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Comparison of FRF Correlation Techniques

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U.S. DEPARTMENT OF ENERGY

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Outline

- What is Similarity?
- Evaluation Metrics
- Test Setup
- Results

A Vs. B?

- Unit to unit variability a concern amongst multiple agencies
- Assembly errors
  - Wrong torque, Missing hardware, Mis-alignment, etc.
  - Human error
- Shipping damage
  - Extended vibration, Complacency, Temperature variation, etc.
- Testing damage
  - Environmental testing (Vibe, Shock, Thermal, etc)
- Development research requires Apples vs. Apples confidence
- Need fast and non-intrusive test to evaluate similarity concerns
  - Modal testing is ideal but difficult
  - FRF comparison is quick
  - Existing metrics for model validation exist

FRF Comparison Metrics

- Visual comparison of FRF
  - Quick and easy determination of similarity in a modal sense
  - Unit to unit variability large in complicated structures make visual comparison difficult
  - Un-reliable and non-universal metric

- Frequency Peak Picking
  - Natural frequencies are characteristic of the structure
  - Similarity term must be relaxed to accept small frequency shifts due to parts settling, non-linear behavior, unknowns

- RMS Percent Error
  - Measurement of overall energy of the FRF allows for small frequency discrepancies
  - Possible for two visually different structures to have similar RMS values

FRF Comparison Metrics

- R^2 Coefficient of the Imaginary Response
  - Linear fit of the imaginary components from both FRF's give a similarity metric

- Nyquist Comparison
  - Damping heavily influences real component
  - Averaging discrepancies in Nyquist plots provide a similarity metric sensitive to changes in damping

- Cross Signature Scale Factor (CSF)[1]
  - Used to evaluate discrepancies between amplitudes for model correlation efforts
  - Ranges from zero to one and is sensitive to changes in damping

$$CSF(\omega_k) = \frac{2\left|H_1^H(\omega_k)H_2(\omega_k)\right|}{\left(H_1^H(\omega_k)H_1(\omega_k)\right)+\left(H_2^H(\omega_k)H_2(\omega_k)\right)}$$

1. Dascotte, E. and Strobbe, J. "Updating Finite Element Models Using FRF Correlation Functions", Proceedings of the 17th International Modal Analysis Conference, 1999

FRF Comparison Metrics

- Frequency Response Function Scaling Factor (FRFSF)[2]
  - Also used to evaluate discrepancies between amplitudes for model correlation efforts
  - Ranges from zero to one and is sensitive to changes in damping

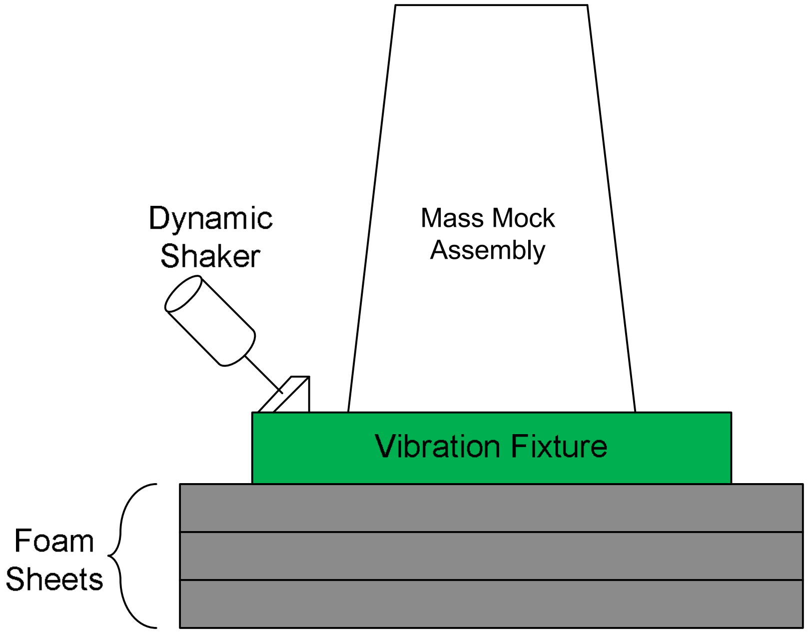
- Cross Signature Assurance Criterion (CSAC, MAC) [1]
  - Evaluates differences between the shape of the functions
  - Similar to Modal Assurance Criterion (MAC)
  - Sensitive to changes in mass and stiffness

1. Dascotte, E. and Strobbe, J. "Updating Finite Element Models Using FRF Correlation Functions", Proceedings of the 17th International Modal Analysis Conference, 1999

