Assessment of Validation Metrics for UNDEX Simulations

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Underwater Explosion (UNDEX) Event

- **USS Arkansas (CGN-41) Full Ship Shock Test**

- **Floating Shock Platform (FSP) Test**

Image courtesy of
Hi-Test Laboratories, Inc.

Response Quantities of Interest (QoIs)

- **Various response quantities of interest (QoIs) are applied to assess validity of UNDEX simulations**
  - **Windowed acceleration shock spectra**
  - **Windowed pseudo-velocity shock spectra**
  - **Windowed RMS time-history**
  - **Windowed input energy**
  - **Windowed strain energy**
  - **Windowed energy equivalent velocity**
  - **Band limited temporal moments**
- **Windowing is used to discretize continuous spectral or temporal measures for subsequent use in quantifying margin and uncertainty.**

Energy Based QoIs

- **The relative input energy to a single degree of freedom (SDOF) base excited system is defined as**

$$\frac{dE_i}{m} = -\int \ddot{u}\, \dot{z}\, dt = E_I$$

  where   *m* – **mass,**

          $\ddot{u}$ – **base acceleration, and**

          $\dot{z}$ – **relative velocity of mass**

- **Energy equivalent velocity was developed because it scales linearly with input**

$$V_{EQ} = \sqrt{2E_I}$$

- **Peak strain energy is the maximum stored potential energy in the SDOF spring used for the spectral calculations**

Bandpass Temporal Moments

- **Temporal moments are calculated as weighted summations of the time signal squared**

$$M_i(t_s) = \int (t - t_s)^i (y(t))^2 dt$$

- **The temporal moments are normalized to generate central moments**

$$E = M_0, \quad A_e^2 = \frac{E}{D}, \quad T = \frac{M_1}{M_0}, \quad D^2 = \frac{M_2}{M_0} - \left(\frac{M_1}{M_0}\right)^2$$

$$S_t^3 = \frac{M_3}{M_0} - 3\left(\frac{M_1 M_2}{M_0^2}\right) + 2\left(\frac{M_1}{M_0}\right)^3, \quad S = \frac{S_t}{D}$$

$$K_t^4 = \frac{M_4}{M_0} - 4\left(\frac{M_1 M_3}{M_0^2}\right) + 6\left(\frac{M_1^2 M_2}{M_0^3}\right) - 3\left(\frac{M_1}{M_0}\right)^4, \quad K = \frac{K_t}{D}$$

- **Bandpass filtering is used to separate time history signal into meaningful bandwidth components**

