Simulation of Structural Health Monitoring of a 1U CubeSat

Ian Pylkkanen Master of Engineering Final Presentation

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Introduction

- Overview of Project
- Background
- State of the Art
- Method of Approach
- Results
- Conclusion and Future Steps

Overview of Project

- Performed a simulation of Structural Health Monitoring (SHM) on a 1U CubeSat under launch loads and random vibration
- Goals:
  - Validate the structural integrity of the CubeSat
  - Validate this method as a means to simulate a SHM experiment
  - Understand the process of SHM and how to perform meaningful experiments and analysis

Background

- CubeSats are a class of nanosatellites with standardized sizes
  - 1U: 10x10x10cm

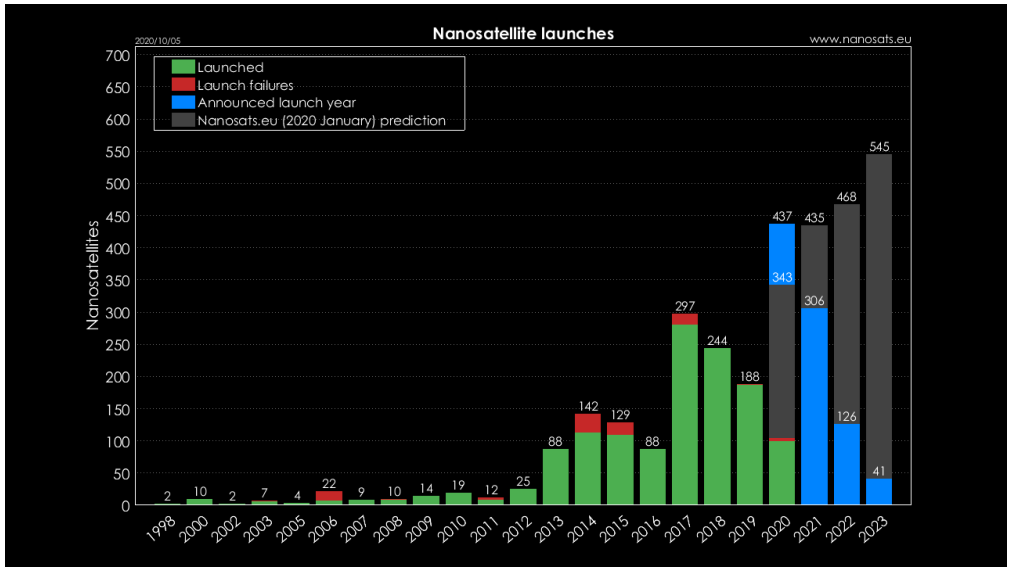
1U CubeSat in Orbit

- Extremely cost effective way to launch satellites
  - Mostly used for science missions, earth observation, and radio
- Growing industry
  - Constellations of CubeSats are being launched to expand capabilities
    - i.e. SpaceX's Starlink (slightly larger than CubeSat but similar idea)

State of the Art

State of the Art

- As of October 4, 2020: 1302 CubeSats launched worldwide since 1998 [1]
  - Anticipated 2500 nanosats to launch in next 6 years
- A comprehensive survey conducted in 2017 found CubeSats to be highly capable of meeting the demands of satellites
  - Major companies manufacturing structures: Pumpkin, ISIS, Radius Space, Clyde Space, Blue Canyon Technologies, Tyvak [2]
- In 2012 a group from Bolgna University showed promising results in plastic CubeSats [3]



Nanosat Launches 1998-2023(estimated) [1]

State of the Art

- Group from University of Patras successfully launched a 2U CubeSat made of Carbon Fiber Reinforced Plastic (CFRP) composite [4]
  - Launched in 2017
- A study performed in November 2020 compared the results of an FEA simulation to a real vibration test [5]
  - They found the FEA model accurately represented the system and captured 8/11 mode shapes
  - They determined that a highly detailed FEA model yielded better results than a highly simplified one, but at a higher computational cost

State of the Art

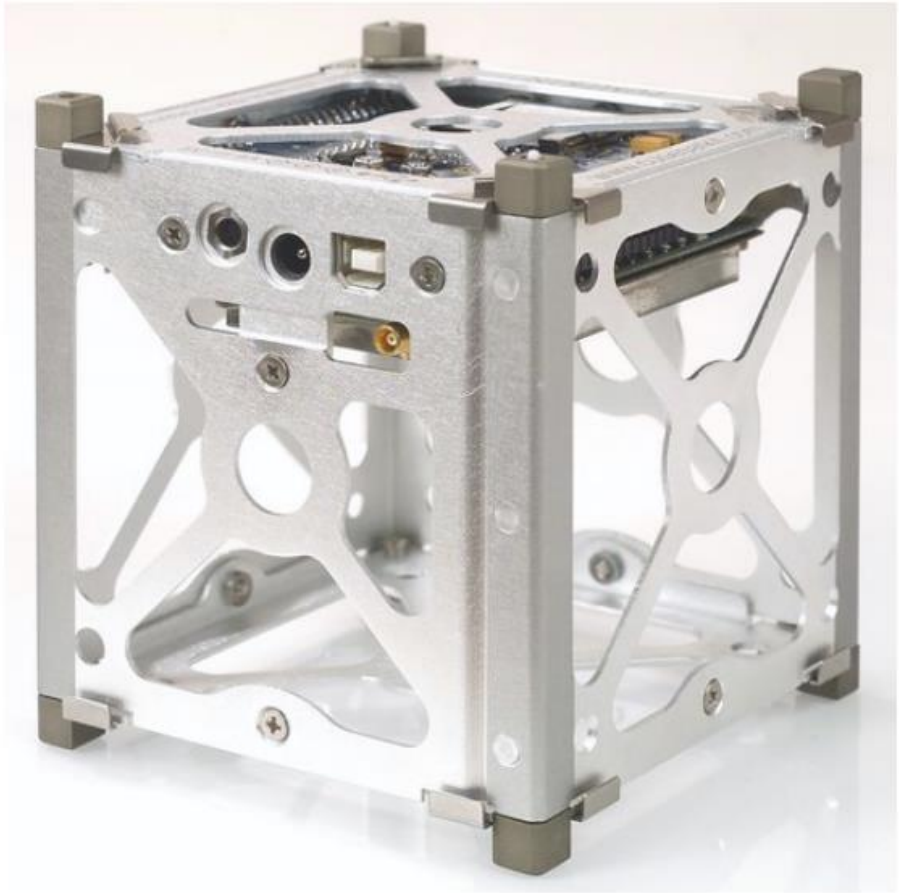
- Results for this project were compared to those done by a team at Istanbul Technical University [6]
  - FEA modal analysis and static load simulations were done on the same Pumpkin 1U CubeSat

- For more information on the state of the art of CubeSat research, the reader is encouraged to visit any of the references listed at the end of the presentation.

Method Of Approach

CubeSat Analyzed

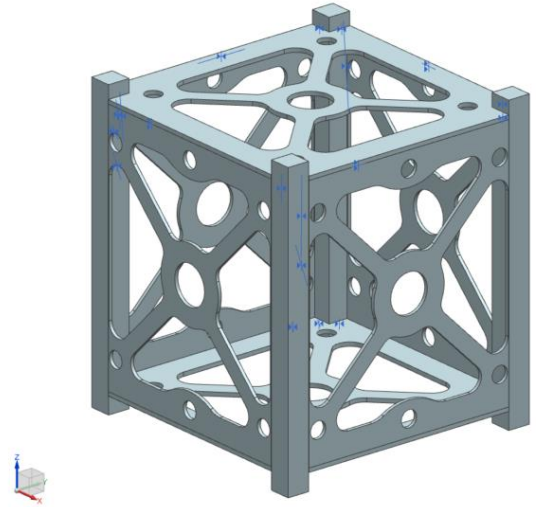
- Pumpkin Space Inc. 1U CubeSat
  - 4 skeletonized chassis walls
  - Base plate
  - Cover plate
- Originally was going to perform random vibration tests in lab, but due to COVID-19, simulations in NX were performed instead



Pumpkin 1U CubeSat

Model

- Model was created using the dimensions provided by Pumpkin Space
  - Simplified geometry
  - Dimensions on next slide
- Materials:
  - Chassis, Cover plate, Base plate: Al 5052-H32
  - Legs: Al 6061

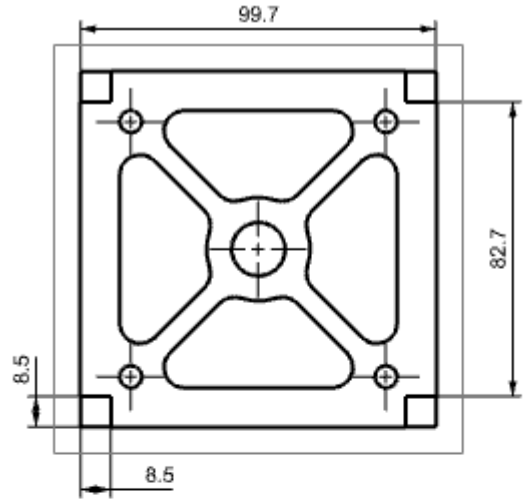


CAD Model

Material Properties

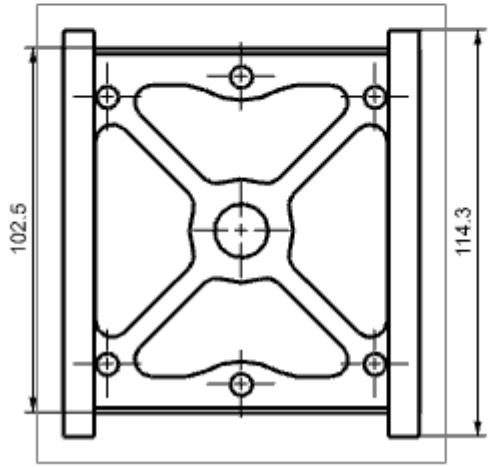
Property	Al 5052-H32	Al 6061
Density	2.68 g/cm^2	2.70 g/cm^2
Young's Modulus	70.3 GPa	68.9 GPa
Yield Strength	193 Mpa	276 MPa
Ultimate Strength	228 MPa	310 MPa

Model Dimensions



Top/Bottom Plate Thickness: 1.524 mm
Side Plate Thickness: 1.27 mm
ALL DIMENSIONS IN MM

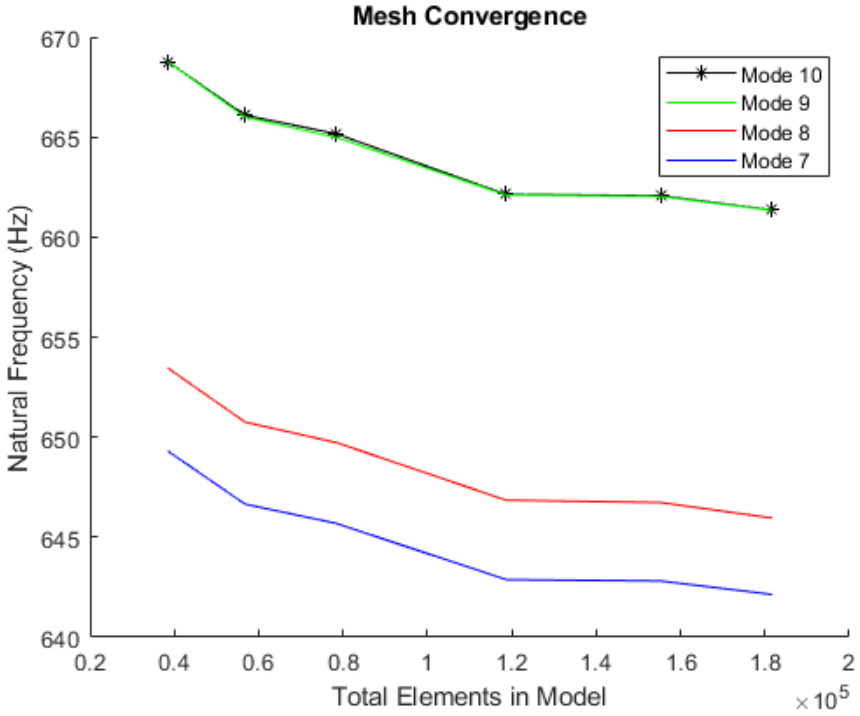
TOP VIEW



SIDE VIEW

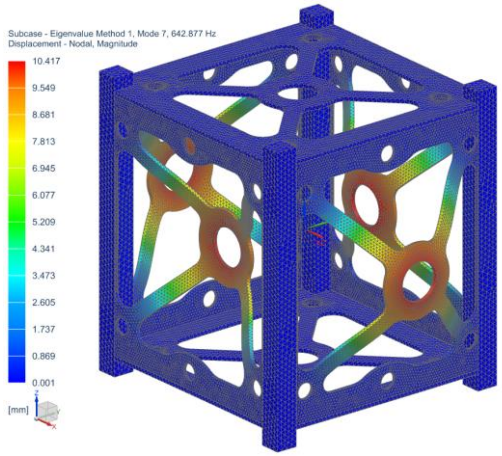
Mesh Convergence

- Mesh Convergence study performed using modal analysis
  - Optimal Number of Elements found to be about 120,000 elements
    - Computation time ~ 2.5 min
  - 3D Tetrahedral mesh
- Total Number of Elements: 188,658