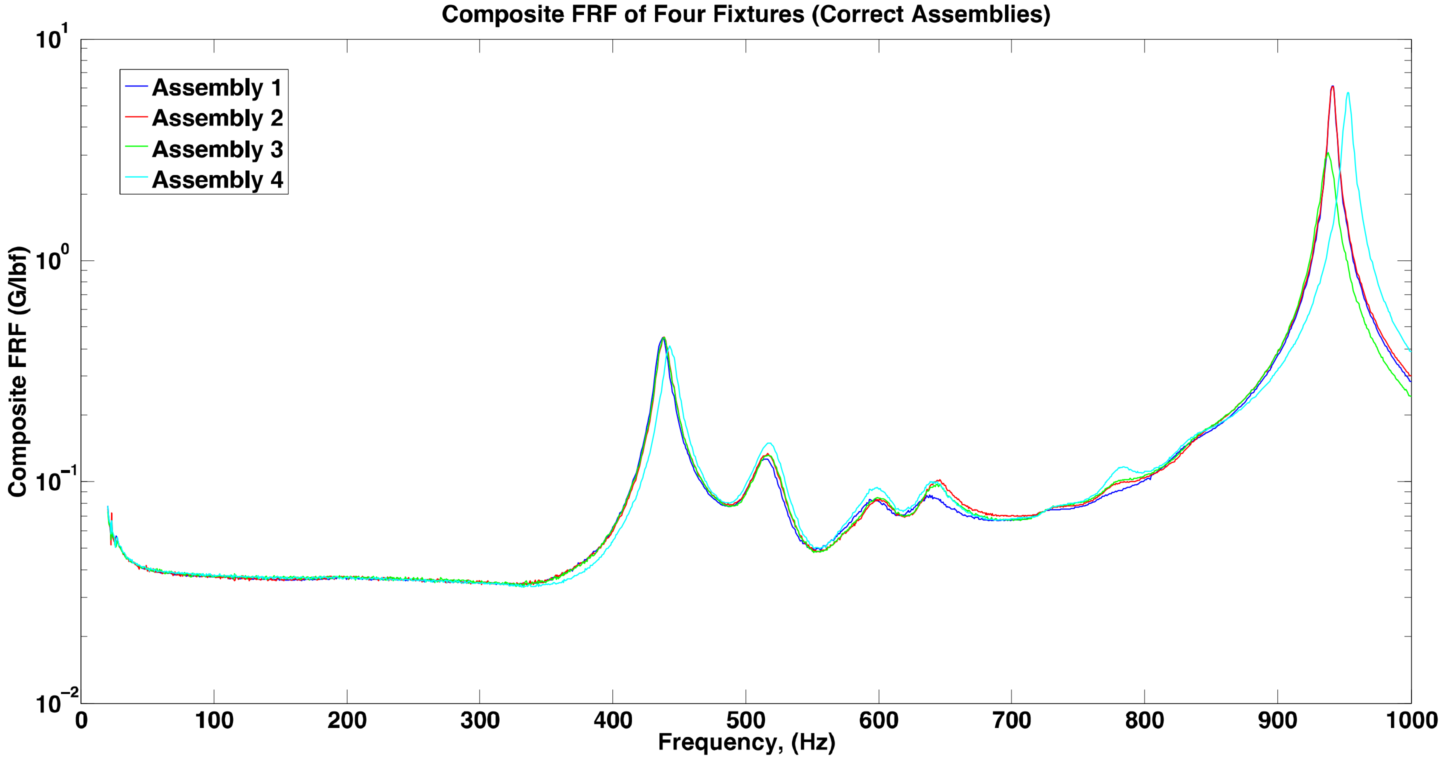
2. Pascual, R., Golinval, J., Razeto, M., "A Frequency Domain Correlation Technique for Model Correlation and Updating," Proceedings of the 15th International Modal Analysis Conference, pp.587-592, 1997.

Case Study: Vibration Fixture and Mass Mock

- Square Vibration fixture and conical assembly with multiple bolted and welded joints
- Mass mock attached via 4 bolts at base
- Full assembly supported on multiple soft foam sheets
- 50lb modal shaker input at a skewed 45 degrees
- Three triax accelerometers at corners of fixture and impedance head at the input
- Burst random force input between 20-1000 Hz