Windowed Metric Example
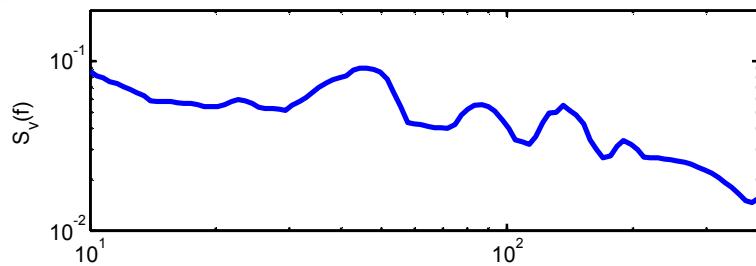


Pseudo-velocity SRS of the acceleration, $S_v(f), f \epsilon F$
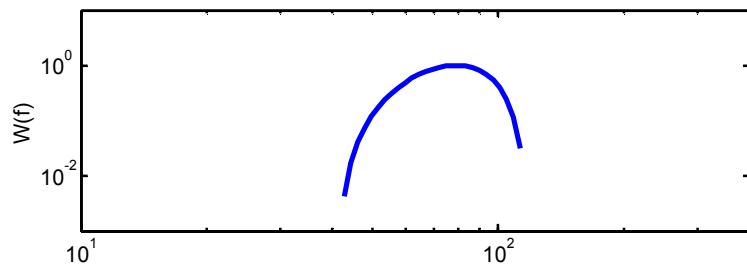
**Nonnegative, finite-valued window,** $W(f), f \epsilon F$
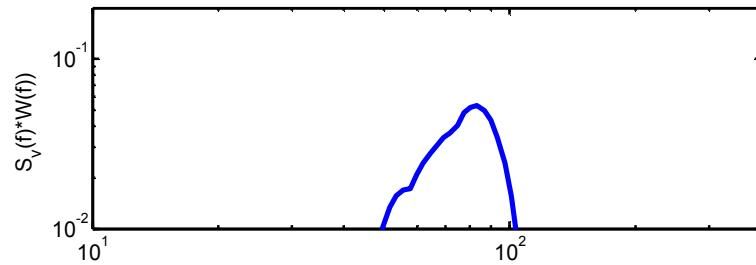
Product of SRS and Window $S_v(f) \times W(f), f \epsilon F$
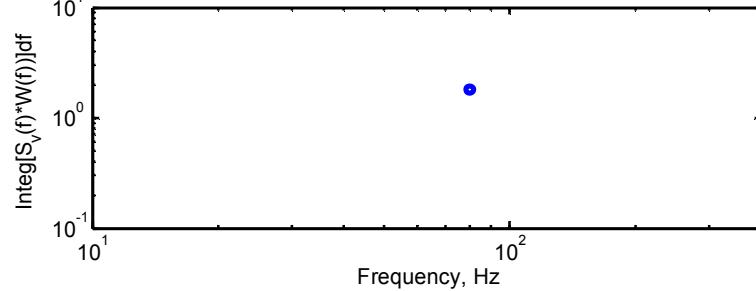
Integral of product of SRS and window, $\int S_v(f) \times W(f) df$. **Weighted average of SRS; discrete measure of SRS within frequency band.**

Windowed Metric Example
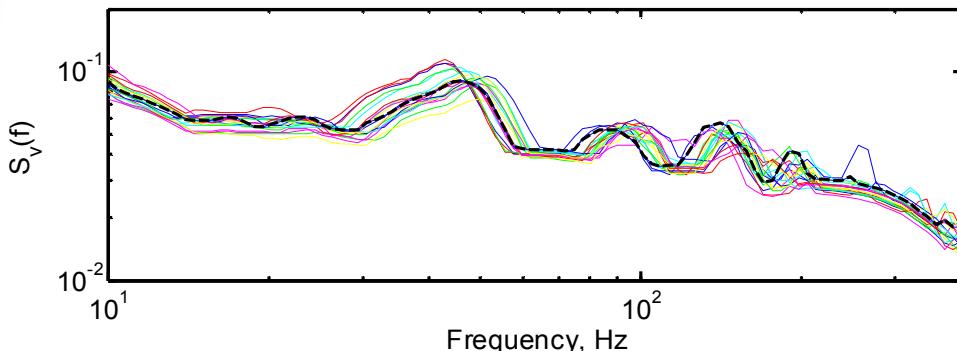
Compute the windowed measures of all model-generated SRS and the experimental SRS (black)
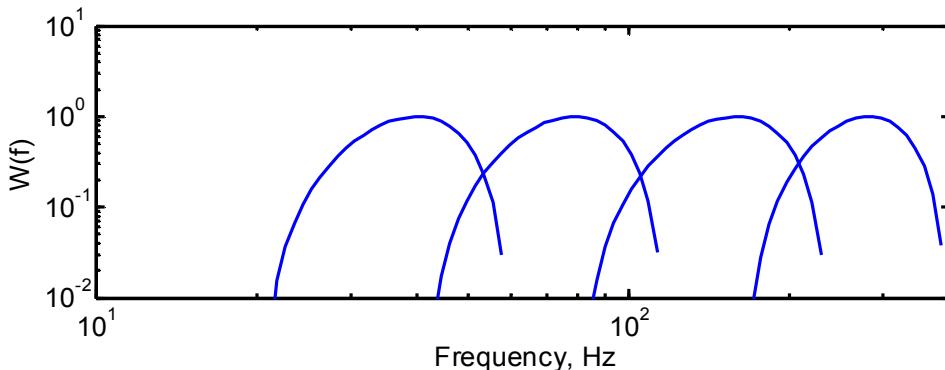
Use multiple windows
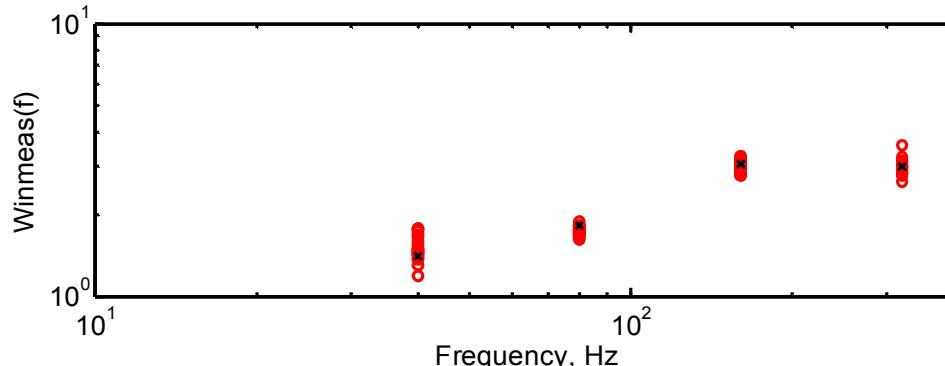
Plot model-generated windowed measures of SRS (red) with windowed measure of SRS from experiment (black)