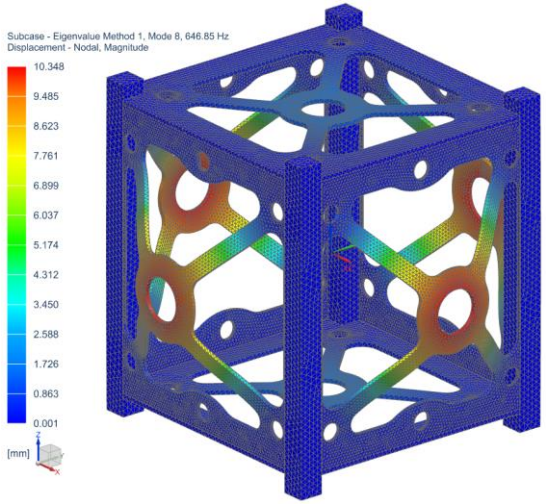


Component	Element Size (mm)
Chassis Walls	1.195
Cover Plate	1.68
Base Plate	1.68
Legs	2.083

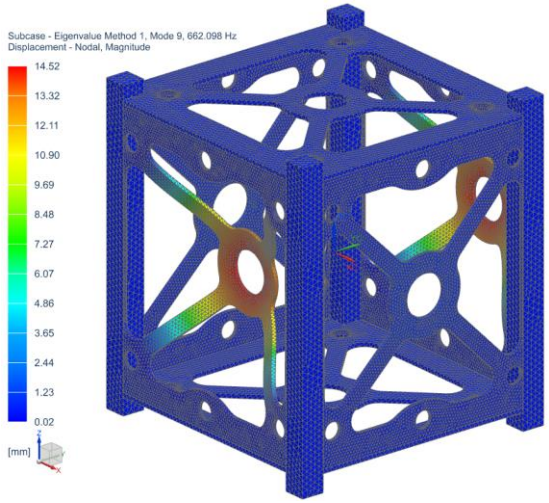
Modal Analysis



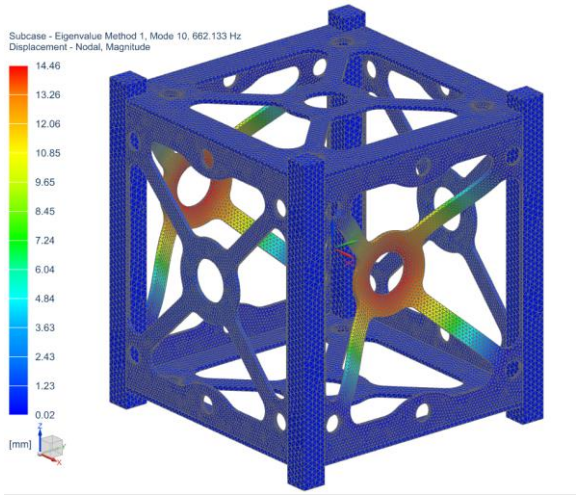
Mode 7
$\omega_n = 644.46\ Hz$



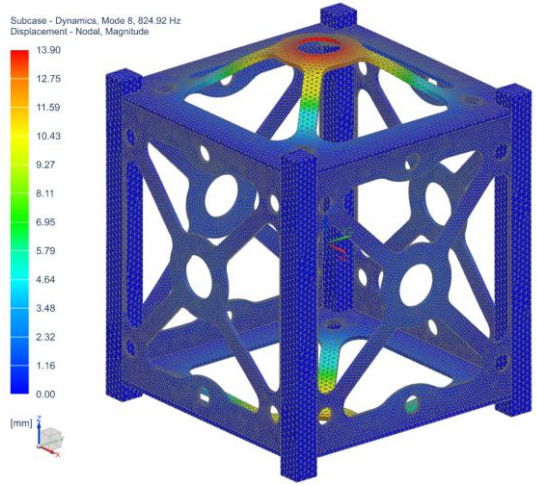
Mode 8
$\omega_n = 647.49\ Hz$



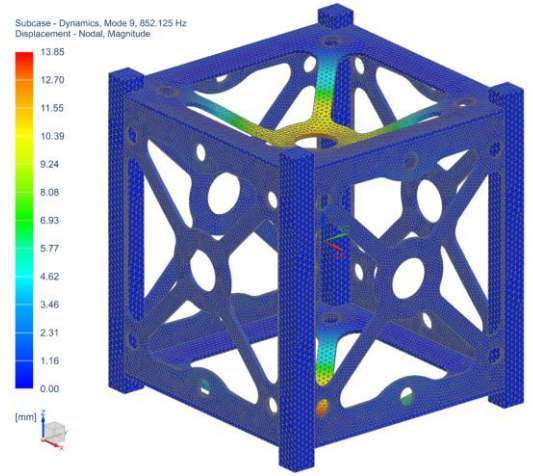
Mode 9
$\omega_n = 654.14\ Hz$



Mode 10
$\omega_n = 654.17\ Hz$



Mode 11
$\omega_n = 824.92\ Hz$



Mode 12
$\omega_n = 852.13\ Hz$

Comparison to Literature

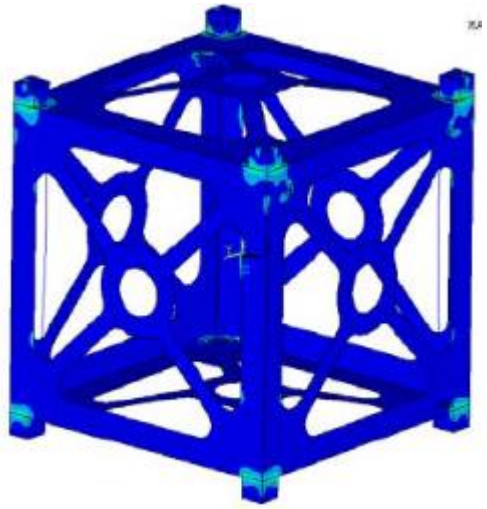
Table: Comparison to Literature

	Natural Frequency (Hz)	
Mode	**Literature**	**Simulation**
7	633.25	644.46
8	639.74	647.49
9	639.81	654.14
10	726.44	654.17
11	810.13	824.92
12	821.84	852.13

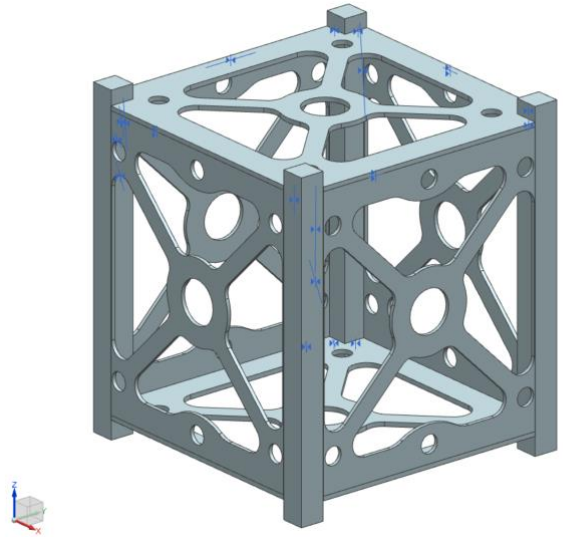
[6]

NOTE: First 6 modes were rigid body modes

- Differences in natural frequencies are likely due to differences in model geometry
- Literature model was more simplified



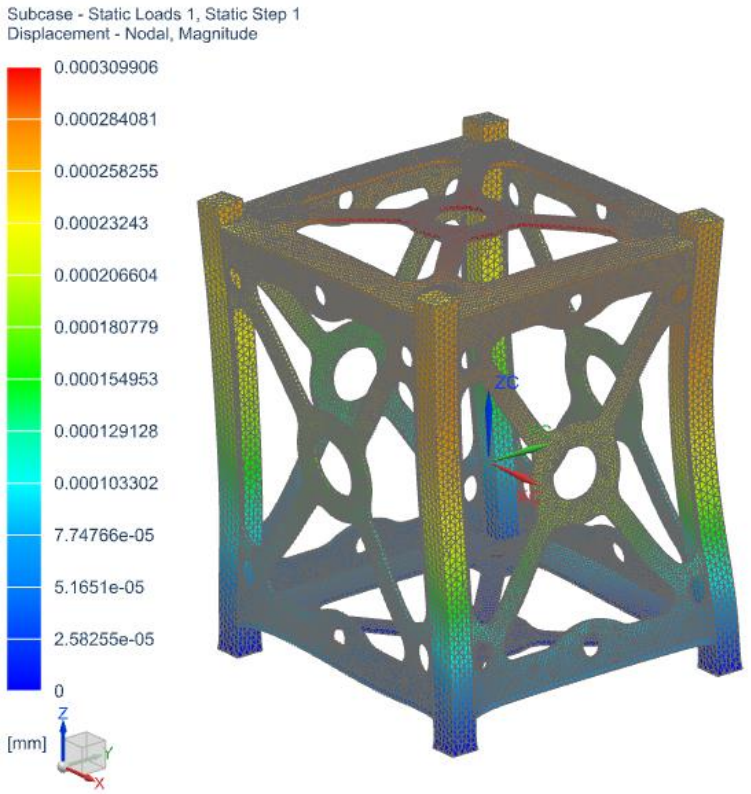
Literature Model [6]



Created Model

Static Load

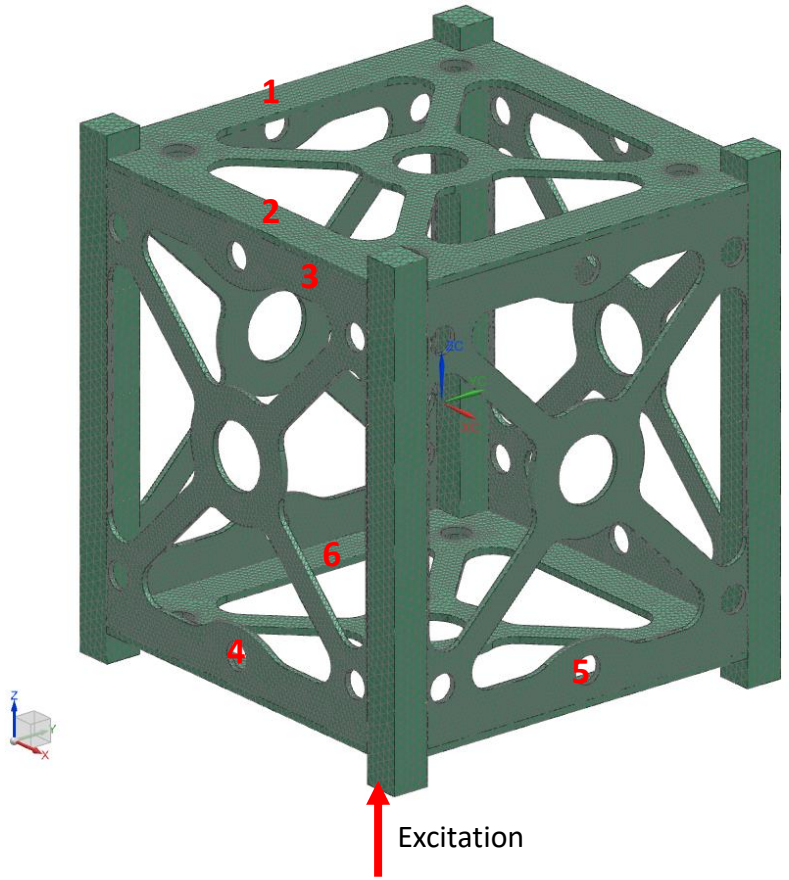
- Static Load applied to entire body
  - Launch load of 8.75g in the z-direction and 1.25g in the x-direction [6]
    - FOS = 1.25
  - Simply supported in x,y,z at base of each leg
- Confirms soundness of model
  - Displacement = .0003 mm
  - Consistent with literature [6]