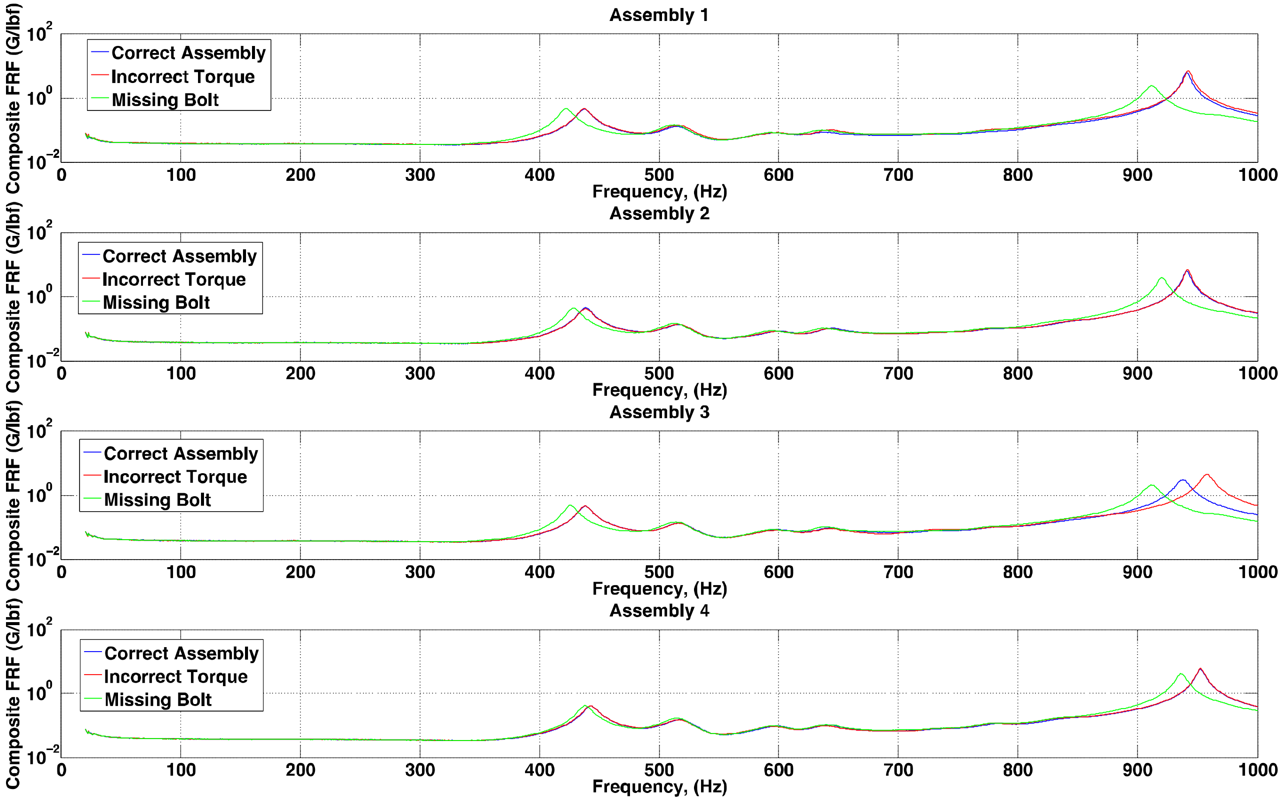


FRF: Correct Assembly



- Correct assembly of multiple fixtures with same mass mock
- Small visual discrepancies in composite FRF
- Small deviations due to possible lack in tolerances in fixture manufacturing and environmental testing

FRF: In-Correct Assembly Comparison



sembly errors simulated

- Missing 45° bolt
- Incorrect torque of 45° bolt

rge shift due to missing lt

ssembly 3" Fixture nibits large differences in quency and amplitude

sual inspection monstrates missing bolt

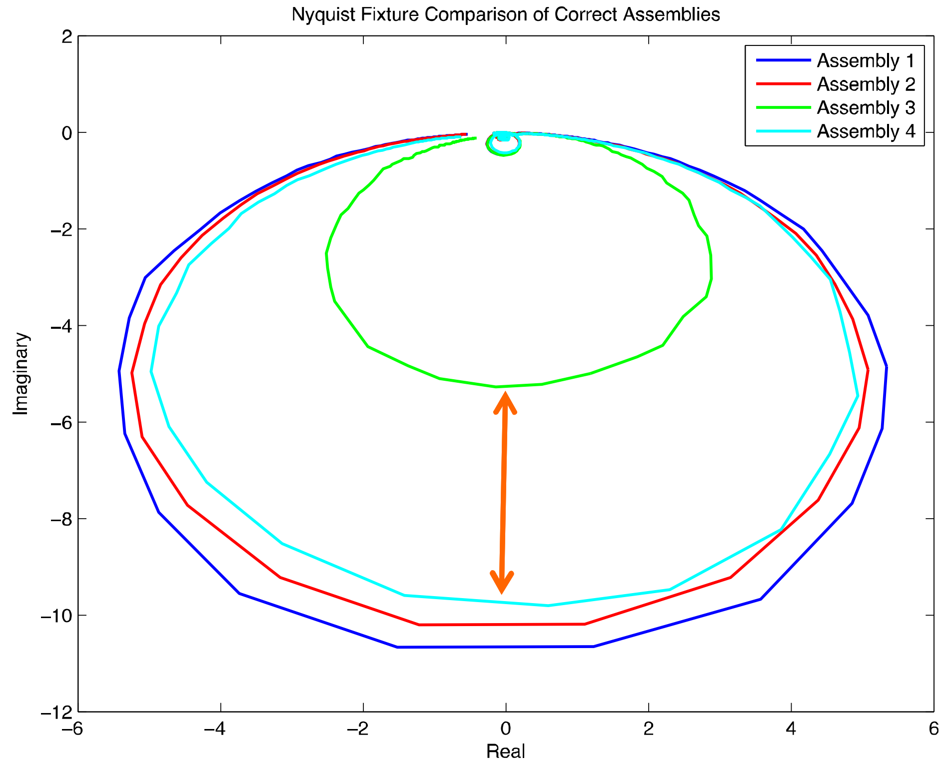
sual inspection misses orrect torque

Nyquist: Correct Assembly

- Nyquist plot for drive-point response at resonance (940 Hz) show large discrepancy in “Assembly 3” fixture