Demonstration Problem

- A standard data set has been identified consisting of a single barge shock test with measurements at eight locations

- Experimental data was obtained using a bandpass 2-pole Bessel filter set at 0.25 and 250 Hz, respectively
- A corresponding set of 10 analyses were conducted where only the charge density was changed

Spectral QoI Parameter Definitions

- Gaussian windows are used in all cases

- Spectral quantities are calculated from 1-250 Hz in 40 logarithmically spaced increments using 5% damping for SRS calculations

- Center frequencies for windowing spectral quantities are 10, 20, 40, 80 and 160 Hz

- Corresponding window widths are 10, 20, 40, 80 and 160 Hz

- This definition of window center frequencies and widths was chosen to maximize coverage of 1-250 Hz frequency range with increased emphasis on the lower frequencies which are most significant for this class of structure

- Experimental and analytical velocity-time histories are numerically differentiated prior to spectral QoI calculations

Temporal QoI Parameter Definitions

- Gaussian windows are used in all cases

- The first 0.021 sec of response was evaluated for the temporal QoIs

- A 1.5 msec interval width with no overlap is used for RMS calculations where an RMS value is calculated for each point in the time domain

- 10 equally spaced windows without overlap are used for the RMS calculations

- The 1-250 Hz frequency range is divided into three, non-overlapping component bandwidths for the moment calculcations

- The bandwidth regions are 1-84 Hz, 84-167 Hz and 167-250 Hz with center frequencies of 42.5, 125.5 and 208.5 Hz, respectively

- Temporal QoI calculations use experimental and analytical velocity-time histories directly

Application of Validation Measures

- **Analysis results were filtered using a bandpass 2-pole Bessel filter set at 0.25 and 250 Hz, respectively, for visual comparison purposes only**

