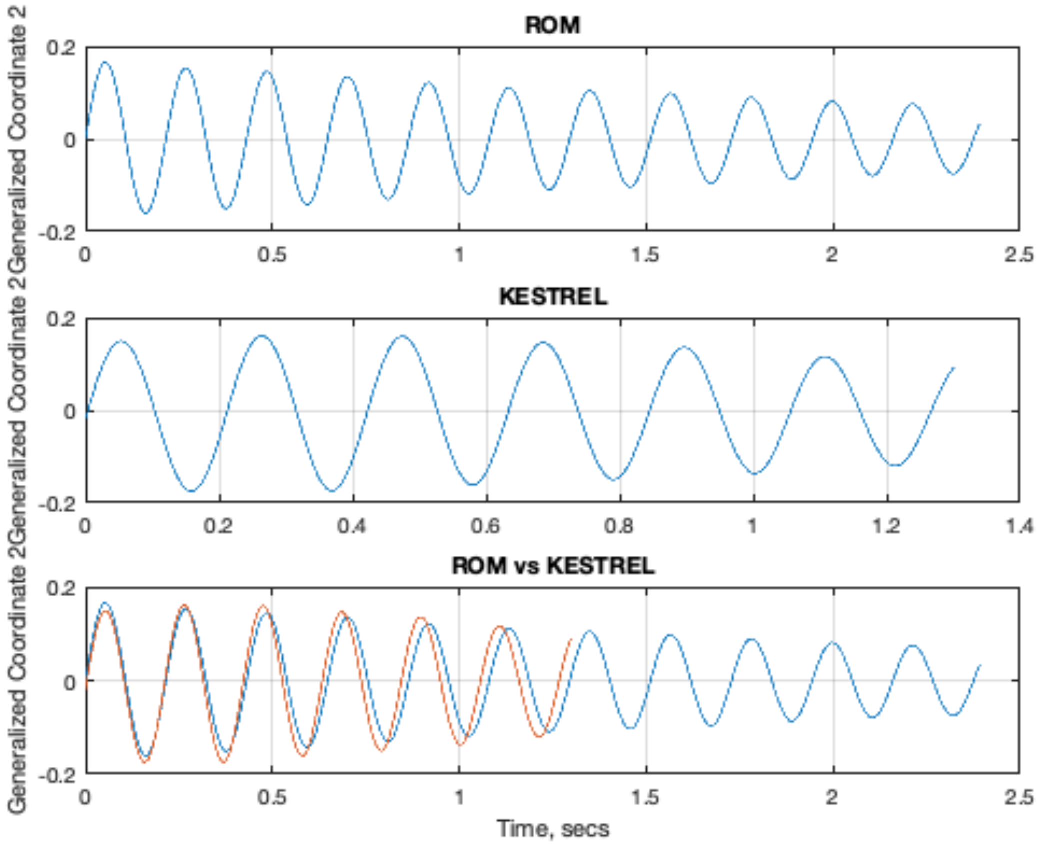
Frequency



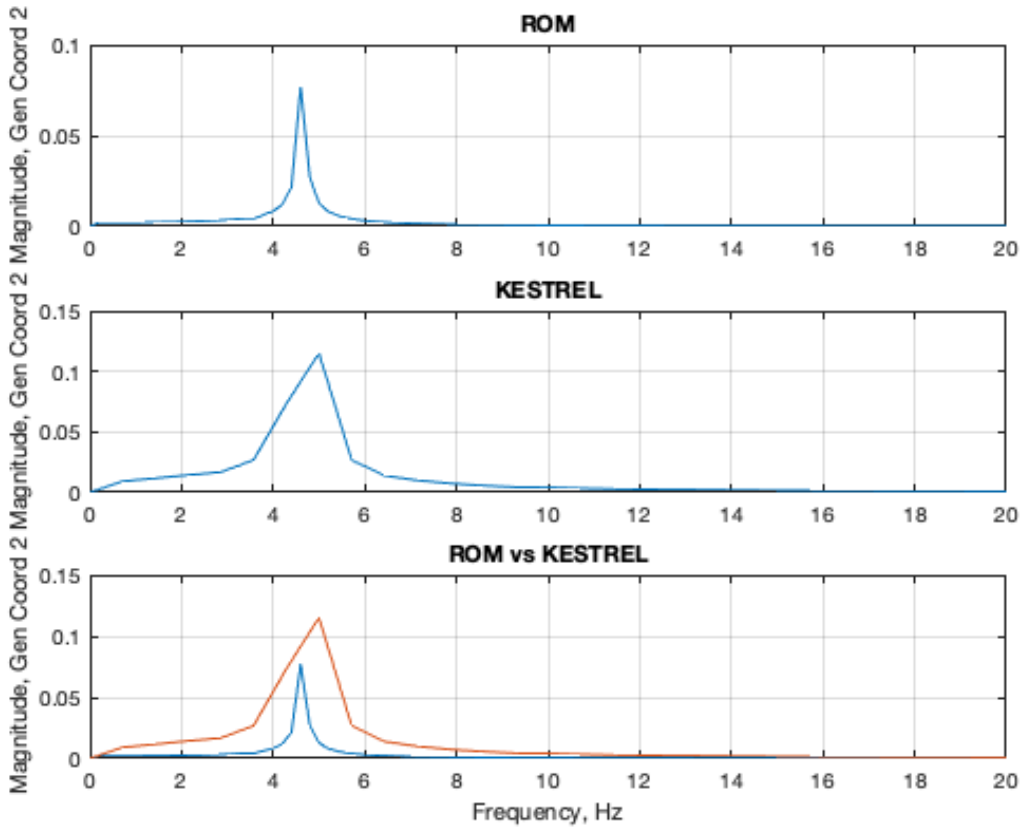
M8A5a – ROM and KESTREL Responses

Q = 130 psf, Mode 2

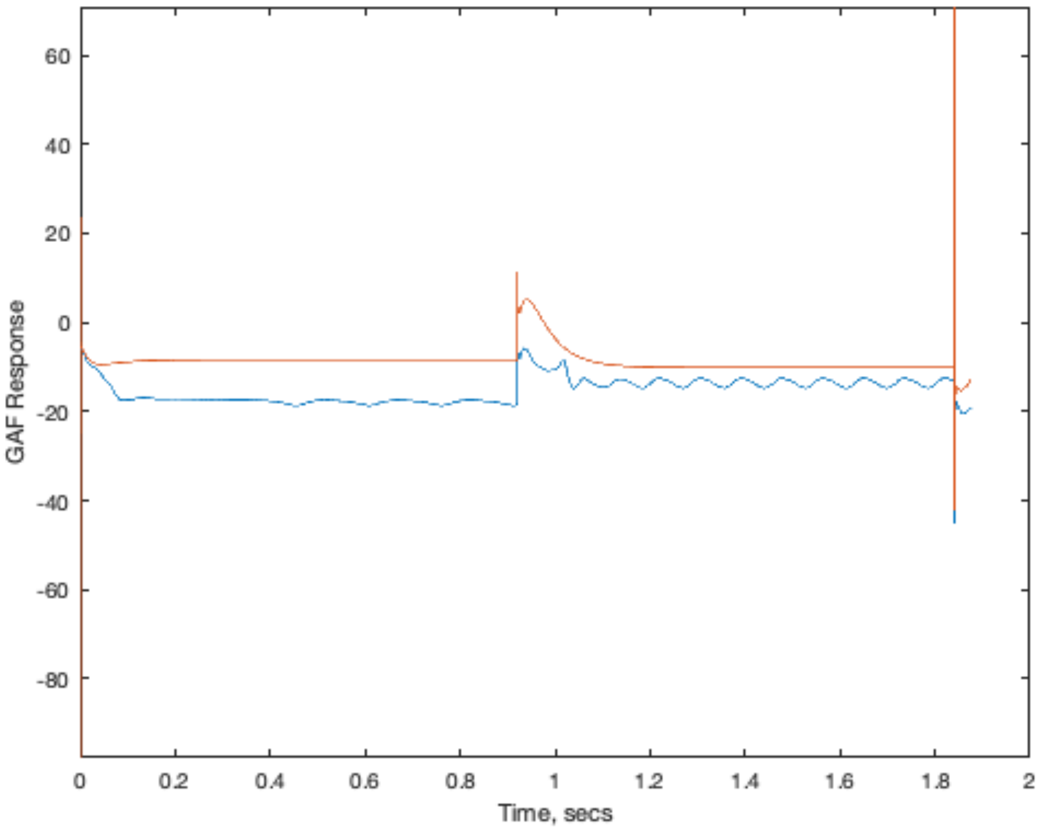