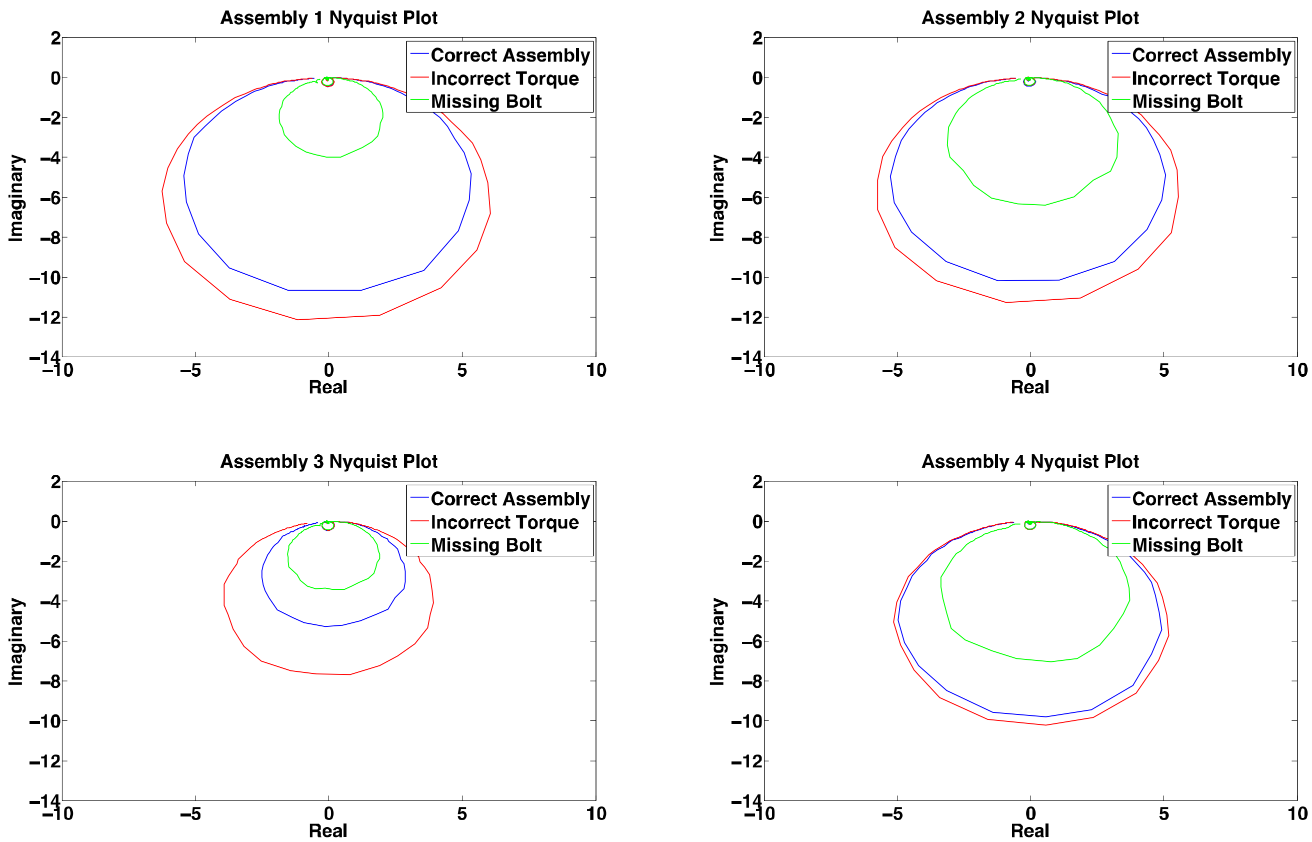
- Less damping in “Assembly 3” fixture characterized by smaller diameter circle

- Corresponds to visual discrepancies seen in FRF comparison



Nyquist: In-Correct Assembly Comparison

- Increase in damping (larger circle) when bolt is incorrectly torqued
- Decrease in damping (smaller circle) when bolt is missing
- Sensitivity to damping and assembly errors can be averaged and normalized for comparison to other metrics