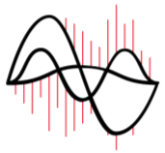
Displacement Under Static Load

Dynamic Simulation

- NX Nastran SOL103 Response Dynamics solver
- Zero-Mean Gaussian White Noise Force excitation applied
  - Applied in vertical (z-direction)
- Sensor applied to measure acceleration
  - 6 sensors randomly located
    - Measure acceleration in z-direction



Sensor Configuration



Results

Data Analysis

- Non-Parametric Method
  - Does not assume data follows any distribution
  - Welch based Frequency Response Function (FRF)
- Parametric Method
  - Assumes parameters
    - Namely that data follow Normal Distribution
    - Models the population from which samples came from rather than a single sample
  - Autoregressive with Exogenous Variable (ARX) Model

ARX Function

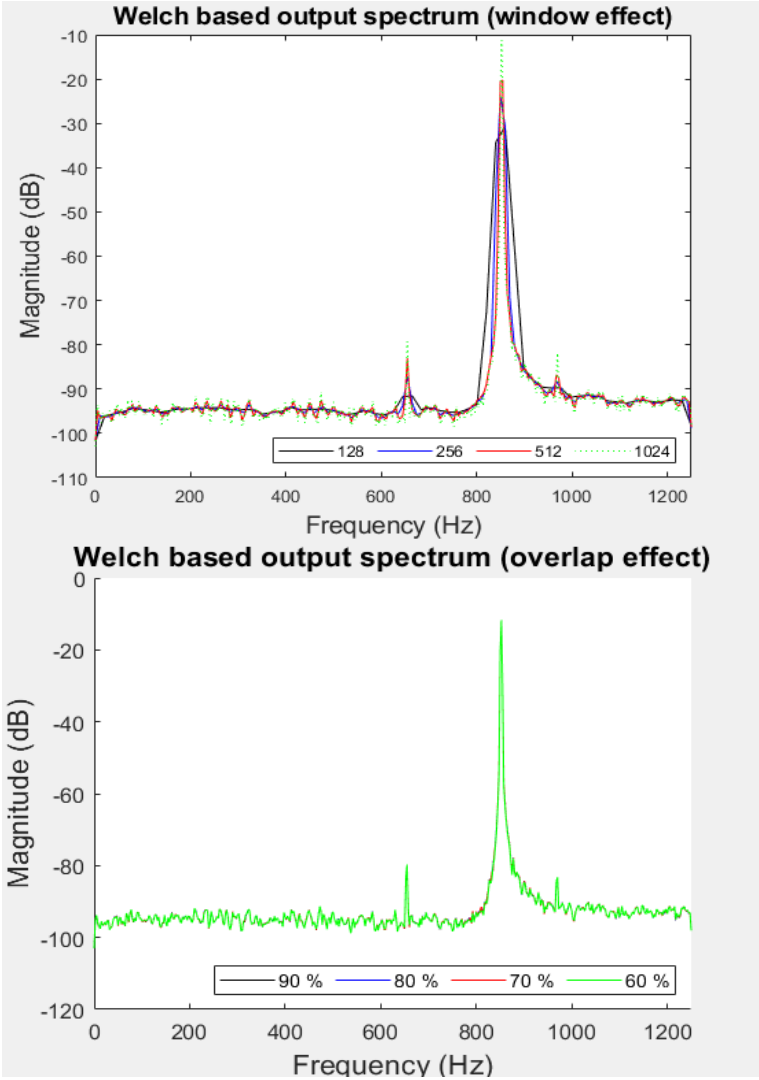
- ARX is a representation of a dynamical system in discrete time
- Relates the current value to past values of both the input and output signals

$$\underbrace{y_{k+1}}_{Current\ Value} = \underbrace{\sum_{i=1}^{n_a} a_i y_{k-i+1}}_{Past\ Output\ Value} + \underbrace{\sum_{i=1}^{n_b} b_i u_{k-i+1}}_{Past\ Input\ Value}$$

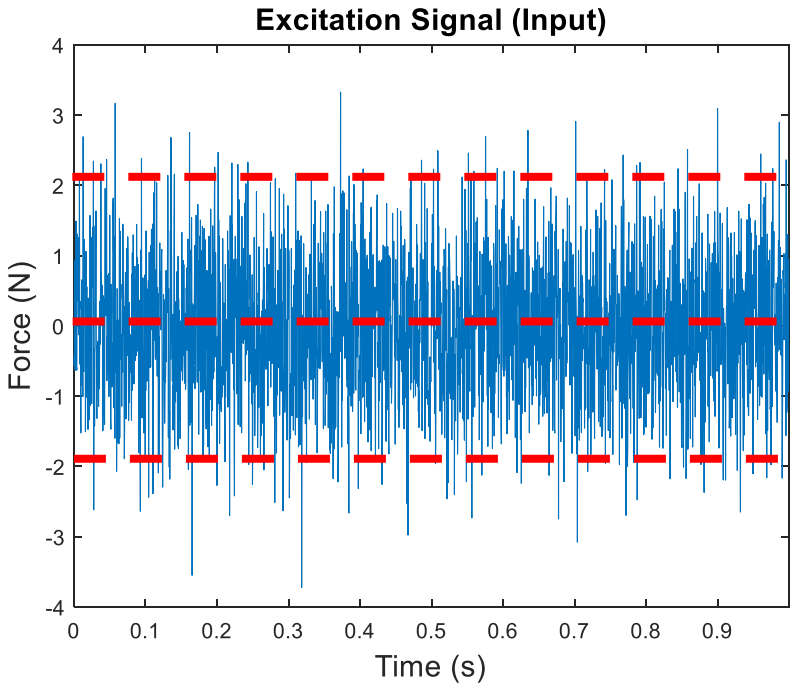
a_i, b_i are constants

Comments on Window and Overlap

- Window Length and Overlap
  - Effect the level of noise present in the signal
  - Want to limit noise without eliminating too much of the response
- All FRF models were run with:
  - Window Length = 1000
  - Overlap = 90%