- **Comparison of filtered results at the eight gauge locations were visually ranked good (3), bad (3) and questionable (2)**
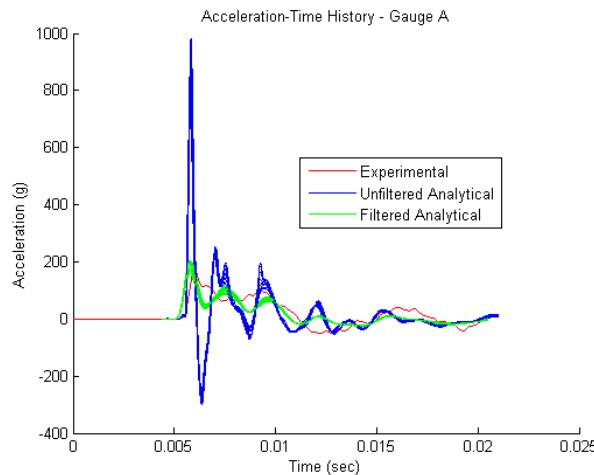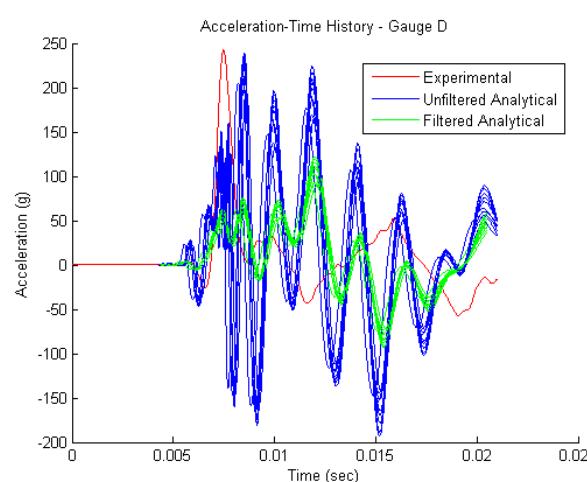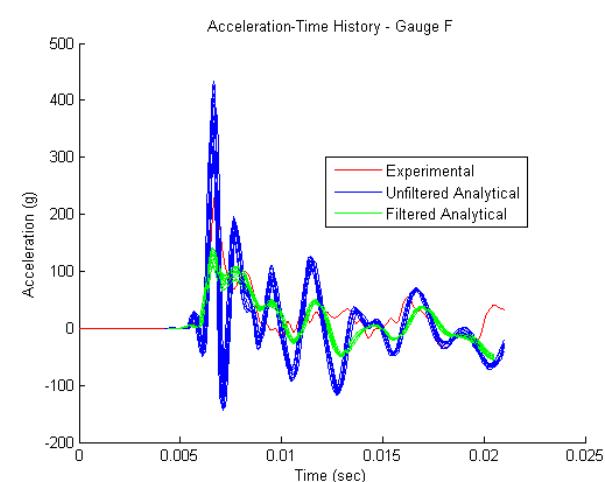