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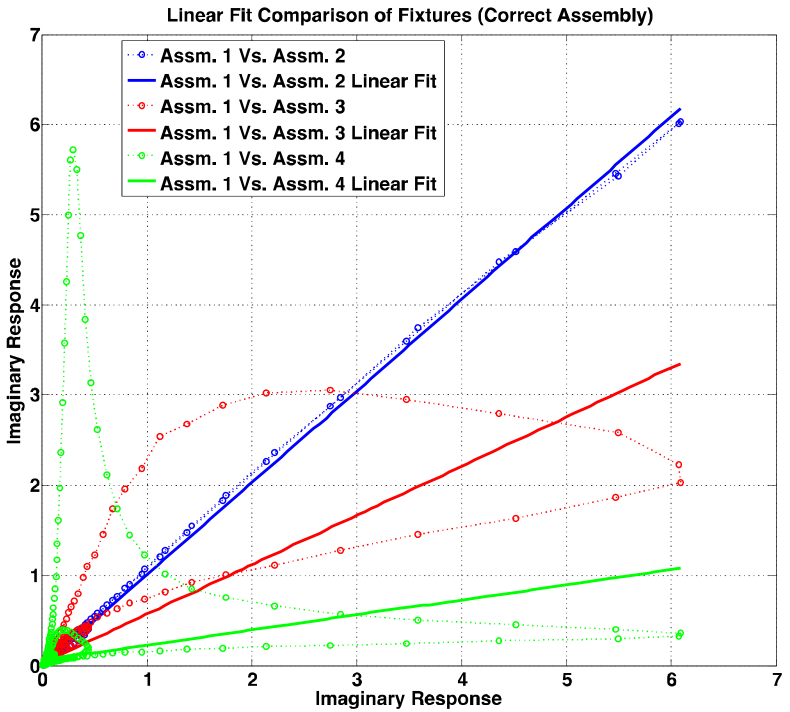
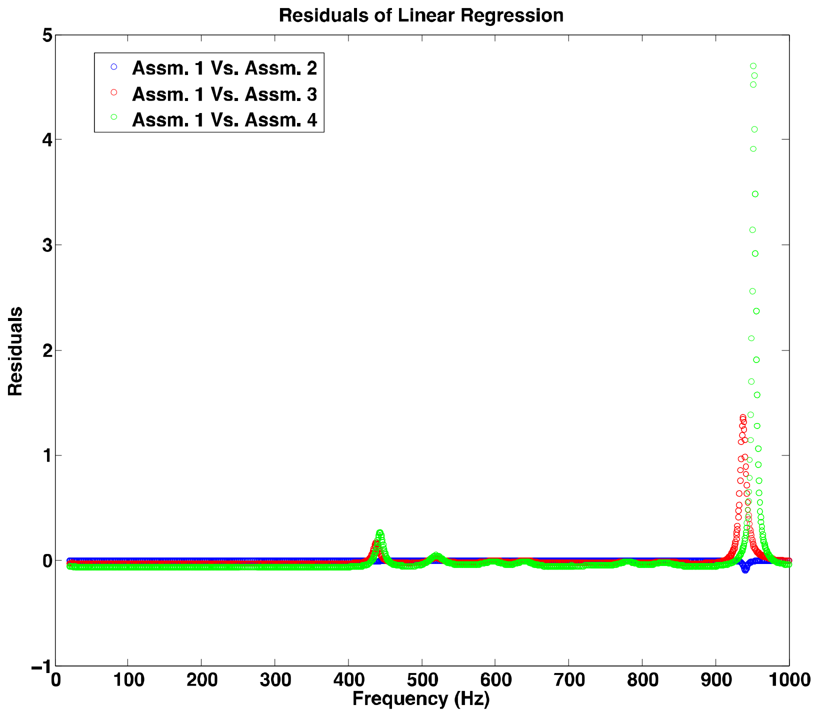
R^2 coefficient of Imaginary Response: Correct Assembly