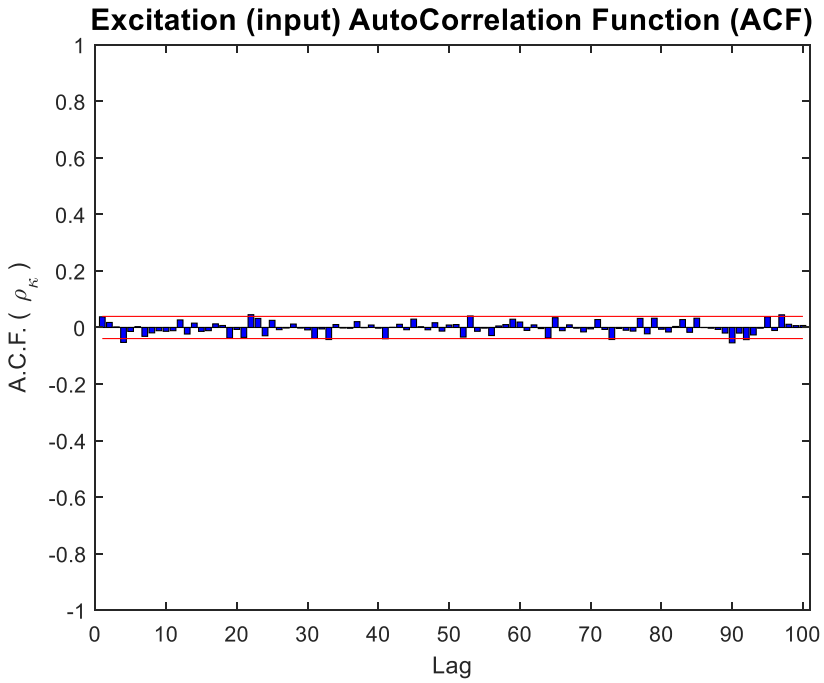


Excitation (Input) Signal



μ=0

Time-Invariant



Gaussian White Noise

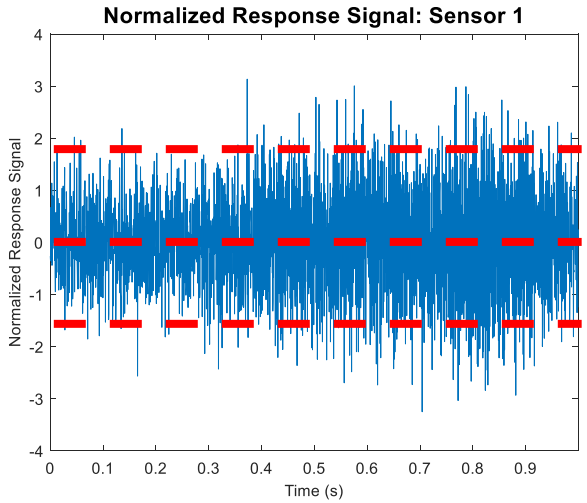
Sampling Freq: 2.5 kHz

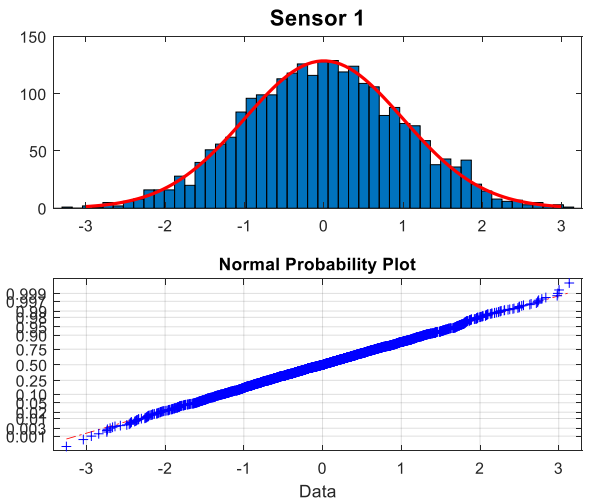
Sampling Time: 10s

Bandwidth: 0-1000 Hz

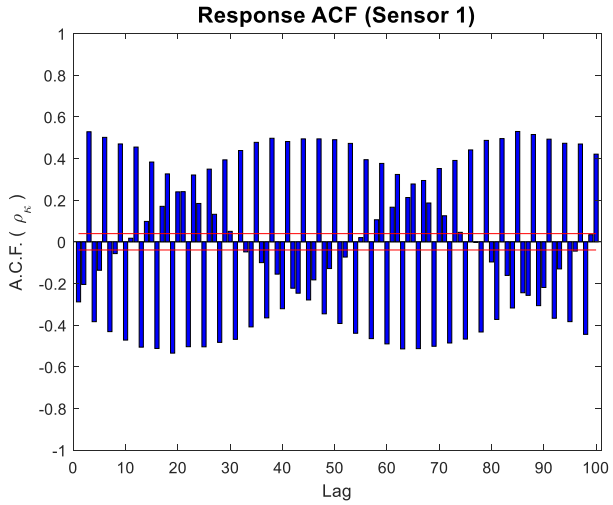
Sensor 1 Response Signal

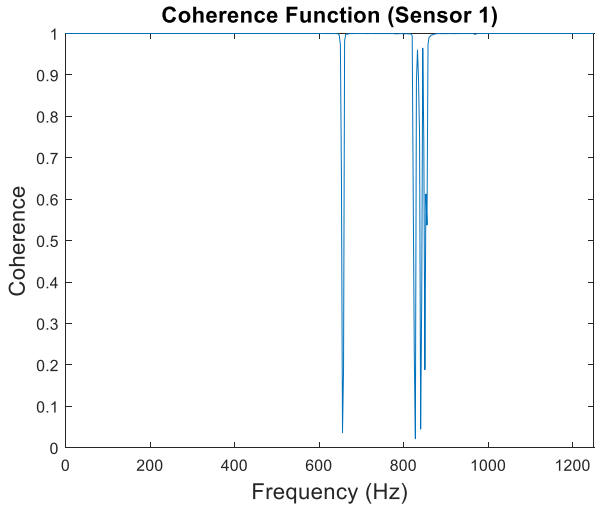
μ=0
Time-Invariant



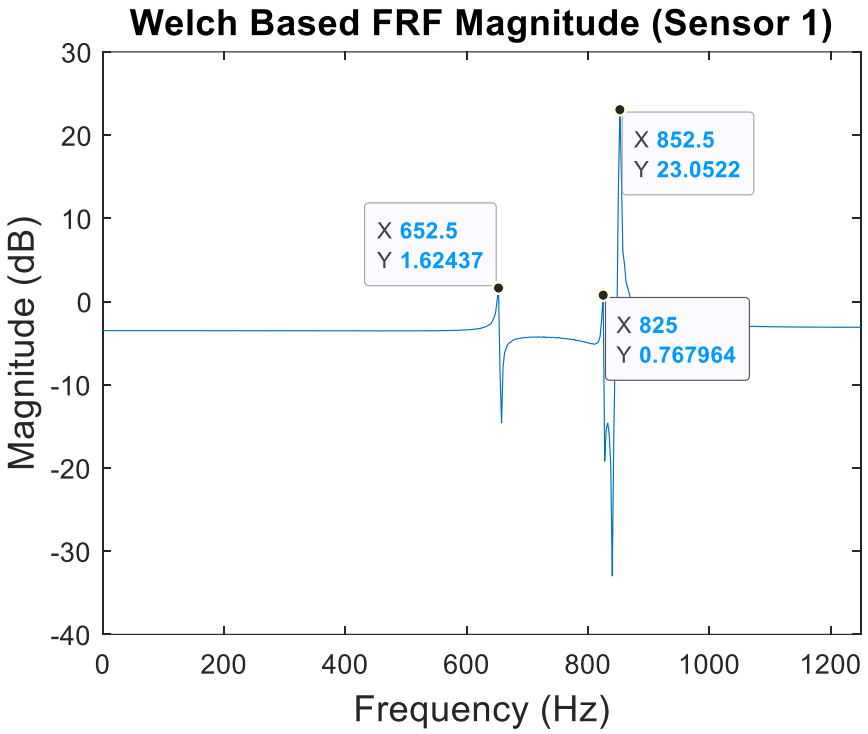


Lags: 100



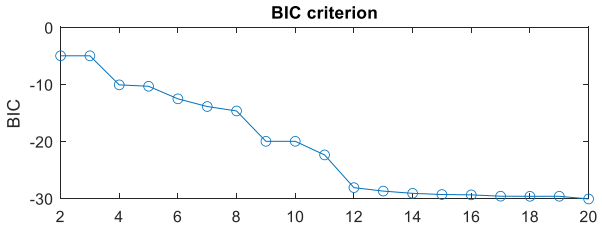


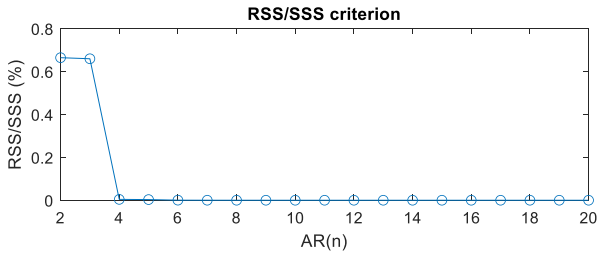
Sensor 1 Welch Based FRF

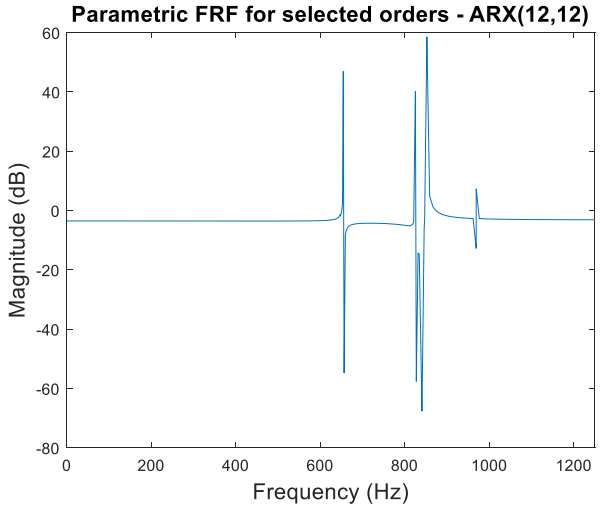


Window Length: 1000
Overlap: 90%

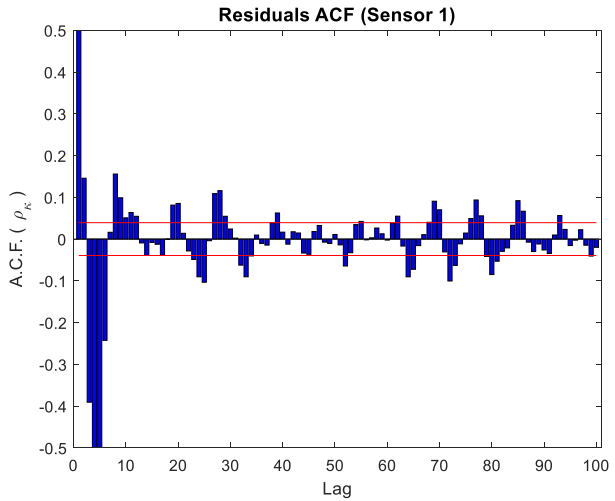
Sensor 1 ARX





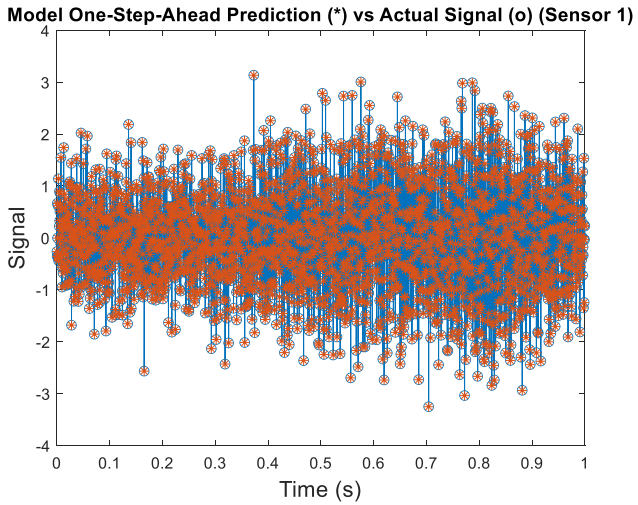


Model Order 12



Lags: 100

White noise

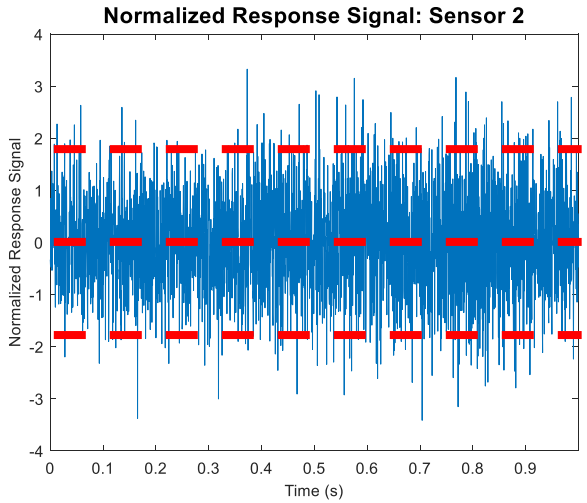


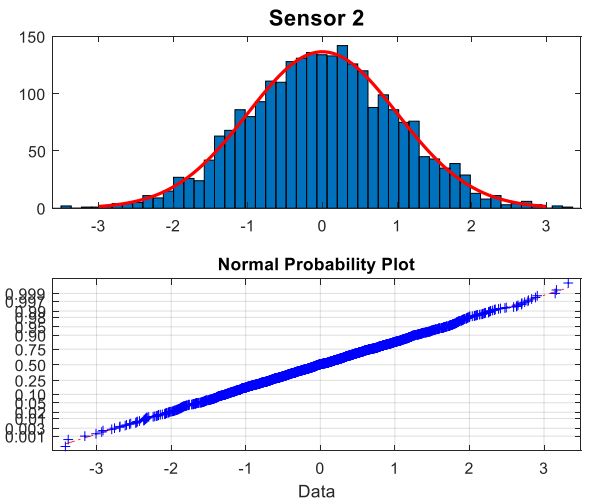
Natural Frequencies Captured

Welch (Hz)	ARX (Hz)