Time

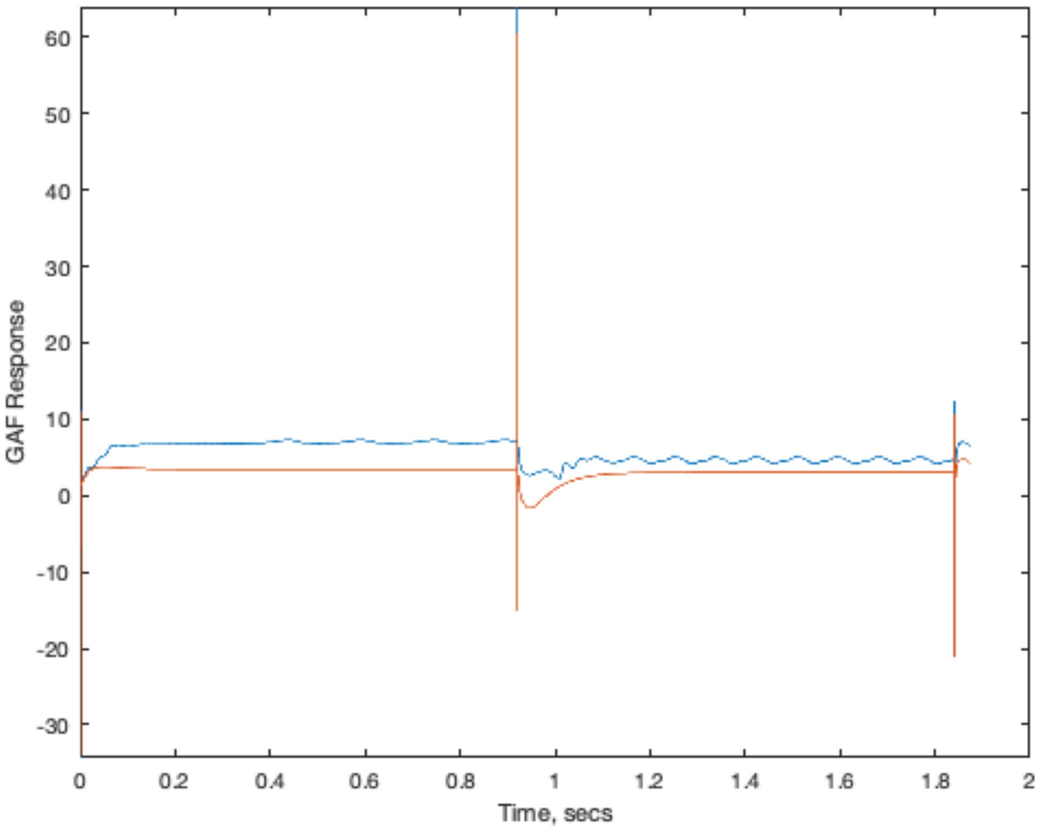


Frequency

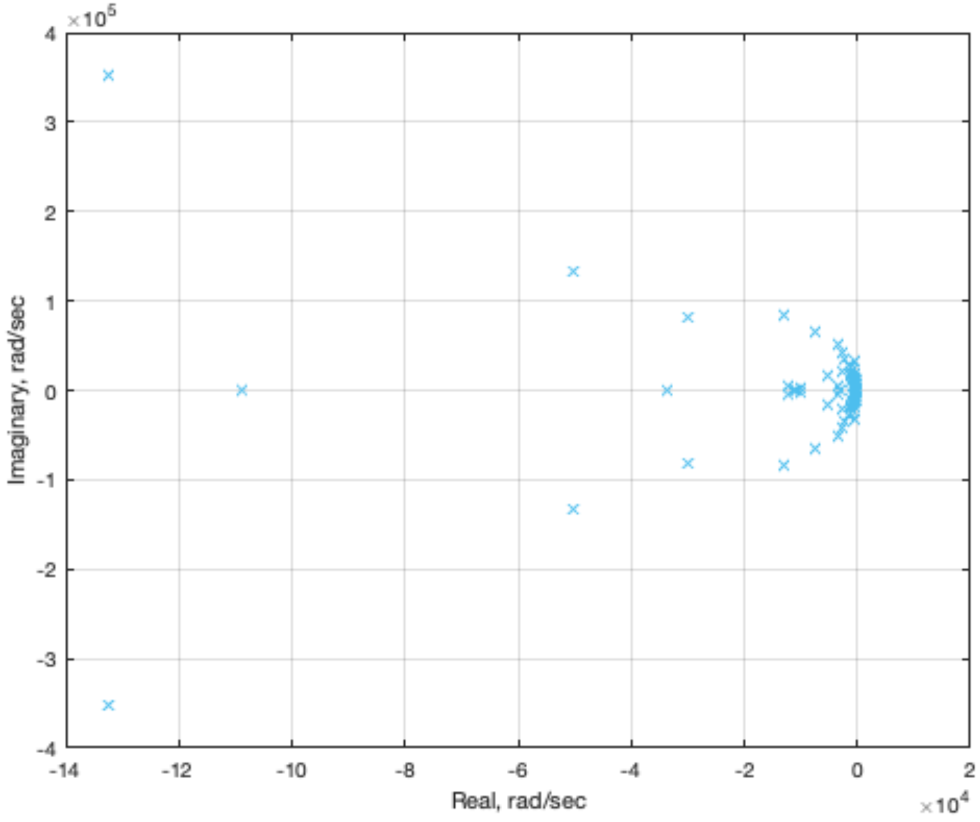


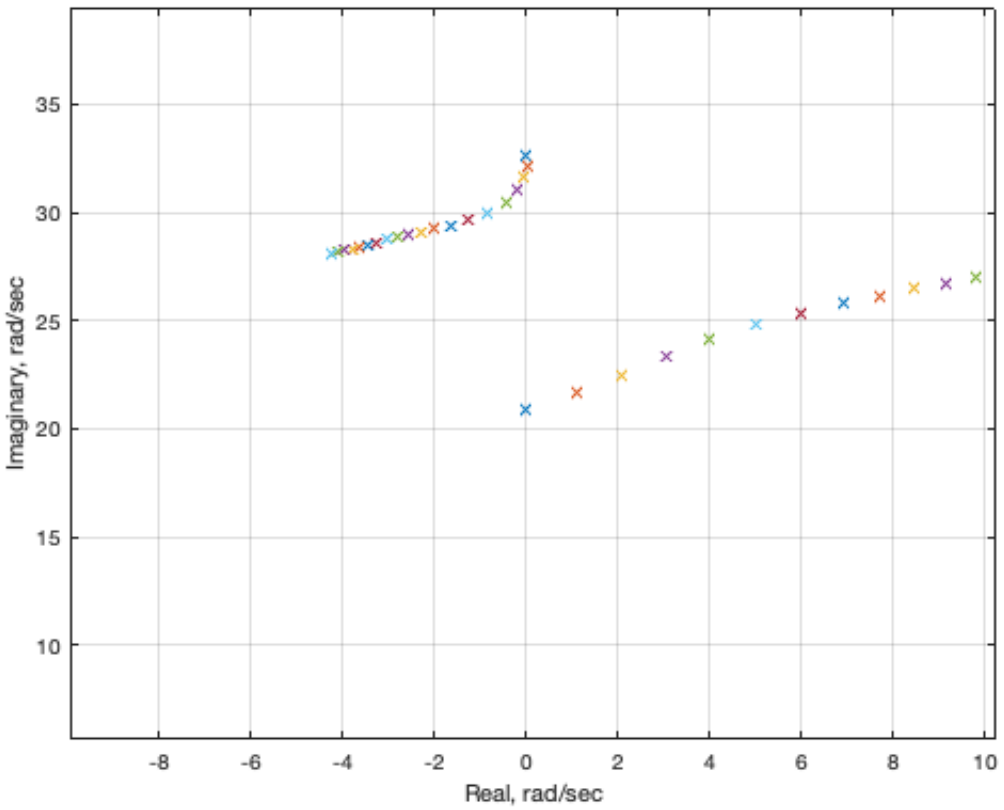