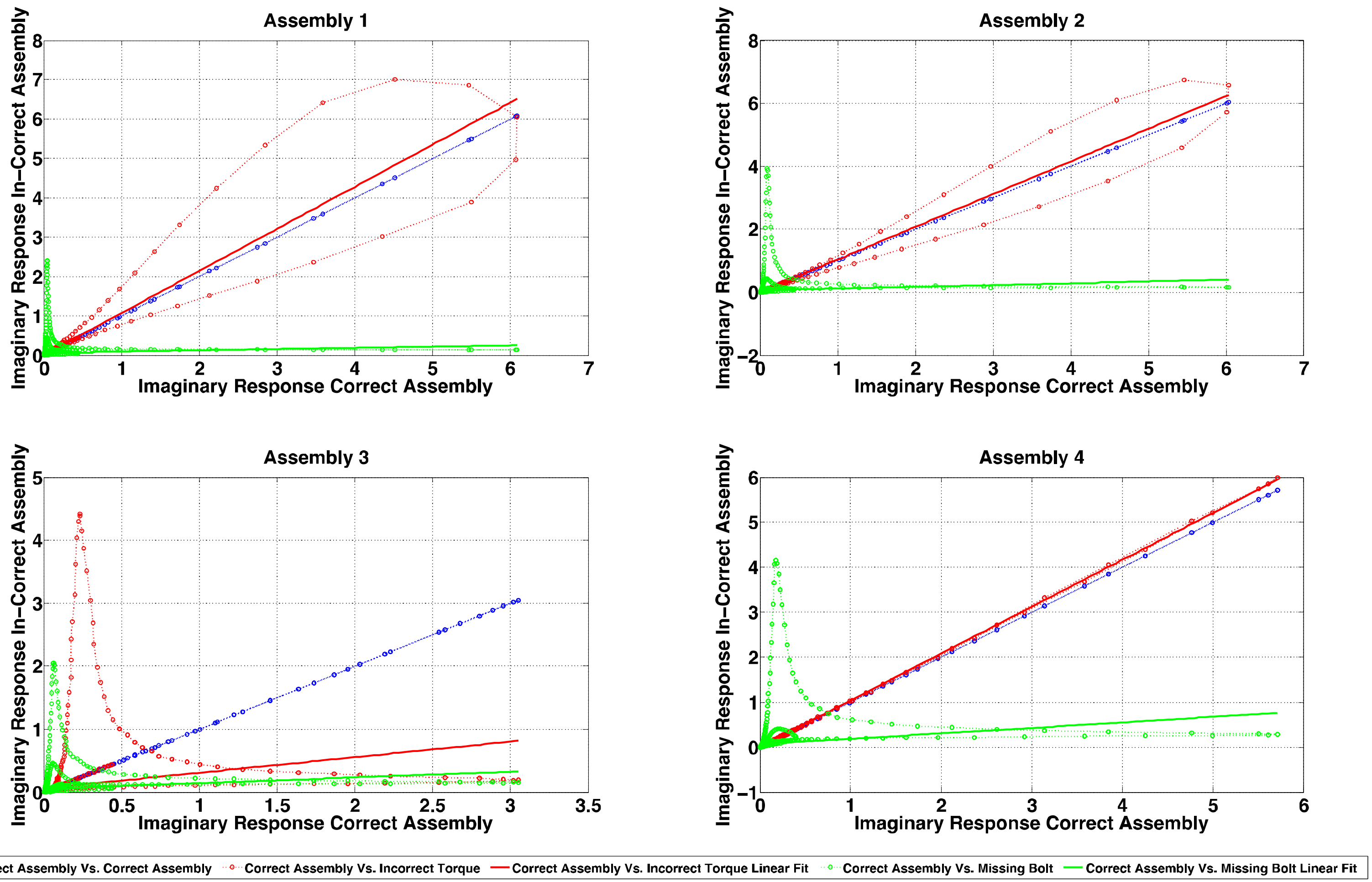
- Visual and Quantitative metric to compare FRF's
- Identical assemblies have a slope and R^2 value of 1
- Residual plots give insight to areas of discrepancies
- Linear fits demonstrate differences between the "Assembly 1" fixture and other fixtures when correctly assembled to test article