	647.38
652.5	654.18
825	824.92
852.5	852.12
	968.88

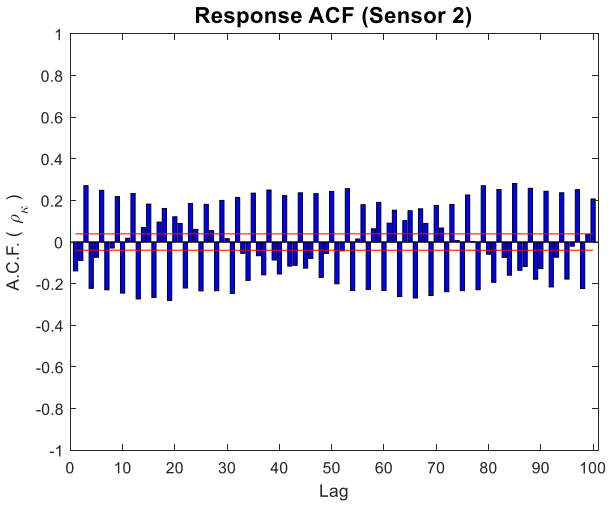
Sensor 2 Response Signal

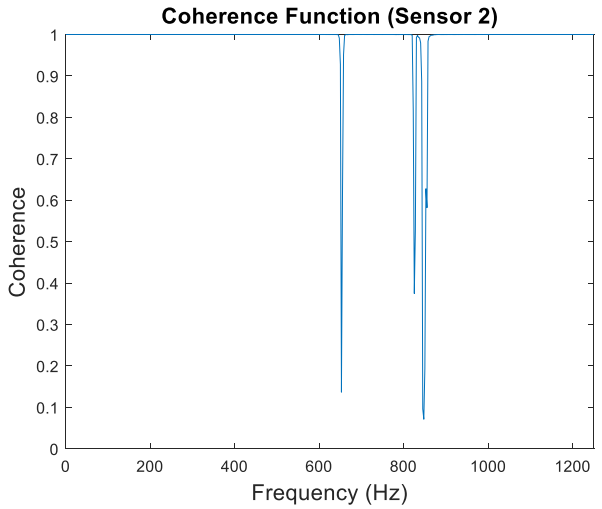
μ=0
Time-Invariant



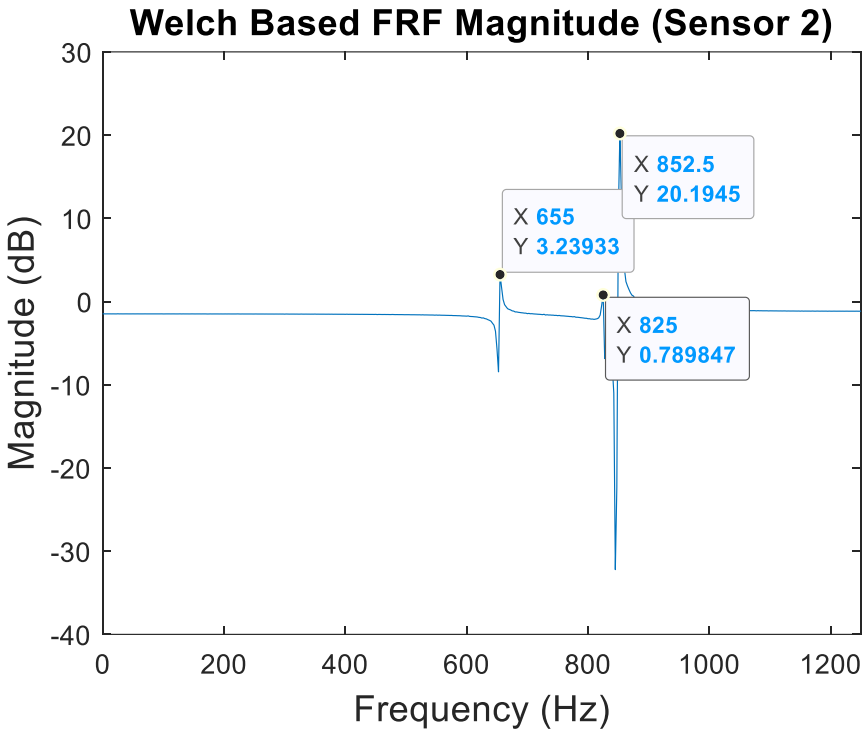


Lags: 100



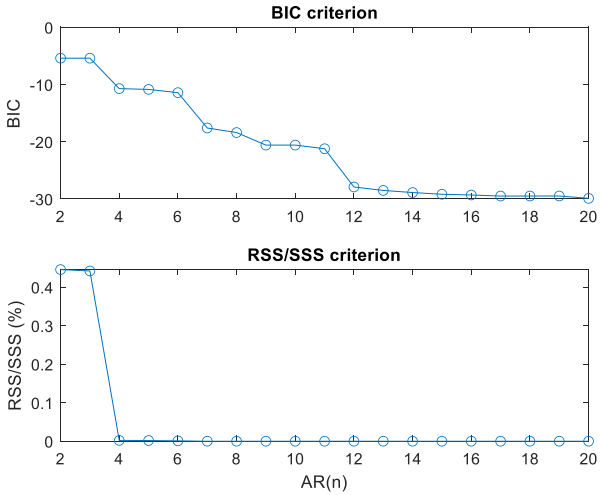


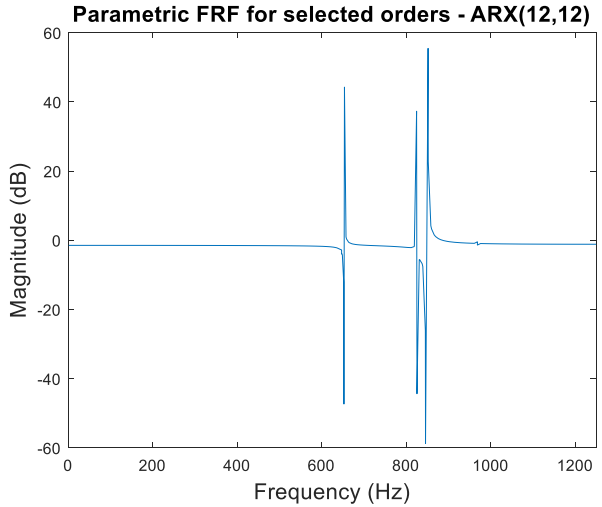
Sensor 2 Welch Based FRF



Window Length: 1000
Overlap: 90%

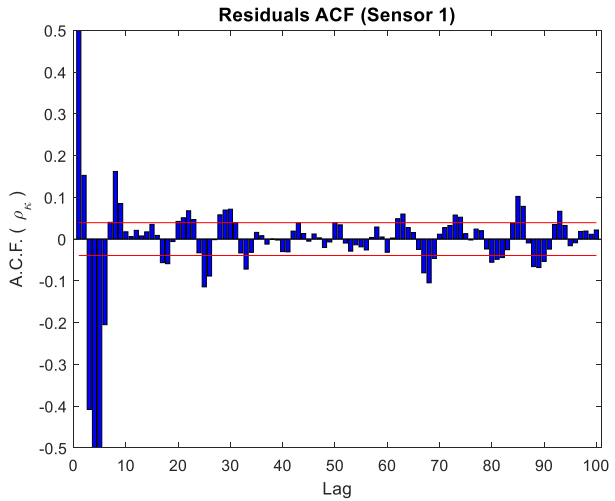
Sensor 2 ARX



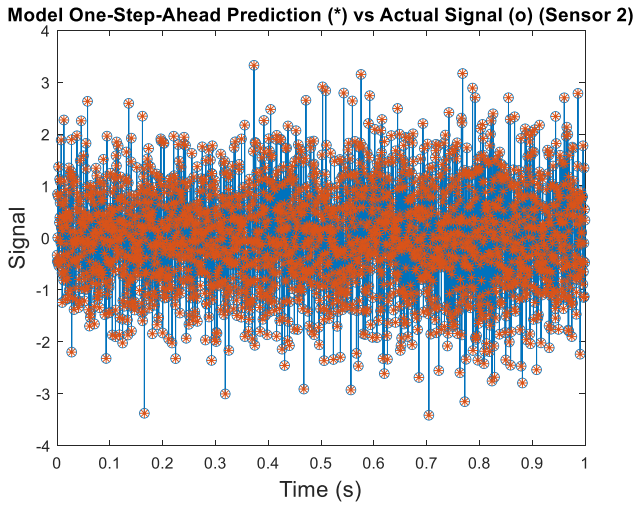


Model Order 12

Lags: 100



White noise



Natural Frequencies Captured

Welch (Hz)	ARX (Hz)
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655	654.14
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852.5	852.12
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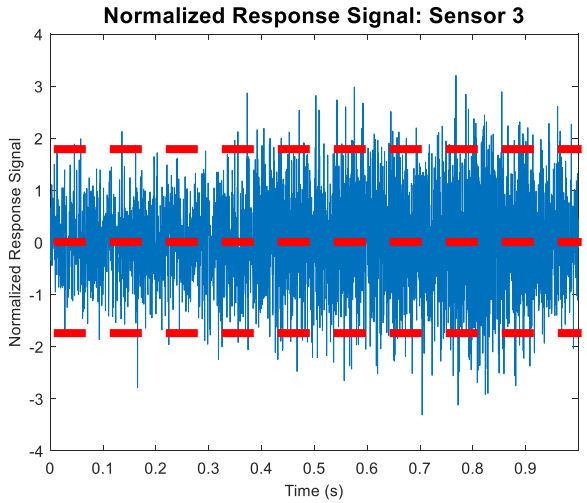
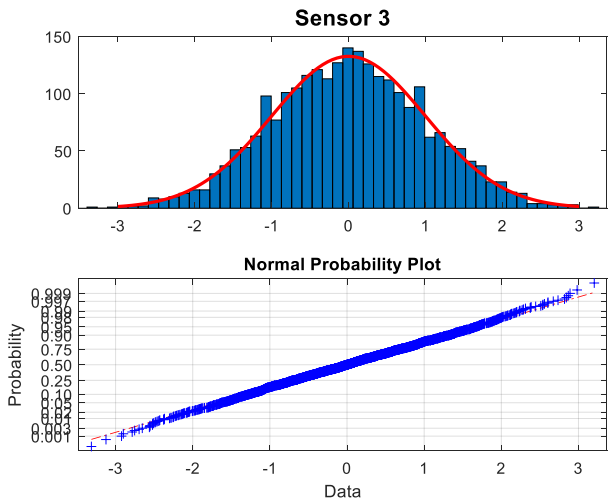
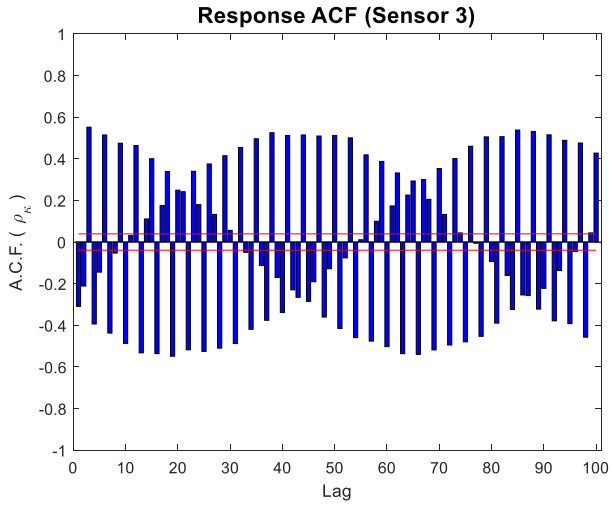
Sensor 3 Response Signal