M8A5b – ROM/KESTREL GAFs





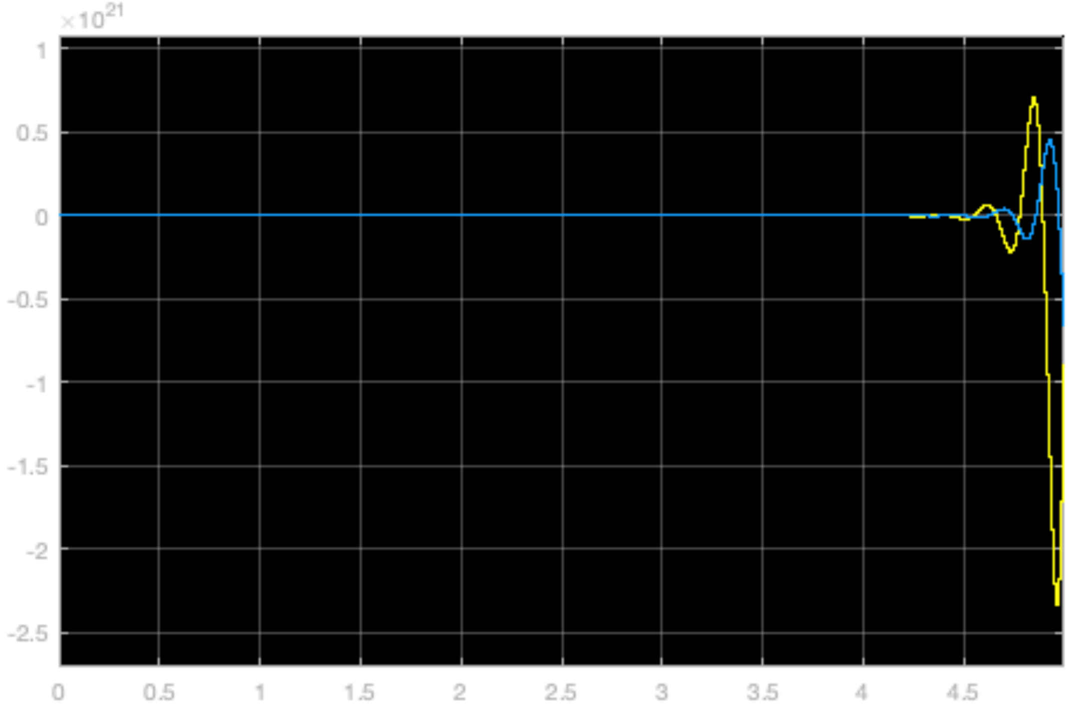
M8A5b – ROM/KESTREL Root Locus



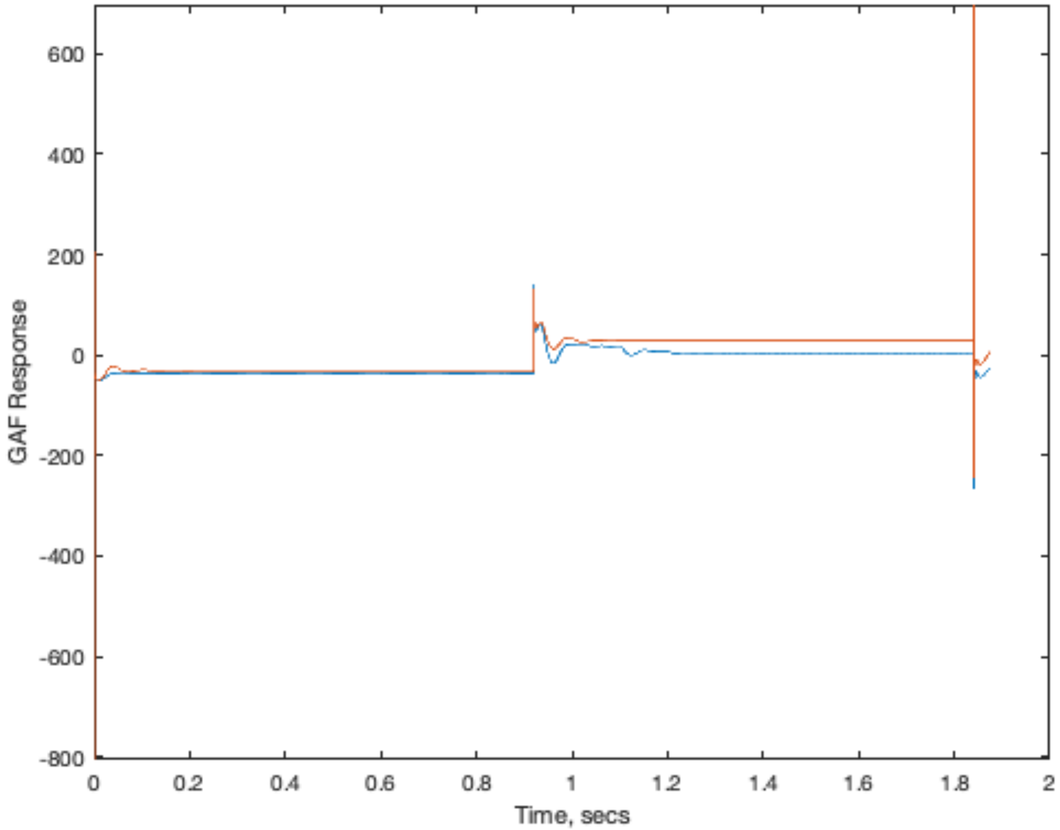


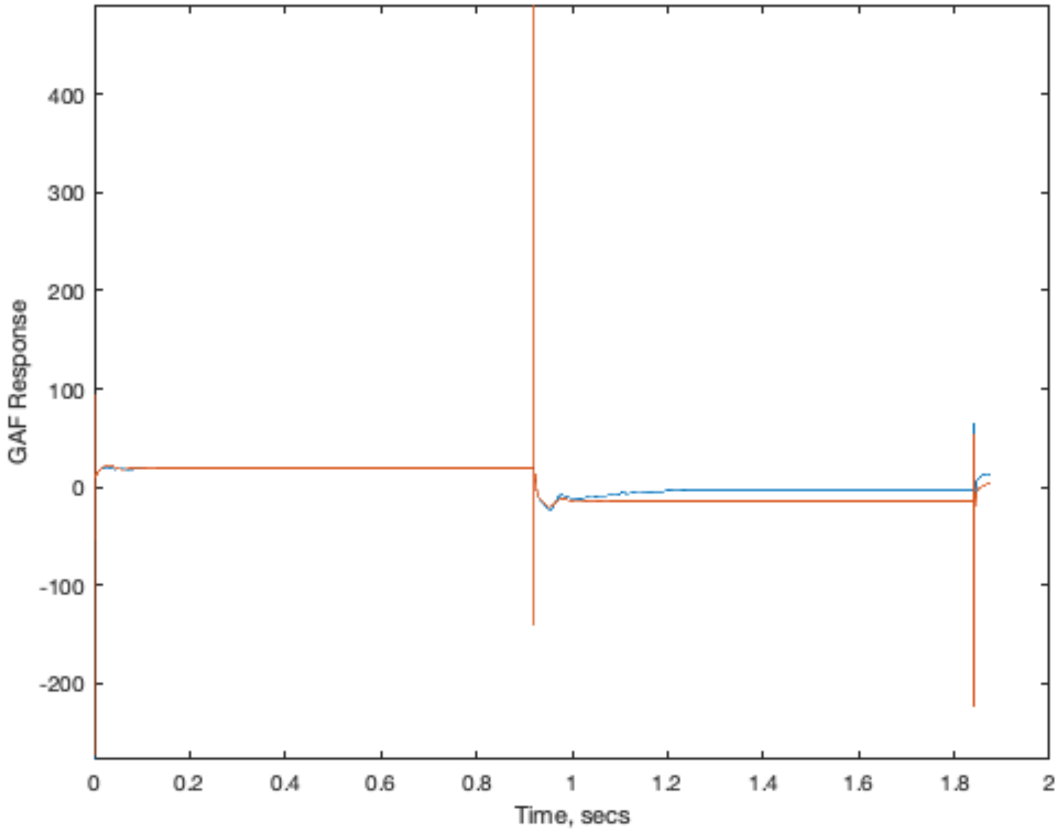