**Good** **Bad** **Questionable**

Spectral QoIs Calculated for Good Results
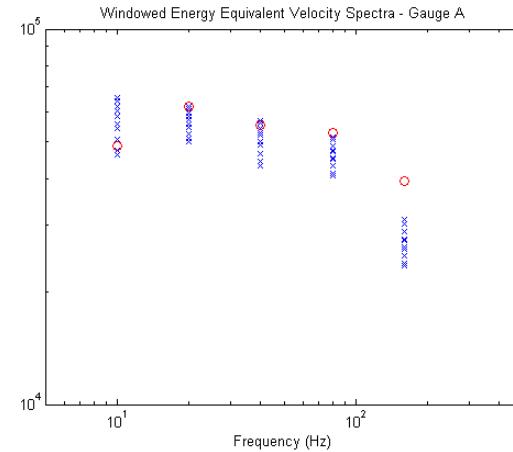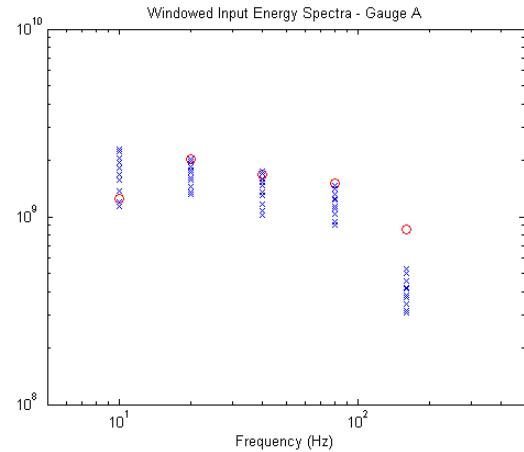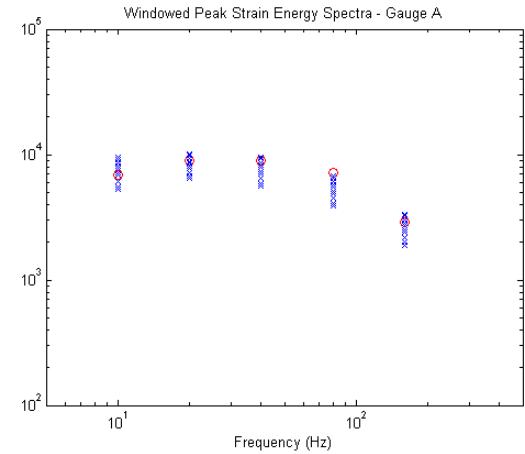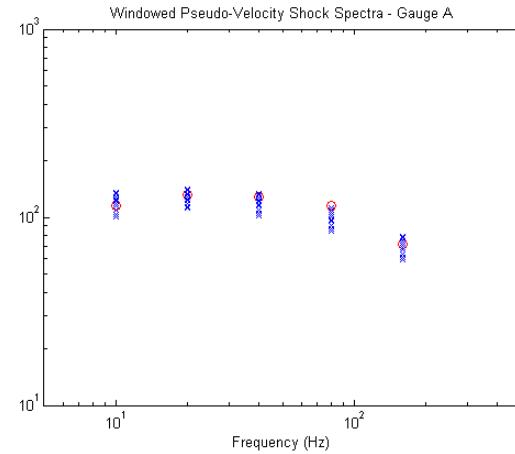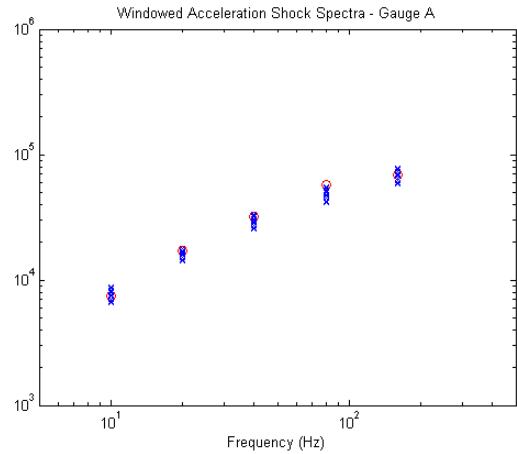