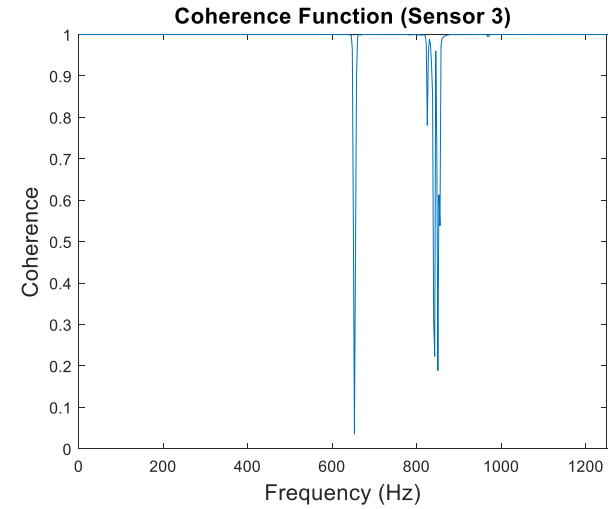
μ=0
Time-Invariant



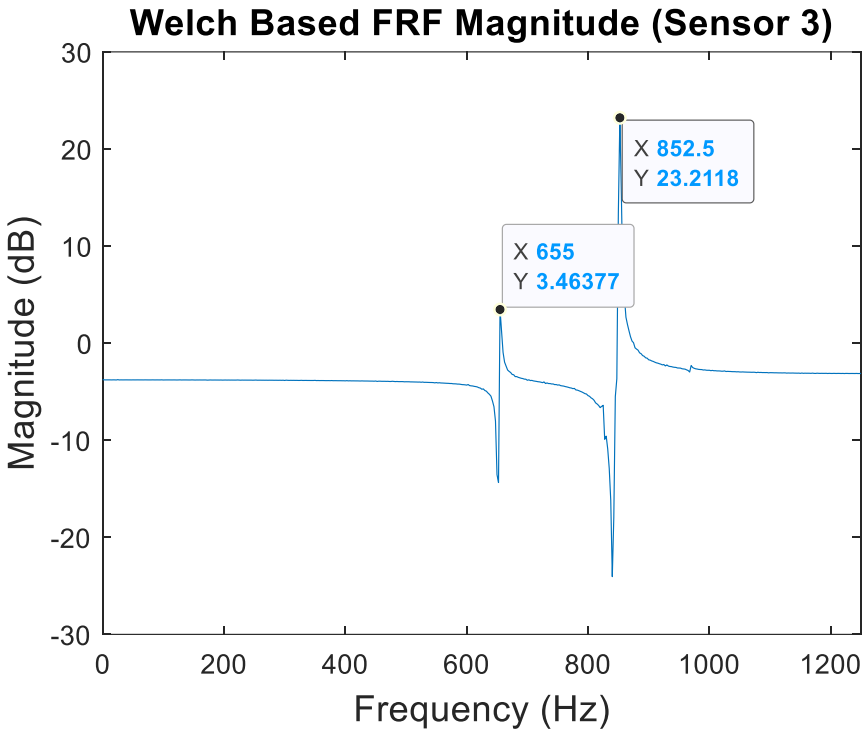


Lags: 100



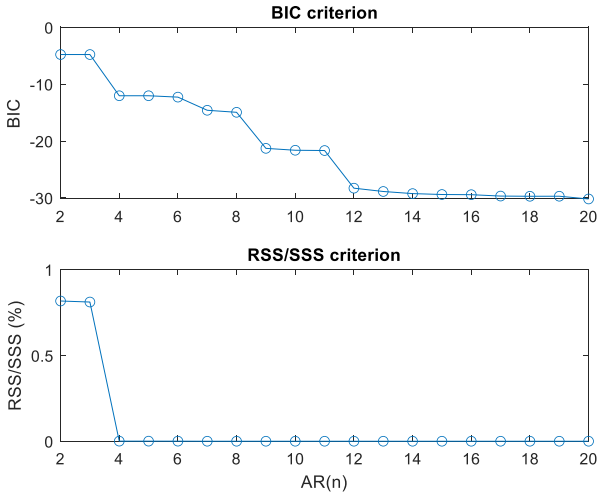


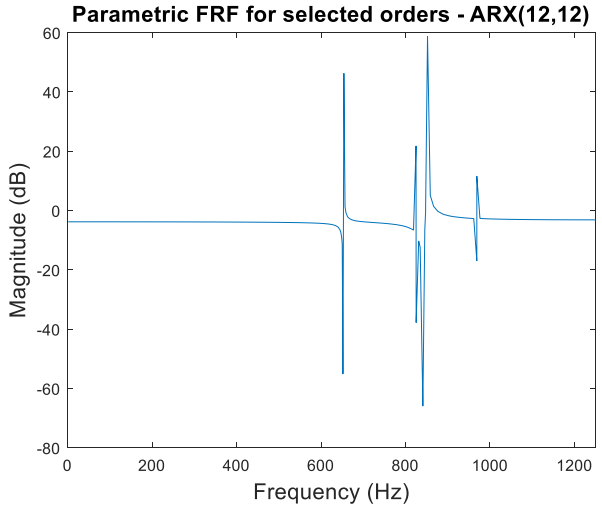
Sensor 3 Welch Based FRF



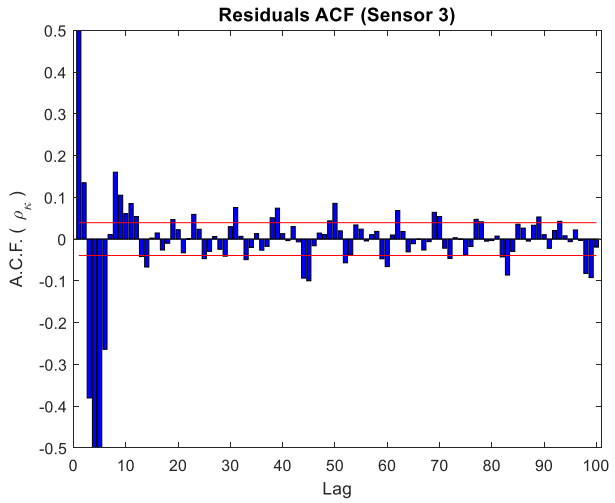
Window Length: 1000
Overlap: 90%

Sensor 3 ARX

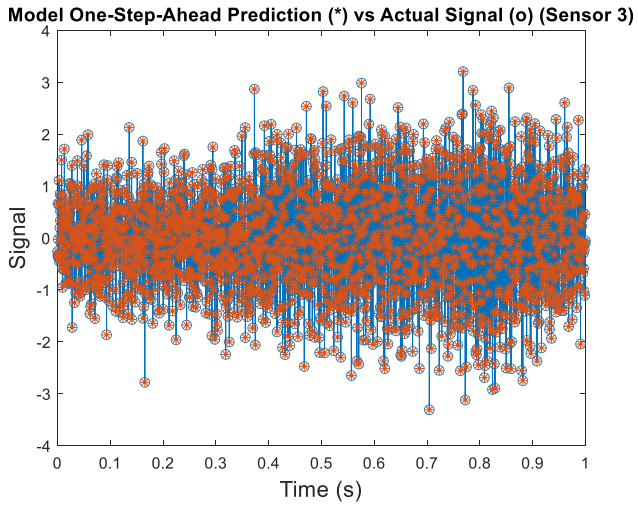




Model Order 12



Lags: 100



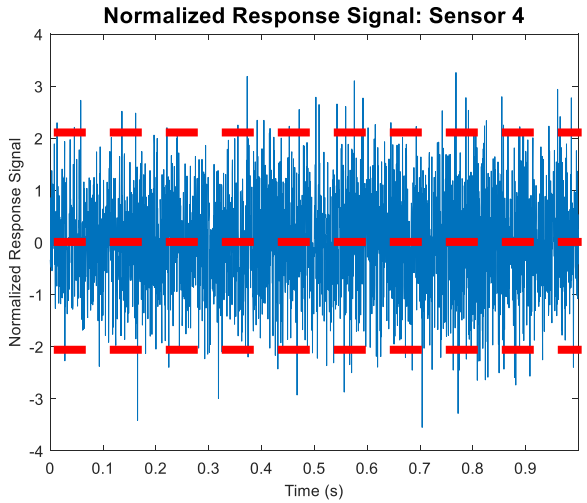
White noise

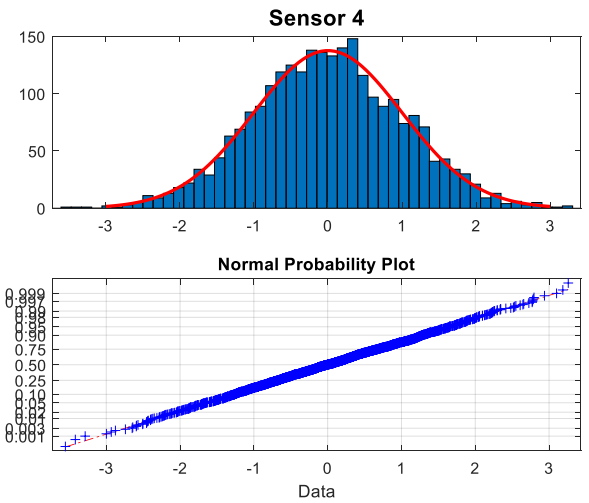
Natural Frequencies Captured

Welch (Hz)	ARX (Hz)
	645.27
655	654.14
	824.92
852.5	852.12
	98.87

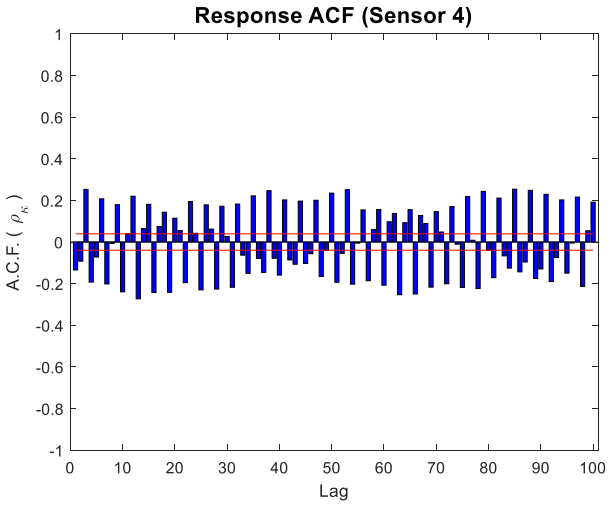
Sensor 4 Response Signal

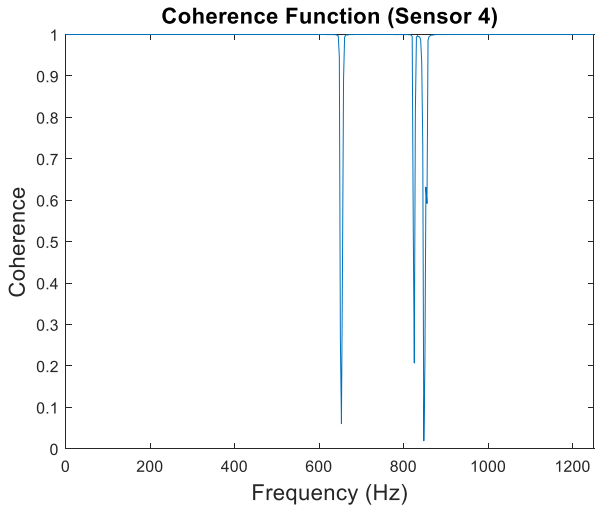
μ=0
Time-Invariant



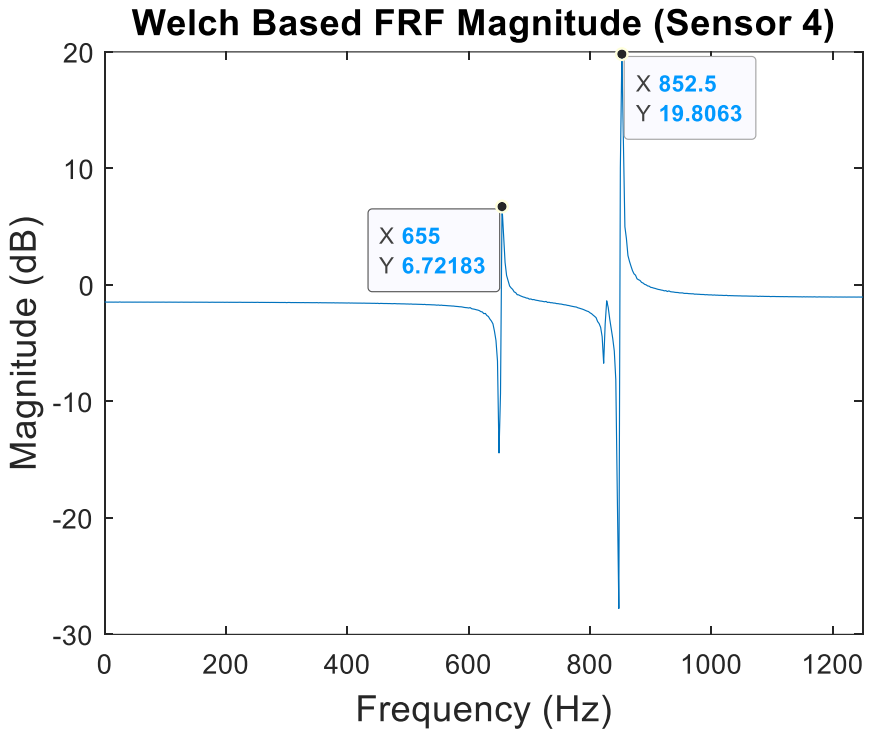


Lags: 100



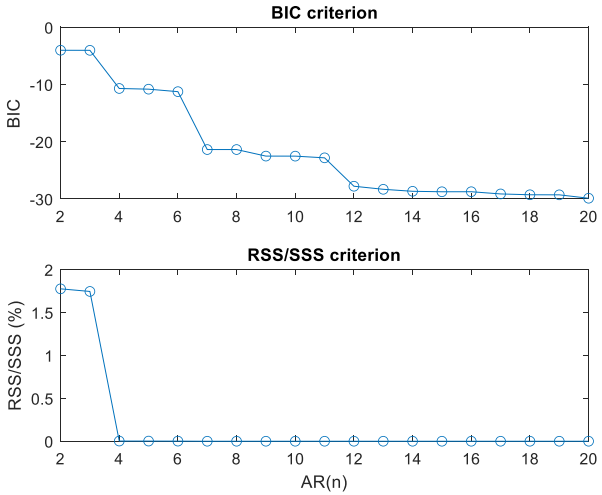


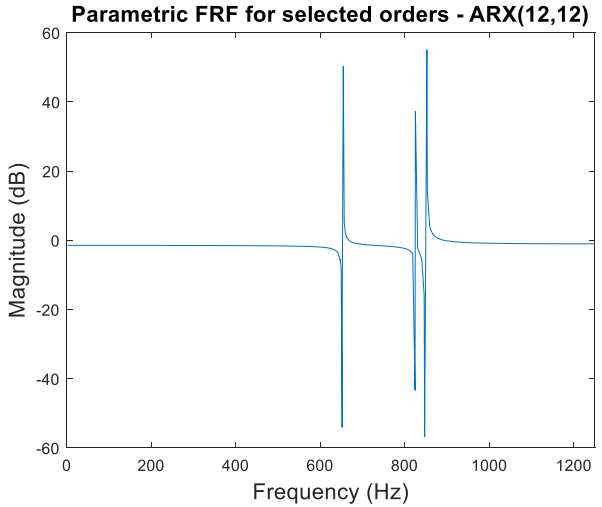
Sensor 4 Welch Based FRF



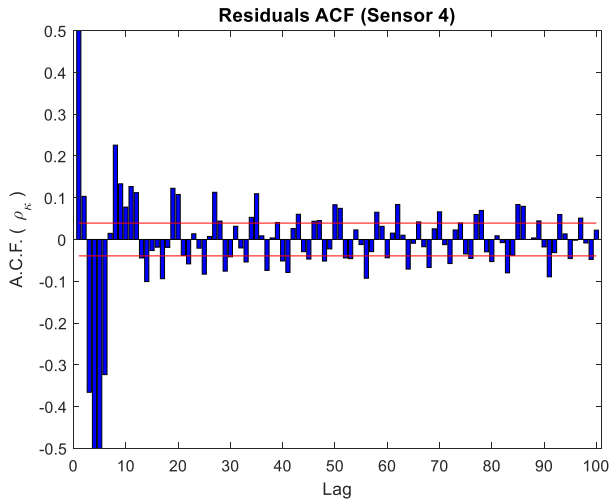
Window Length: 1000
Overlap: 90%

Sensor 4 ARX

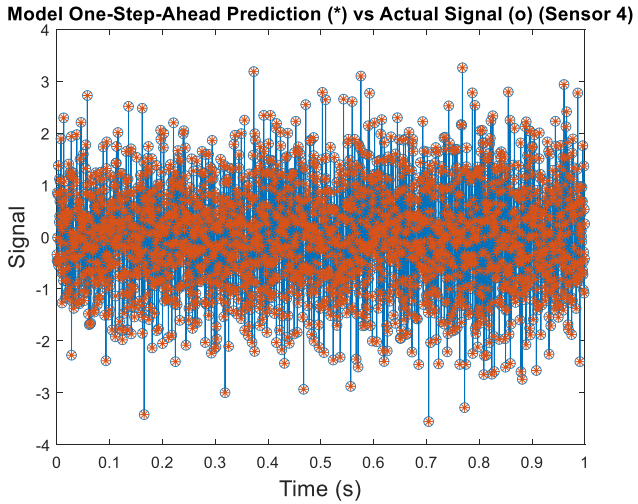




Model Order 12



Lags: 100



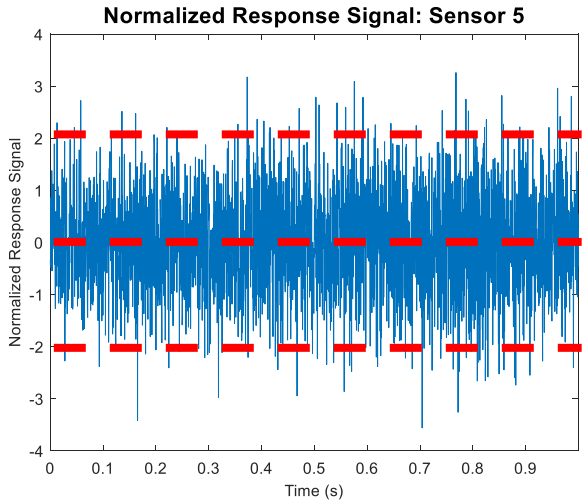
White noise

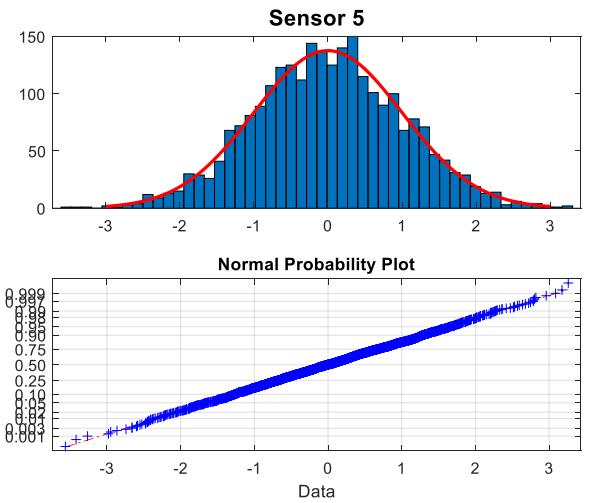