M8A5b – ROM Responses

Q = 1.2 psi

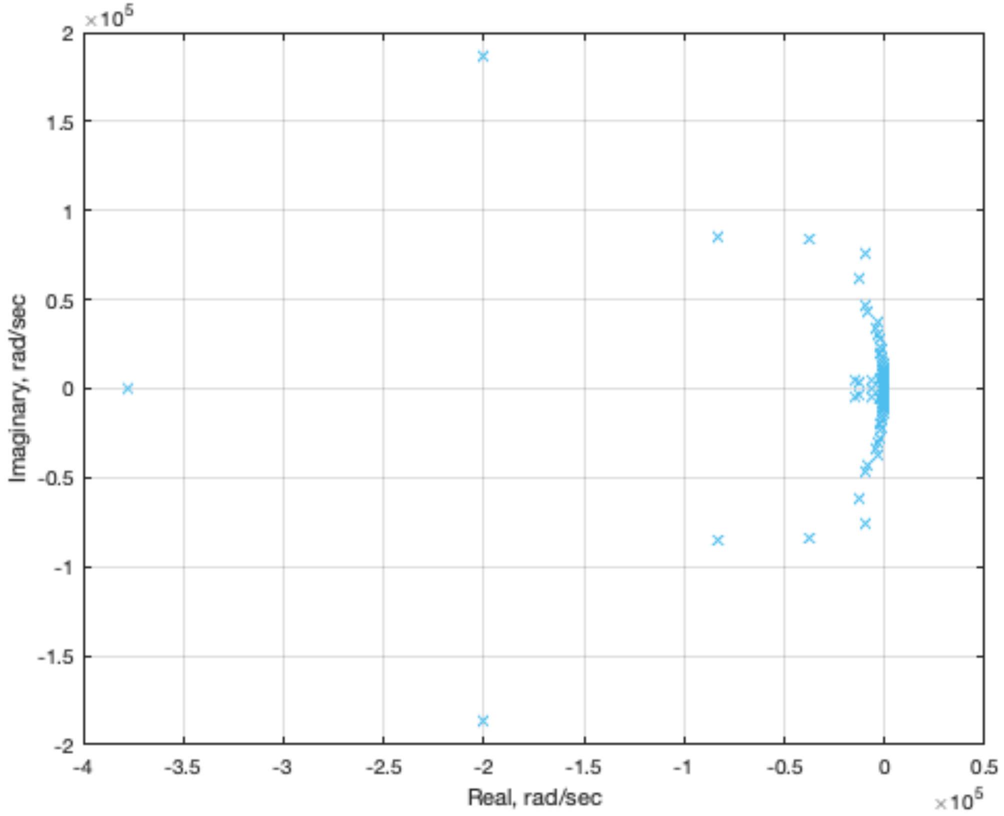


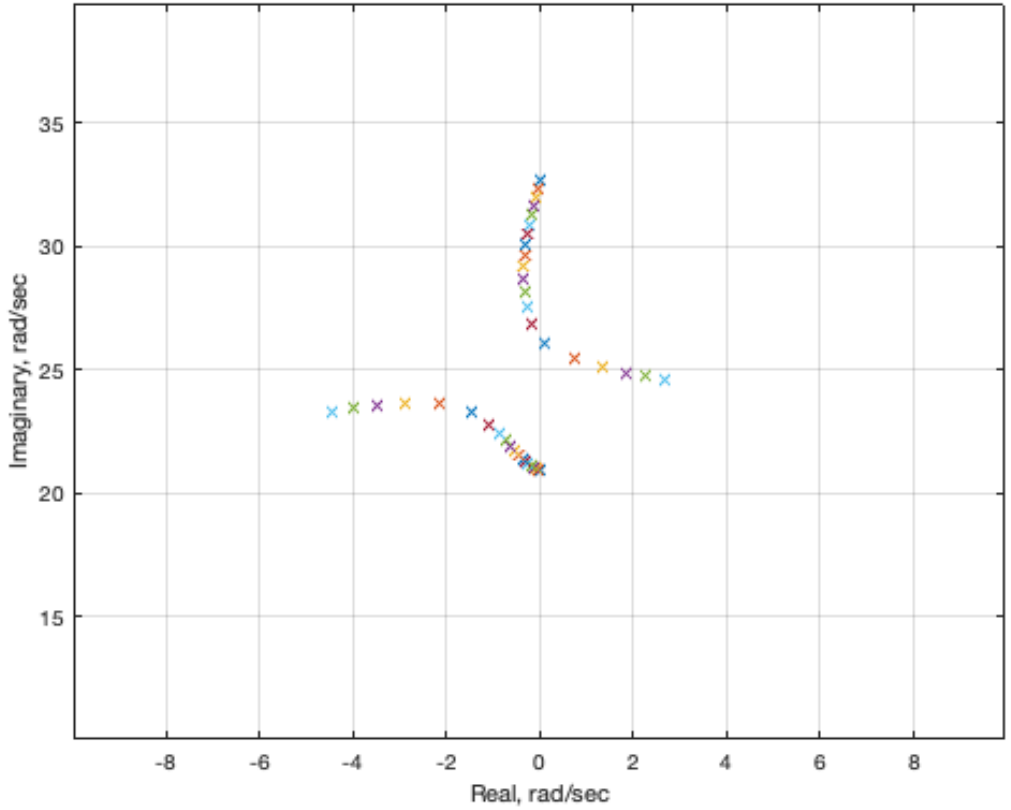
M8A5c – ROM/KESTREL GAFs





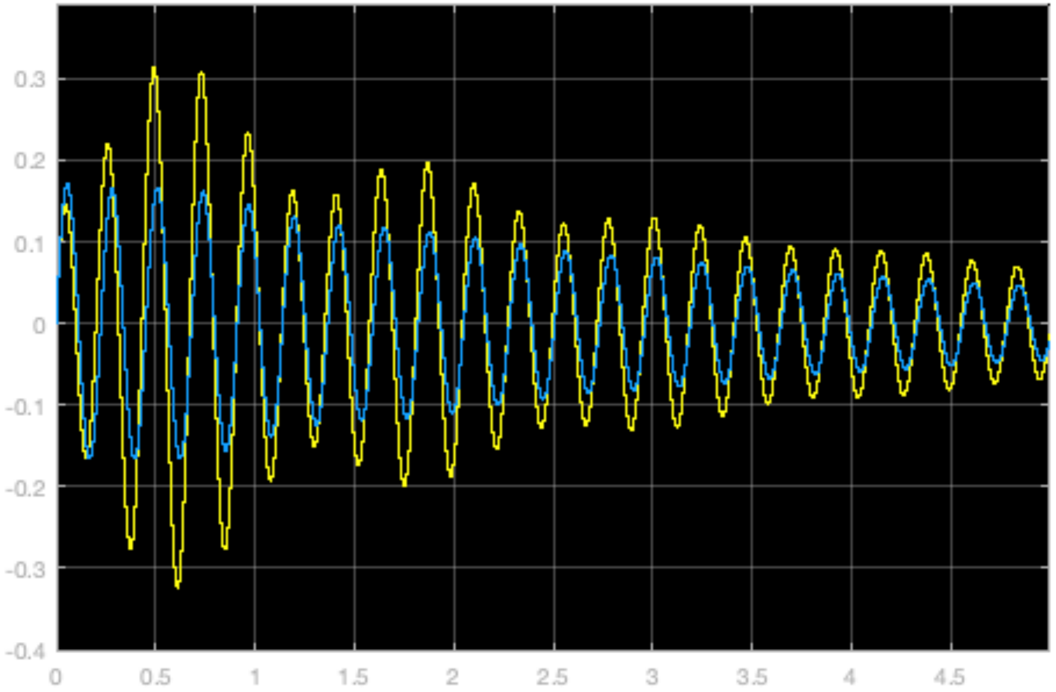