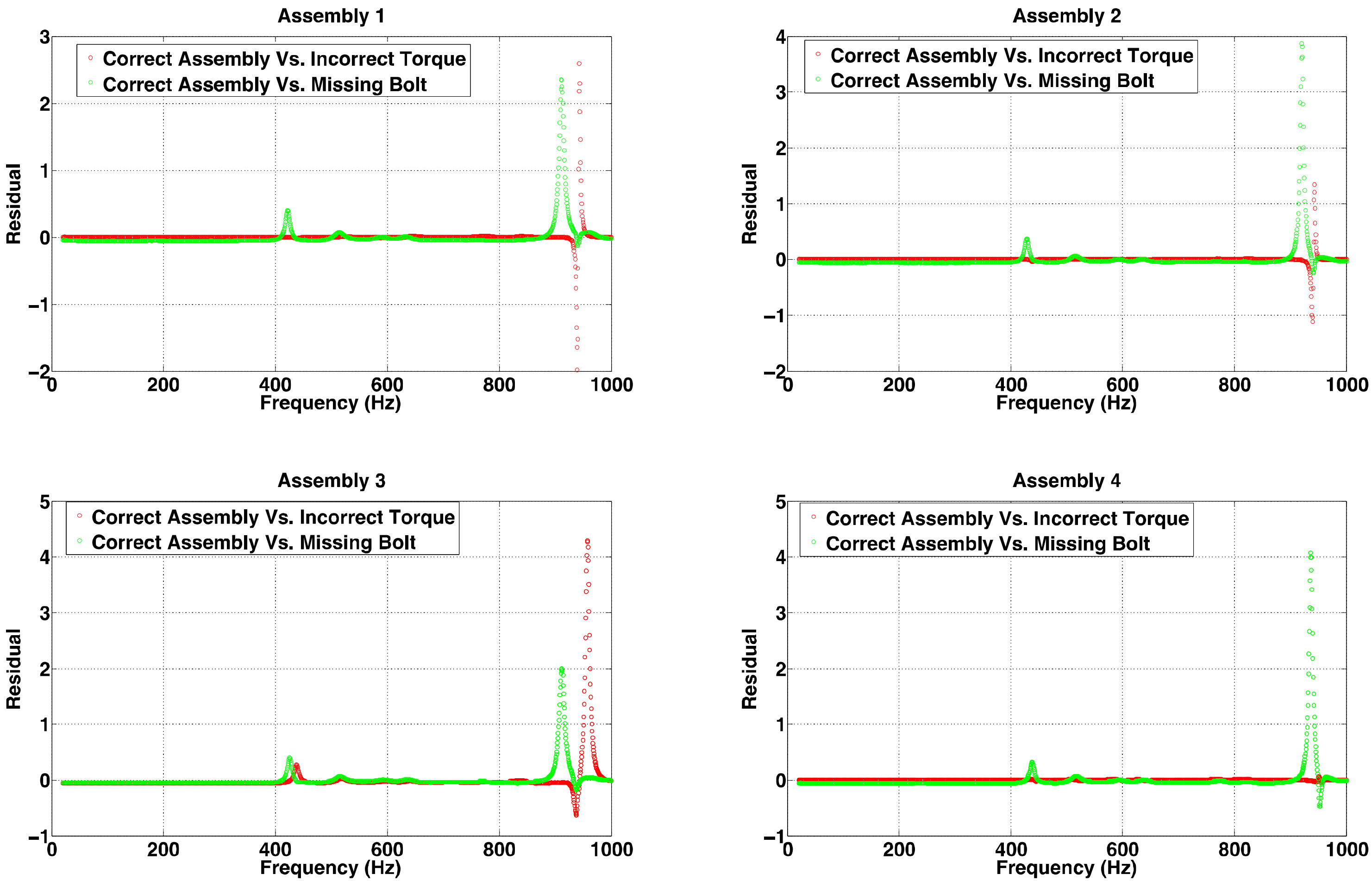
R^2 coefficient of Imaginary Response: In-Correct Assemblies

- R^2 metric captures missing bolt error easily
- R^2 metric does not capture incorrect torque error



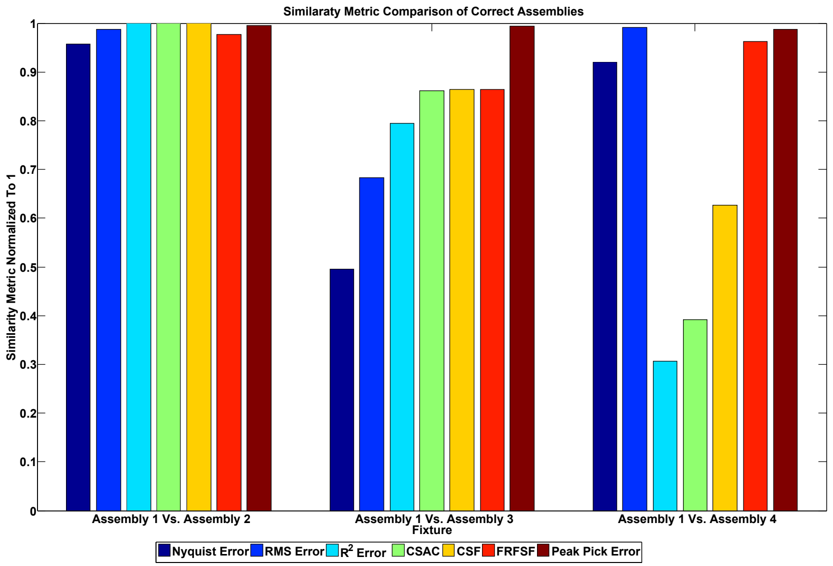
R^2 coefficient of Imaginary Response: Residuals

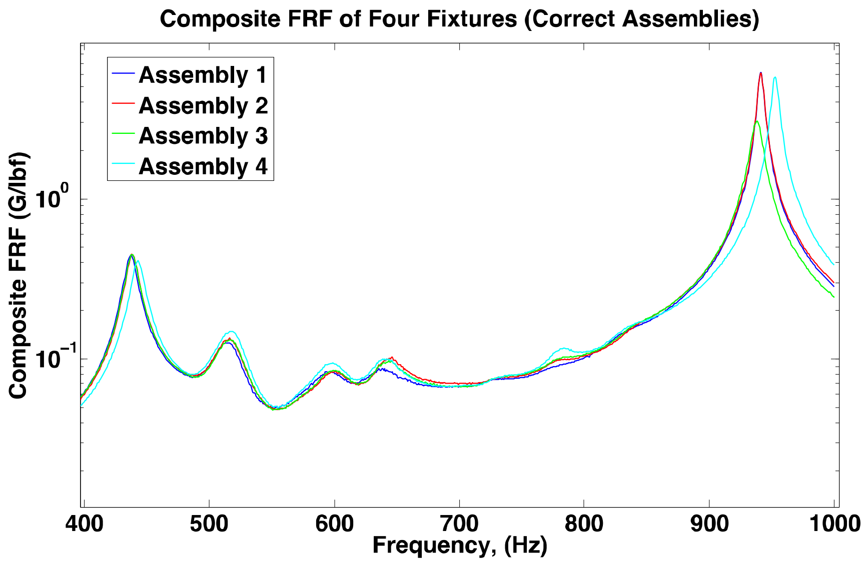
- Higher frequency modes responsible for majority of discrepancies