Natural Frequencies Captured

Welch (Hz)	ARX (Hz)
	646.97
655	654.14
	824.92
852.5	852.12
	968.65

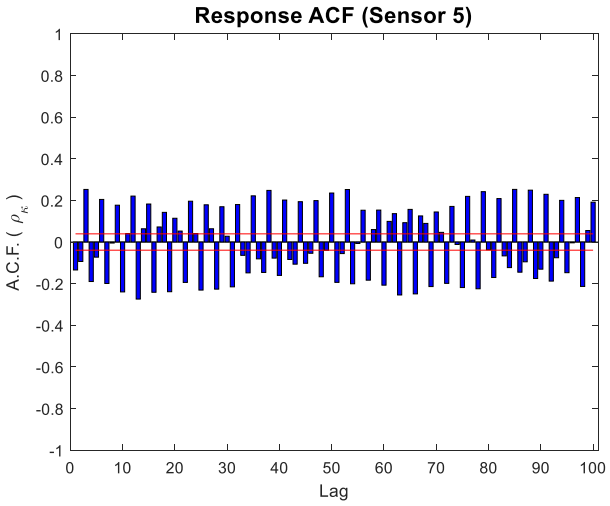
Sensor 5 Response Signal

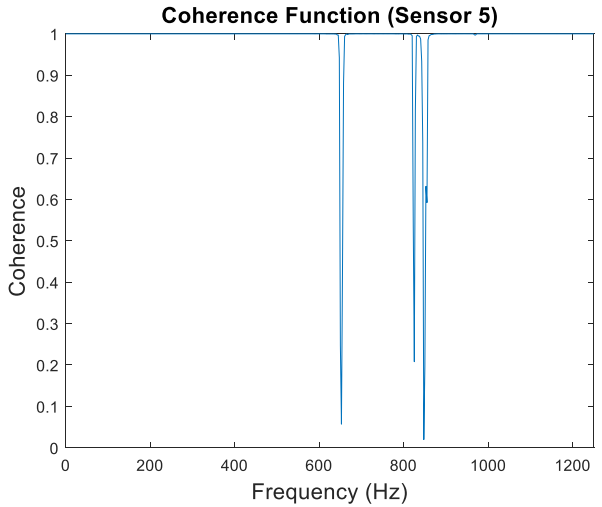
μ=0
Time-Invariant



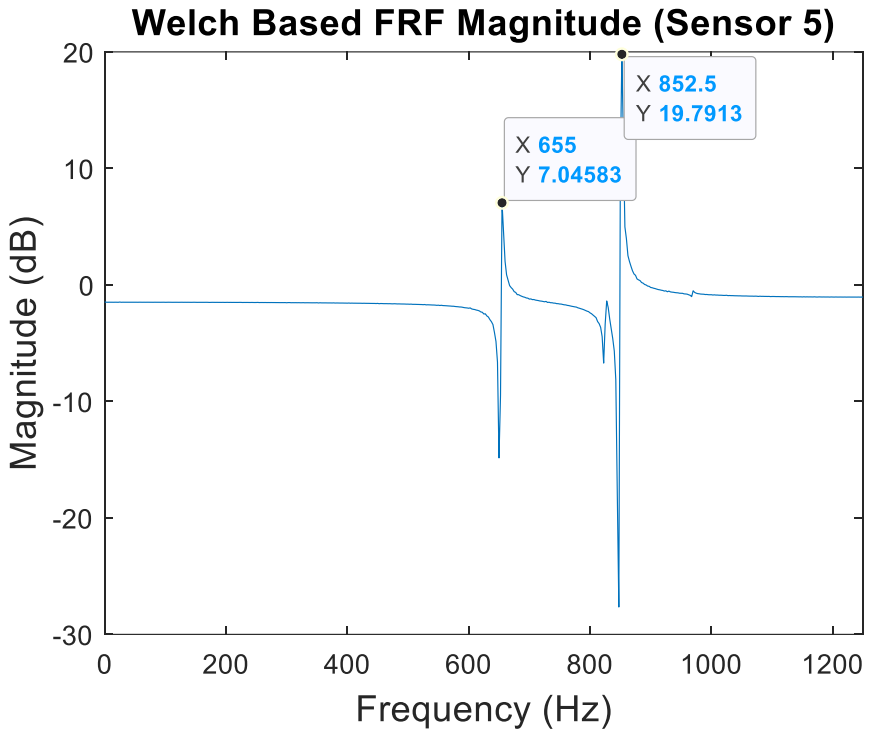


Lags: 100



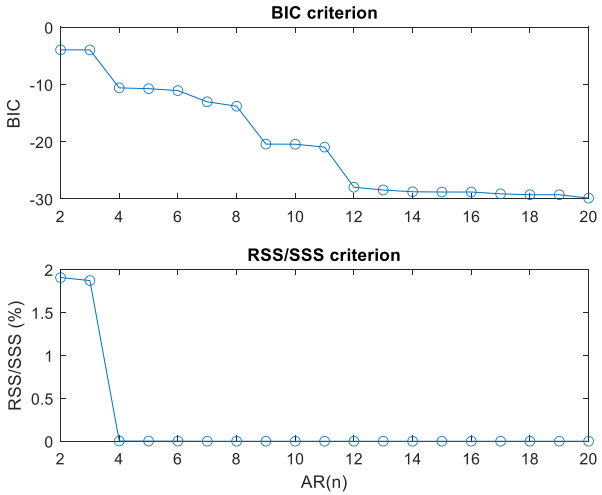


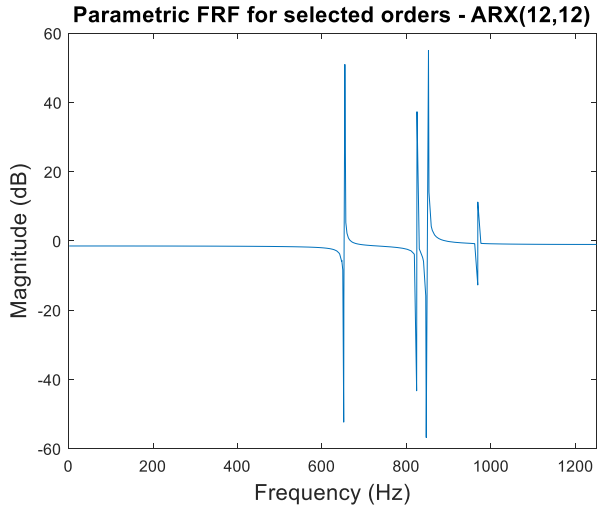
Sensor 5 Welch Based FRF



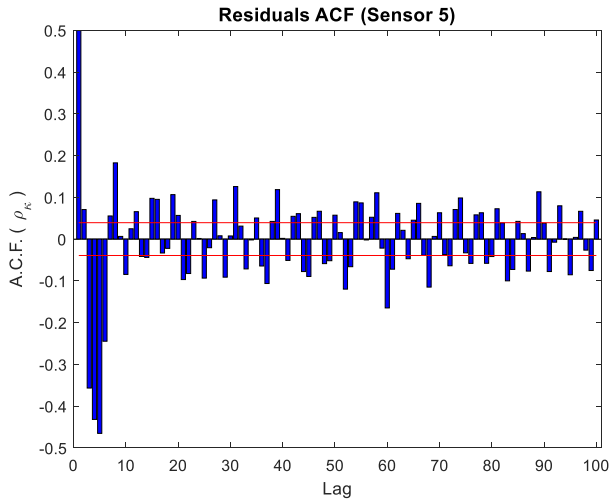
Window Length: 1000
Overlap: 90%

Sensor 5 ARX

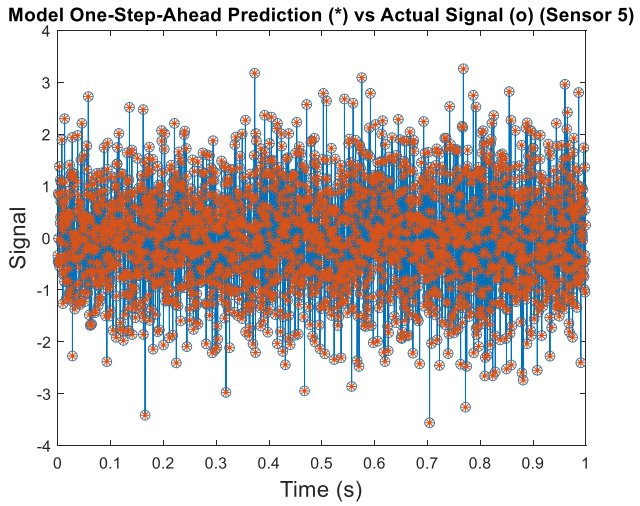




Model Order 12



Lags: 100



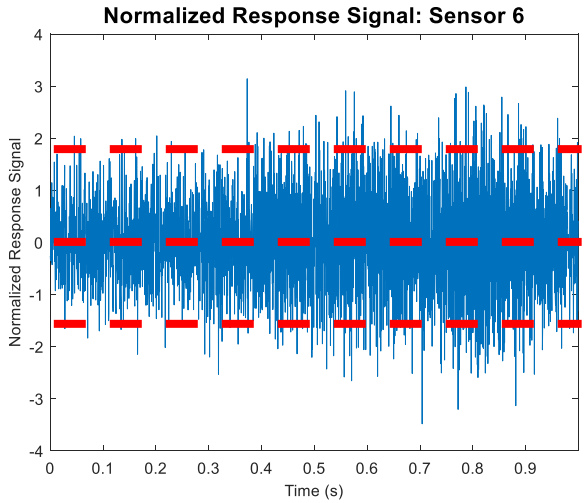
White noise

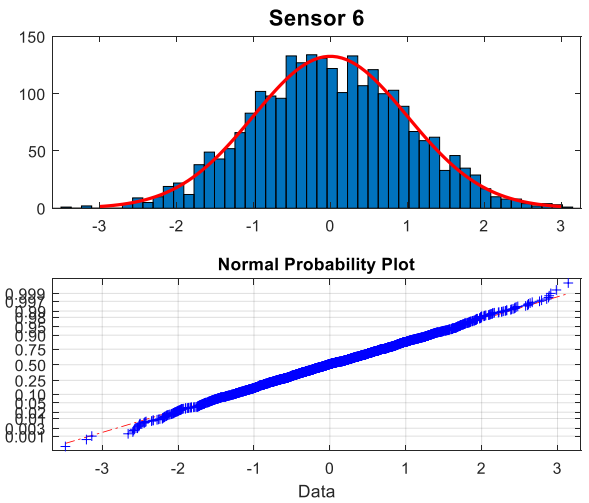
Natural Frequencies Captured

Welch (Hz)	ARX (Hz)
	646.89
655	654.17
	824.92
852.5	852.12
	968.88

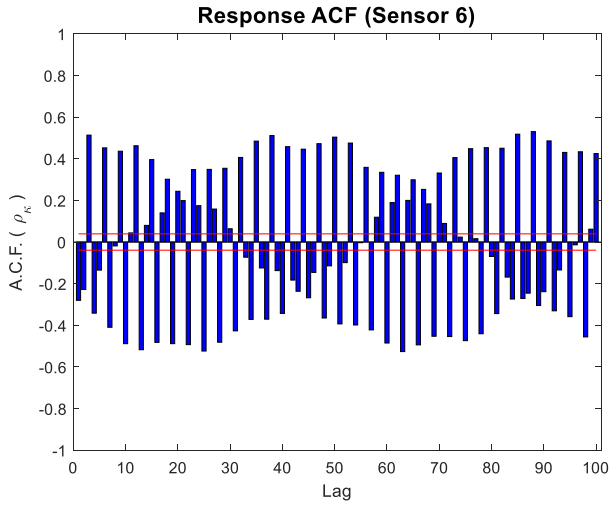
Sensor 6 Response Signal

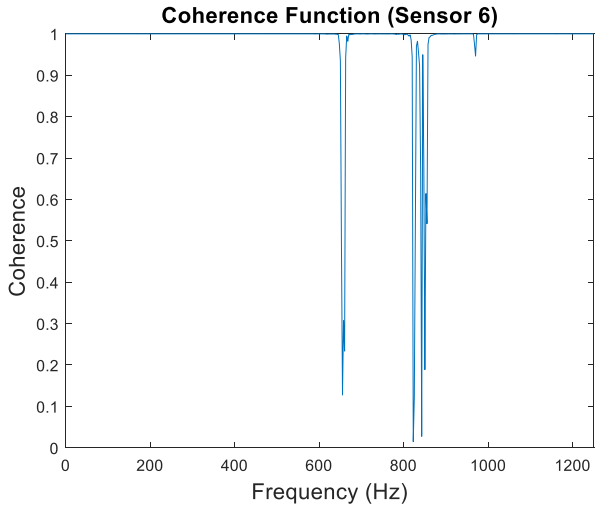
μ=0
Time-Invariant



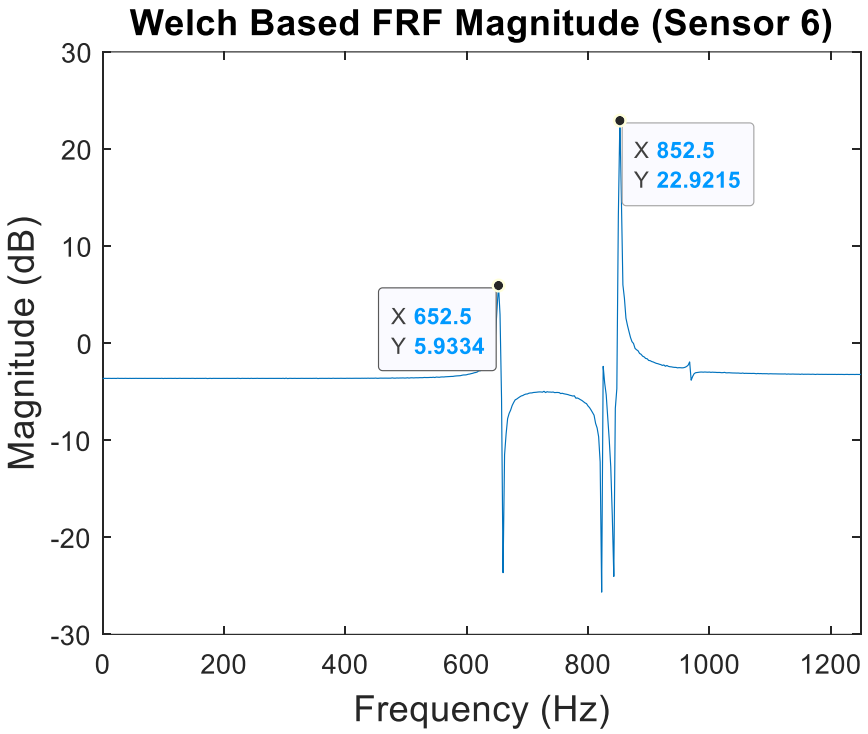


Lags: 100



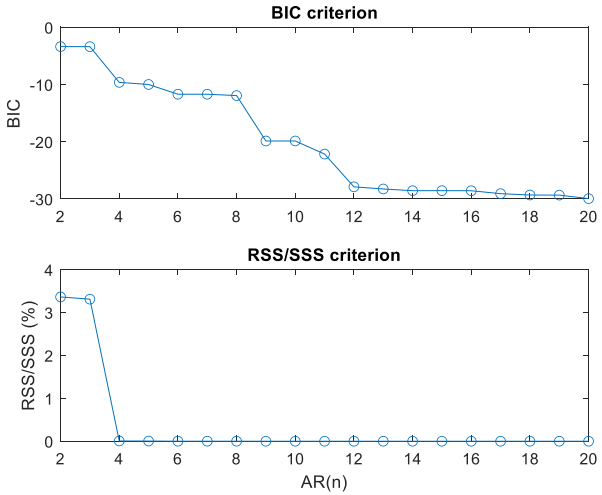


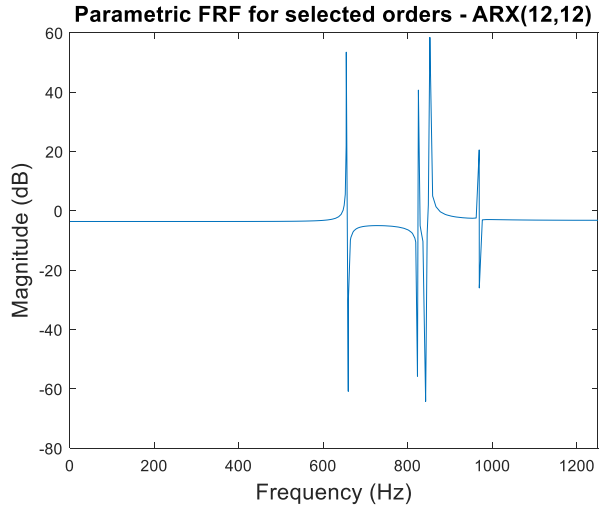
Sensor 6 Welch Based FRF



Window Length: 1000
Overlap: 90%

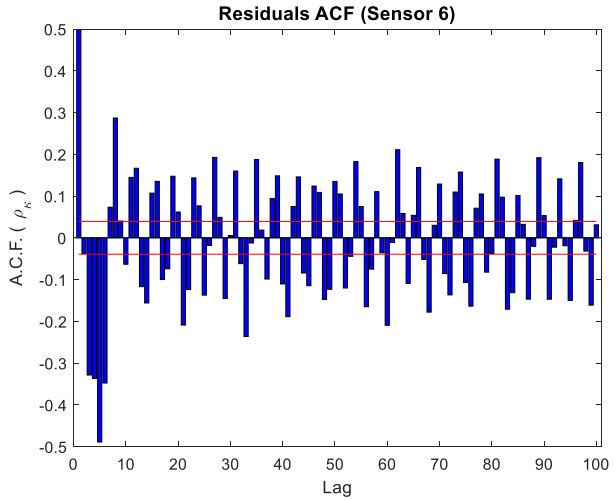
Sensor 6 ARX