M8A5c – ROM/KESTREL Root Locus



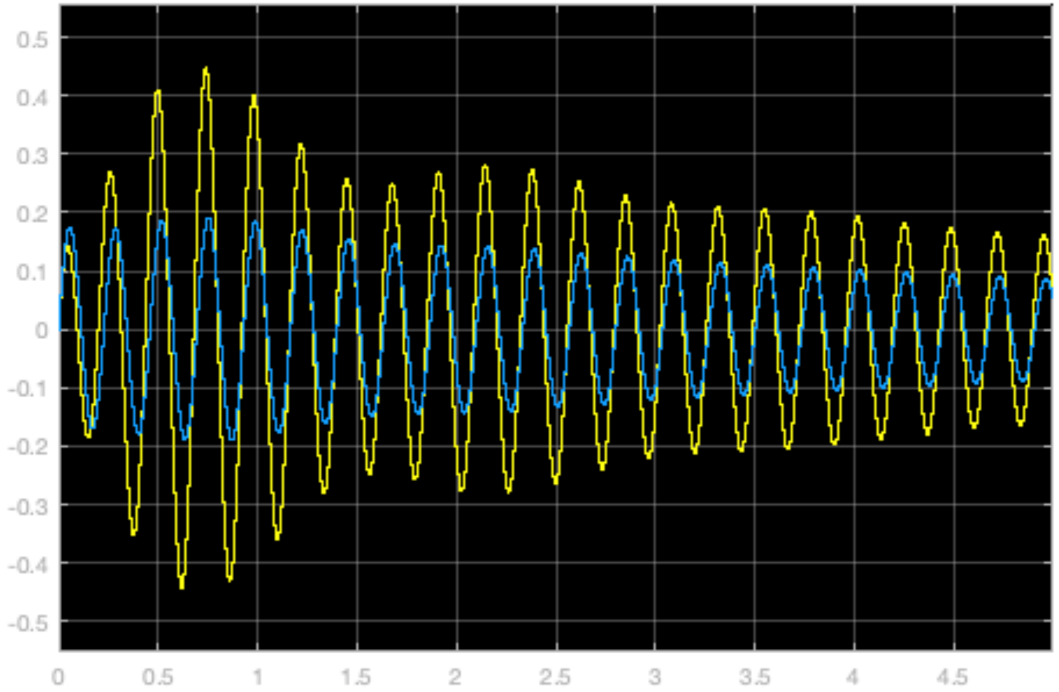


M8A5c – ROM Responses

Q = 1.2 psi

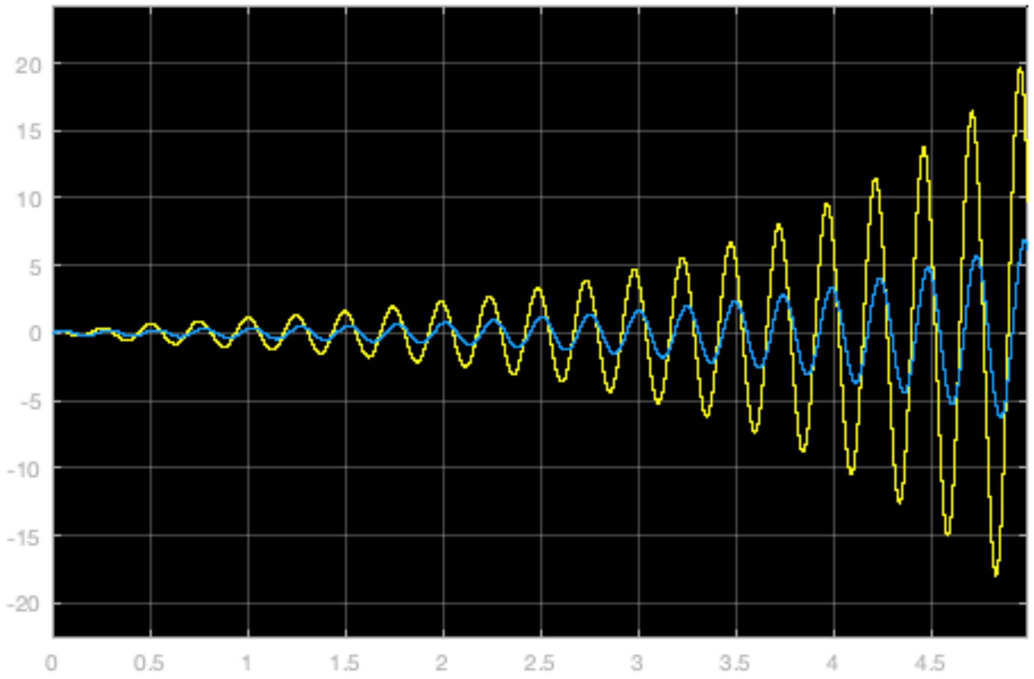