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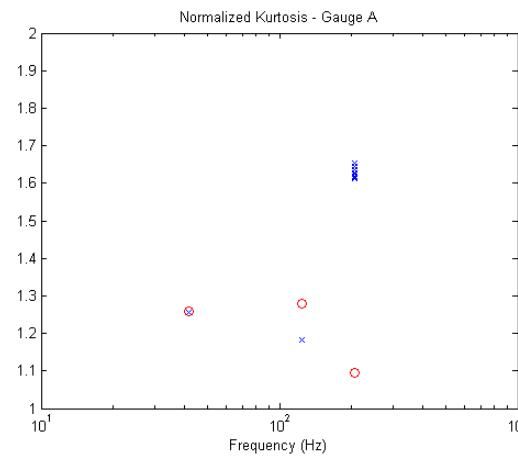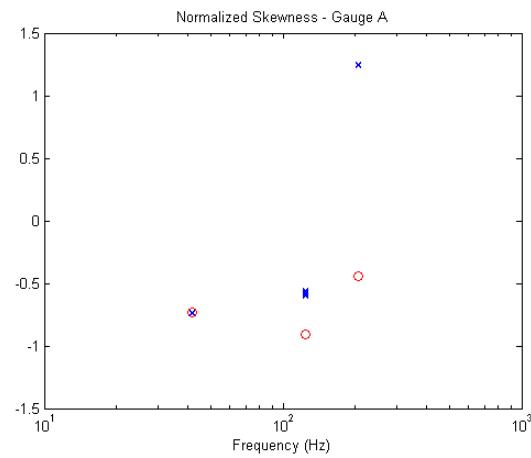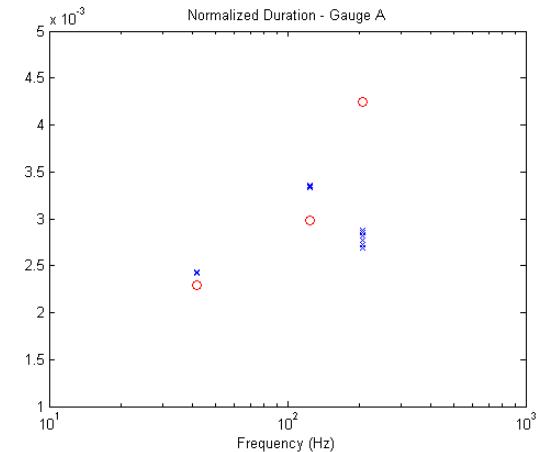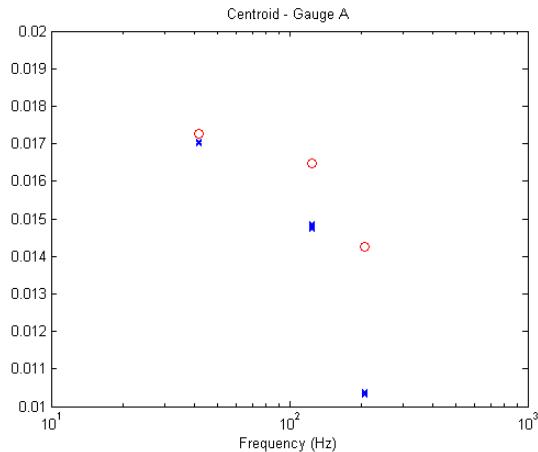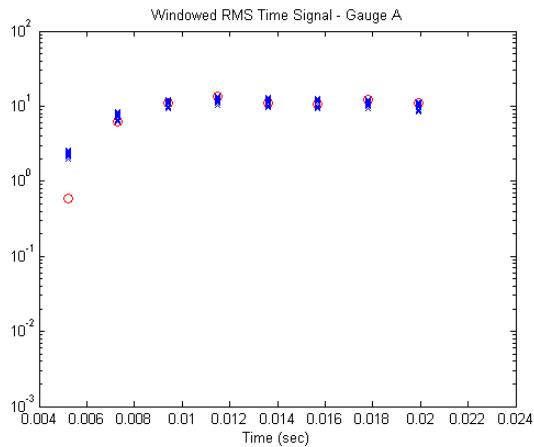
Spectral QoIs Calculated for Bad Results