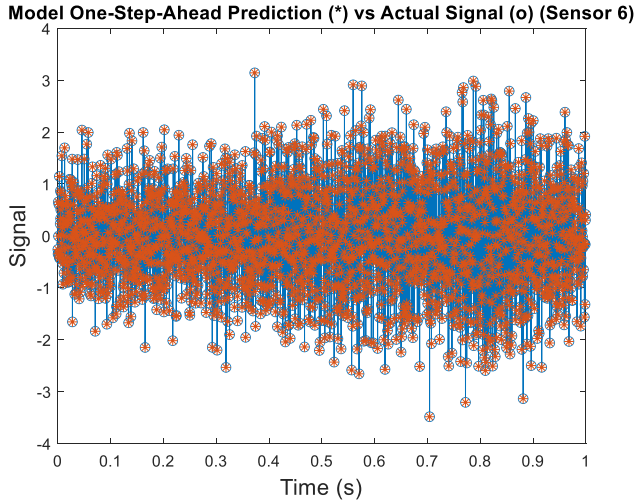


Model Order 12

Lags: 100



Close to white noise



Natural Frequencies Captured

Welch (Hz)	ARX (Hz)
	646.92
652.5	654.17
	824.92
852.5	852.12
	968.88

Natural Frequencies Captured

Comparison of Natural Frequencies

Welch Based FRF (Hz)	ARX (Hz)	NX (Hz)
652.5	645.27	644.46
	647.38	647.49
655	654.14	654.14
	654.17	654.17
825	824.92	824.92
852.5	852.12	852.13

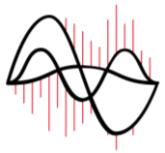
The ARX model does a great job of capturing all the mode shapes.
The Welch based FRF captures 4/6 of them really well

Conclusions and Future Steps

- Acceptable means to simulate a random vibration experiment
- Sensor location is important in obtaining quality results
  - Certain locations may produce time-varying signals
- ARX model does a fantastic job in modeling the system

Future Steps:

- Introduce damage into system
  - I believe there is some documentation on this for NX
- Compare simulated data to real experimental results
- Perform analysis under thermal loads



Rensselaer

Thank You!

For questions contact me at: ian.pylkkanen@gmail.com

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