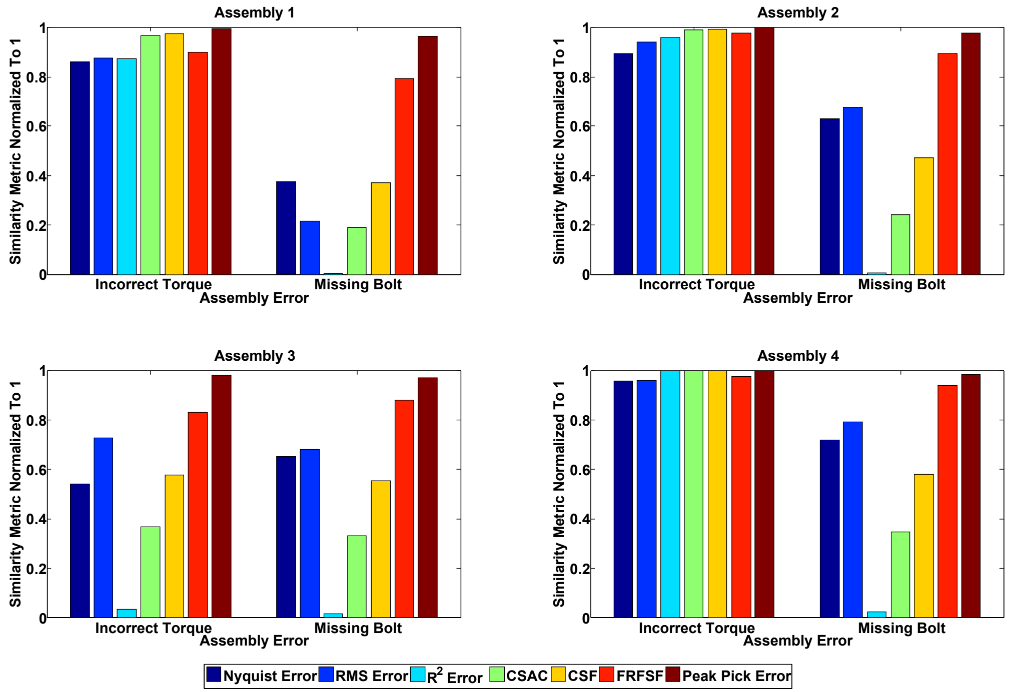
Summary of Metrics: Correct Assembly

- Natural Frequency comparison fails to capture “Assembly 3” and “Assembly 4” fixture differences in FRF
- Nyquist and RMS Error metrics fail to capture difference due to frequency shift in “Assembly 4” fixture
- R^2 error, CSAC, and CSF perform well at identifying different hardware amongst correct assemblies





Summary of Metrics: Incorrect Assembly



- Most metrics capture missing bolt, yet fail to capture incorrect torque
- RMS and Nyquist criteria performs well for both assembly errors
- Natural frequency comparison fails to detect any discernable assembly error
- Wide range of results demonstrate difficulty in similarity assignment

Results

- Averaged Similarity metrics an indication of threshold values that determined similarity
- High similarity metric average for incorrect assemblies demonstrates a “bad” similarity metric (Peak Pick Error, FRFSF)
- Lower similarity metric error demonstrates sensitivity to assembly errors and a “good” similarity metric
- Better statistics required to determine best metric or set of metrics

	Nyquist Error	RMS Error	R^2 Error	CSAC	CSF	FRFSF	Peak Pick Error
Incorrectly Torqued Average Similarity	0.81	0.88	0.72	0.83	0.89	0.92	0.99
Missing Bolt Average Similarity	0.59	0.59	0.01	0.28	0.49	0.88	0.97

Future Work

- Continue to evaluate similarity metrics on upcoming hardware
  - Test identical hardware for comparison
  - Test new, much larger assemblies
  - Test small, simplified geometries to

- Develop possible new metrics or procedures to evaluate similarity
  - Vibration metrics / procedures
  - Develop bounds of acceptability by enveloping responses
  - Acceptance criteria based on energy instead of frequency

- Design specialized similarity fixtures to eliminate un-known fixture dynamics

- Back to basics
  - Simplified test using less joints and simple geometry

Thank You!

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