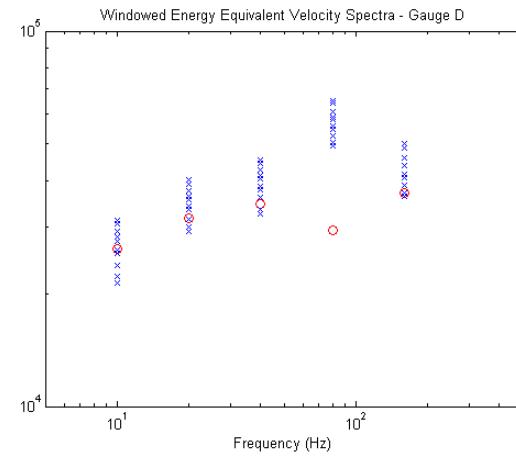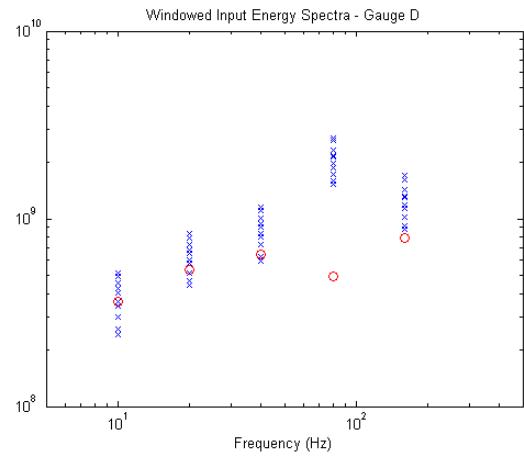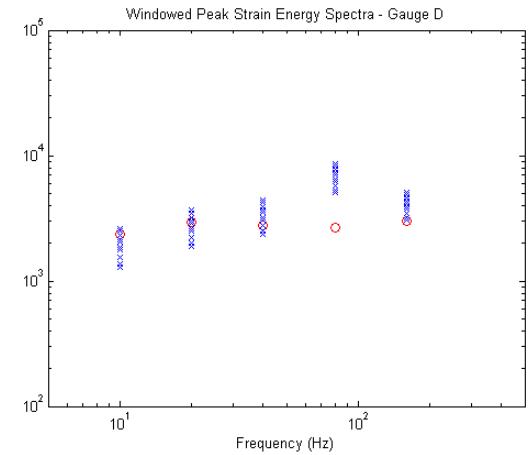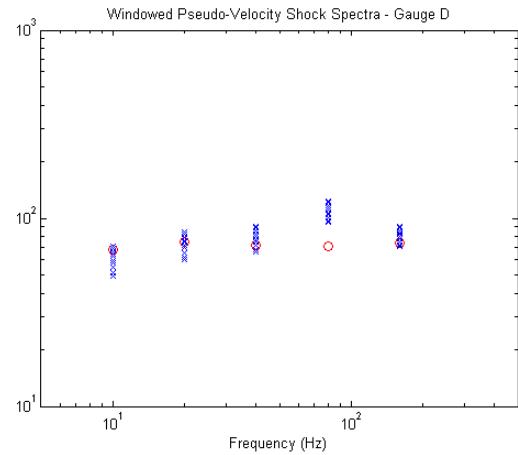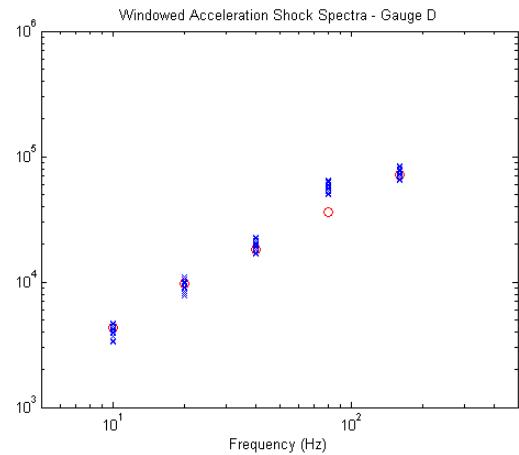
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