Q = 1.3 psi

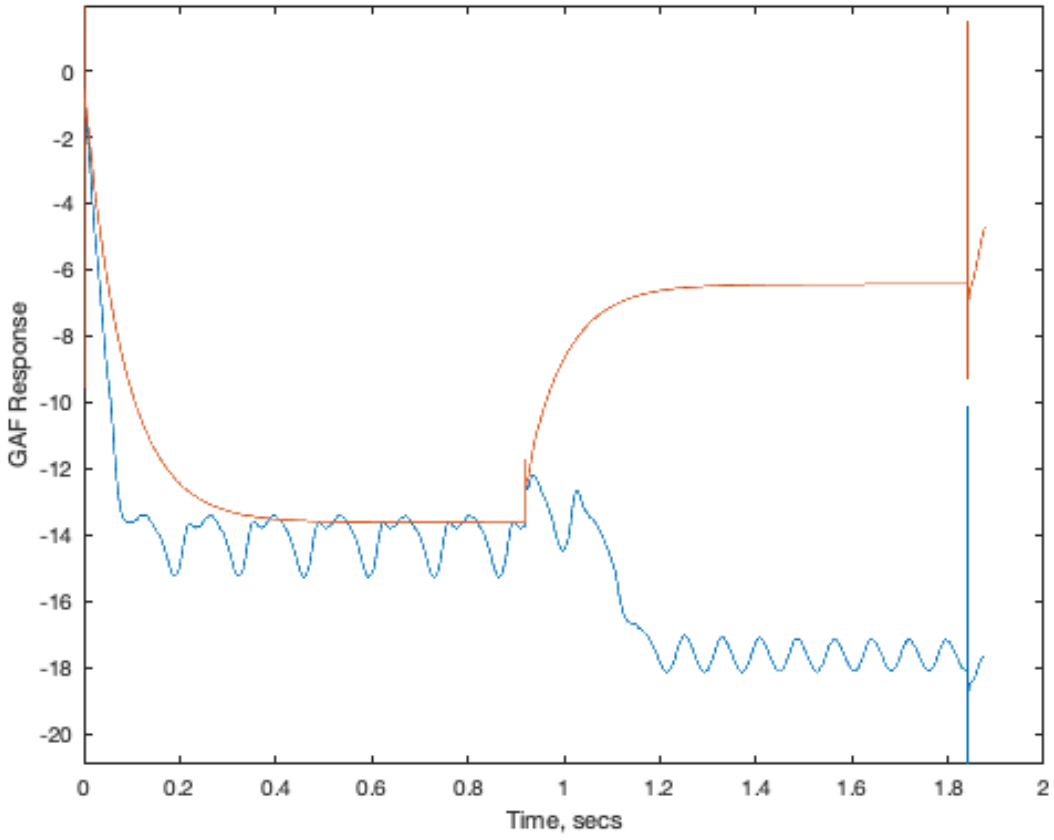


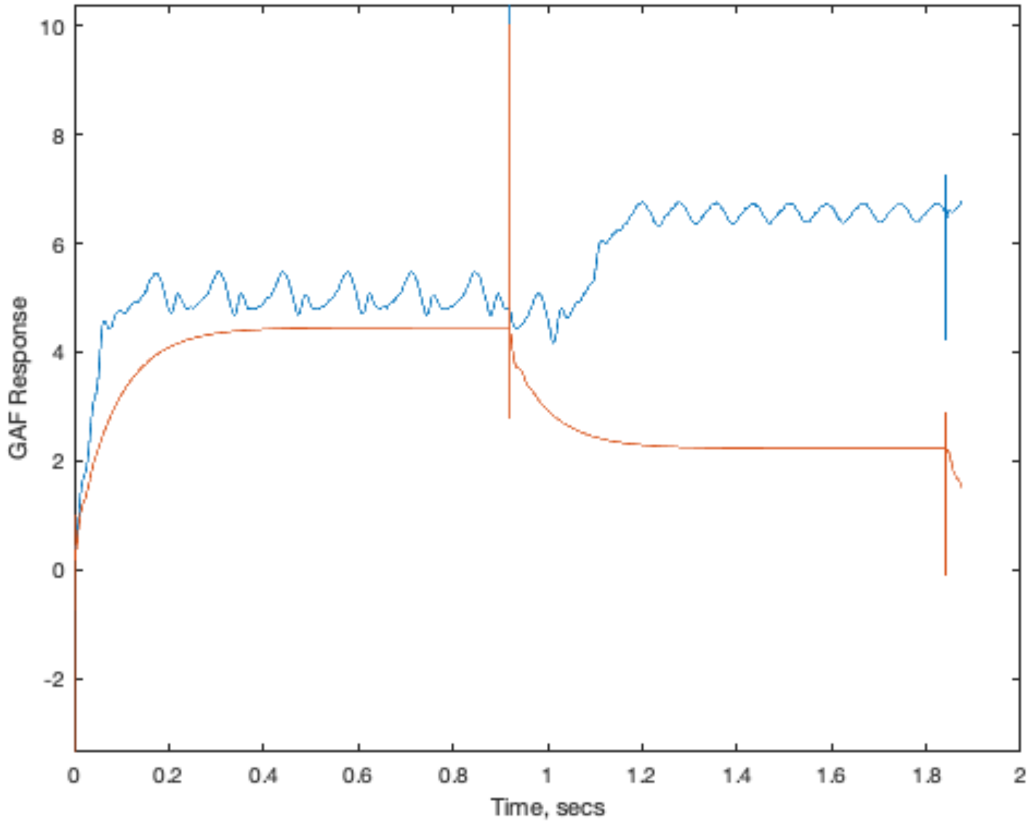
M8A5c – ROM Responses

Q = 1.5 psi

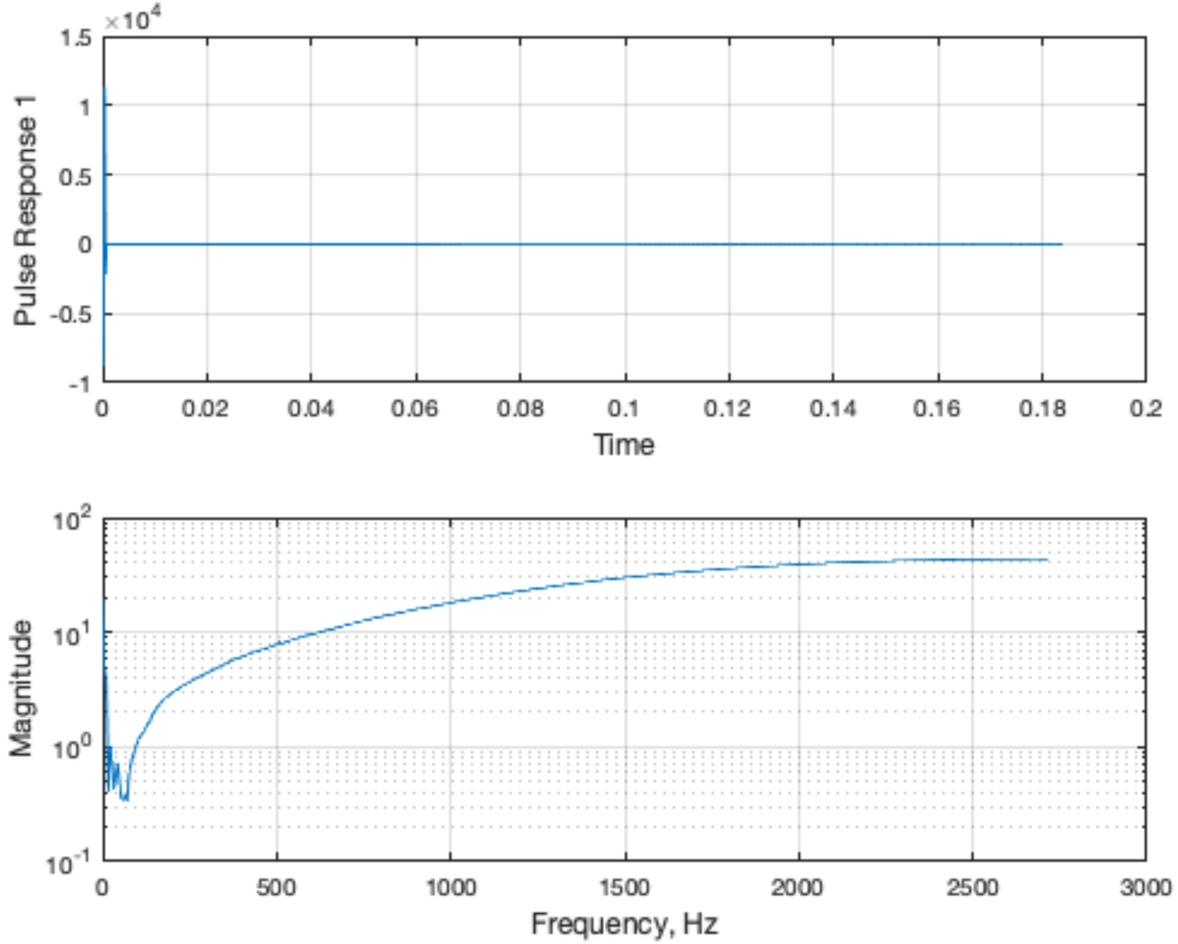


M8A5d – ROM/KESTREL GAFs

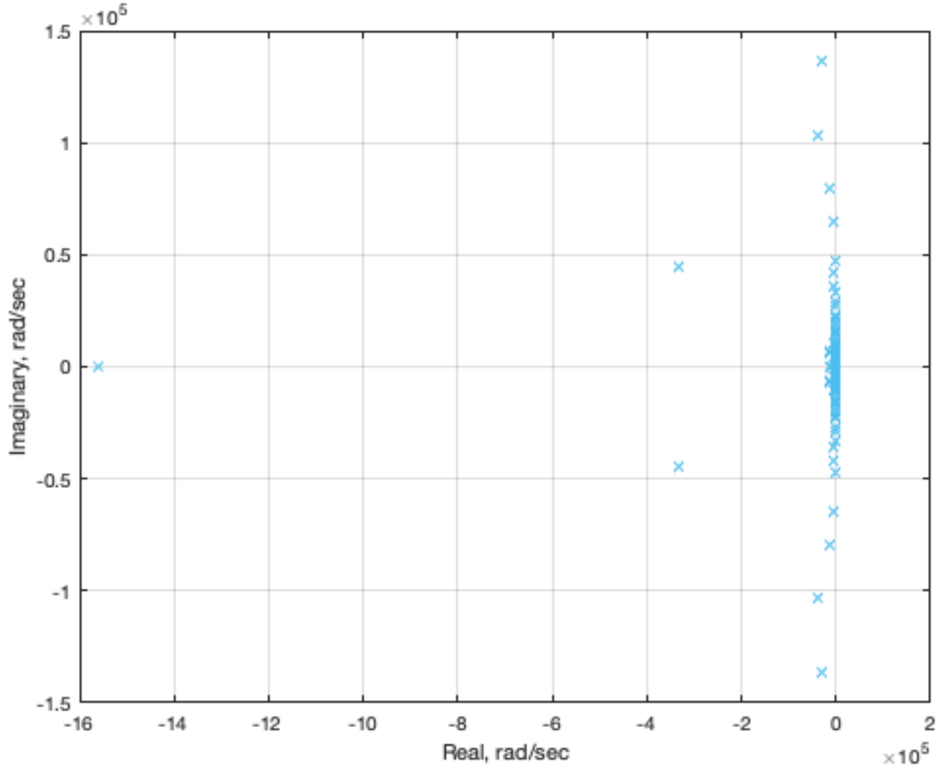


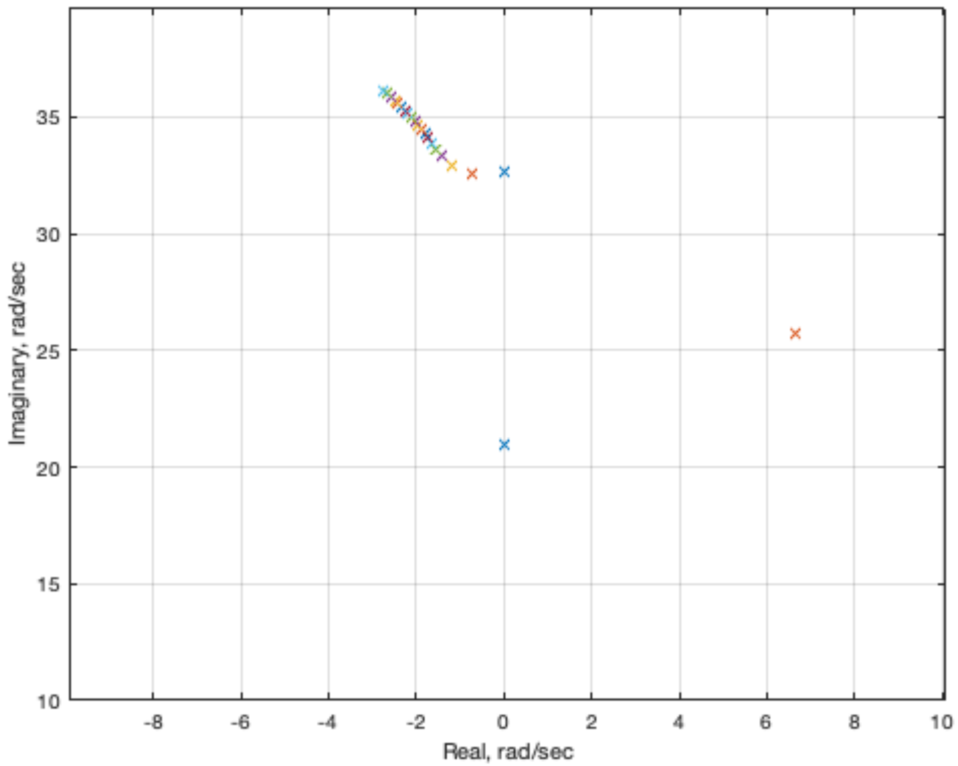


M8A5d – ROM/KESTREL GAFs



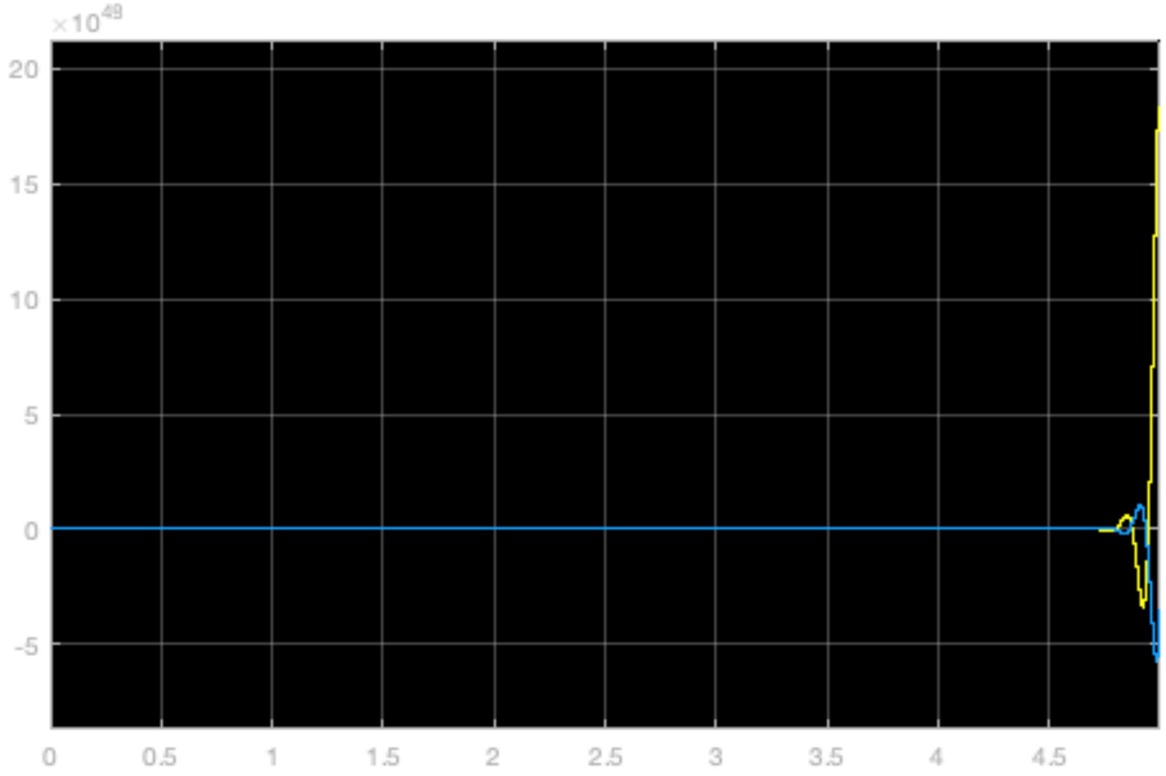
M8A5d – ROM/KESTREL Root Locus





M8A5d – ROM Responses

Q = 1.2 psi



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 start analyses at M=0.85, similar alpha ranges.