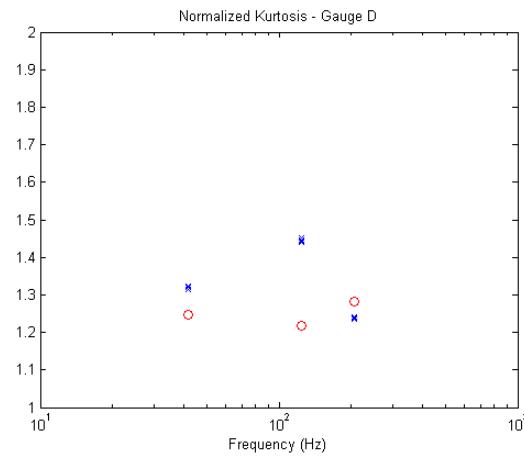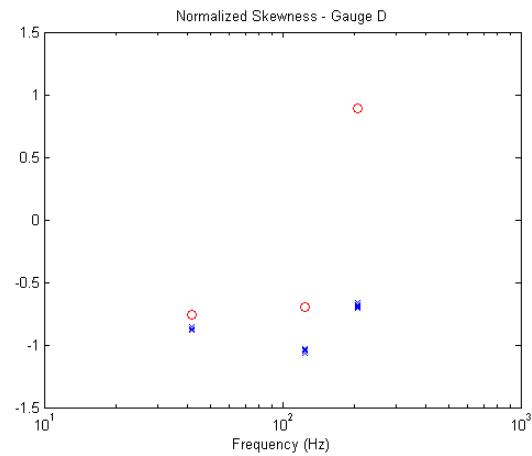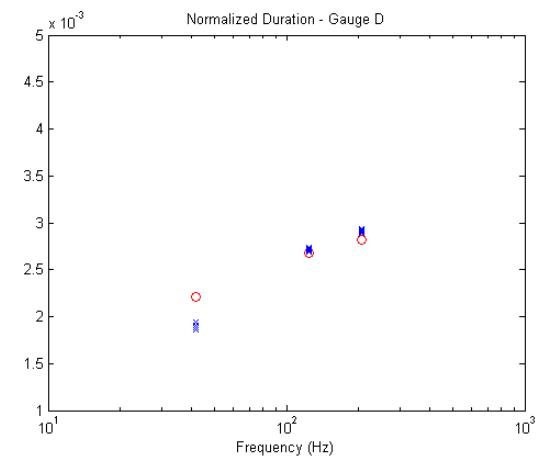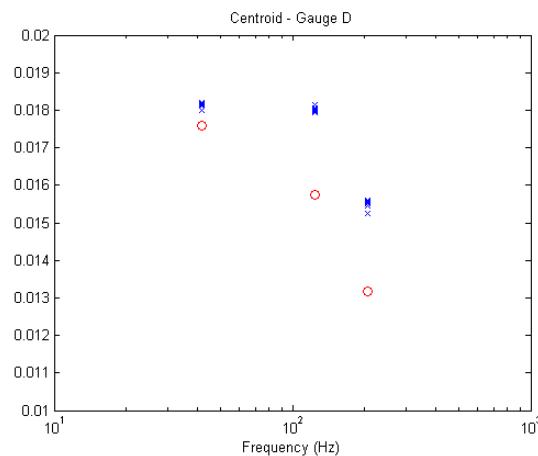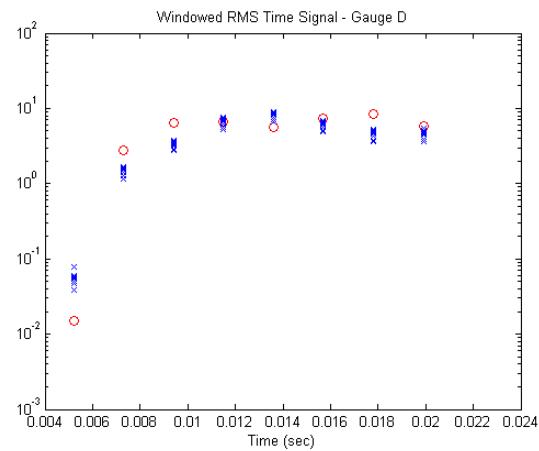
Spectral QoIs Calculated for Questionable Results
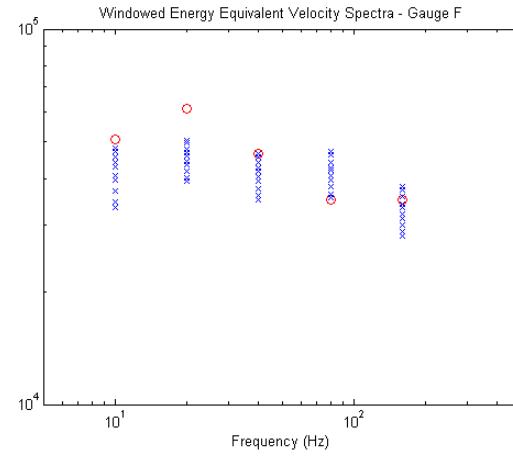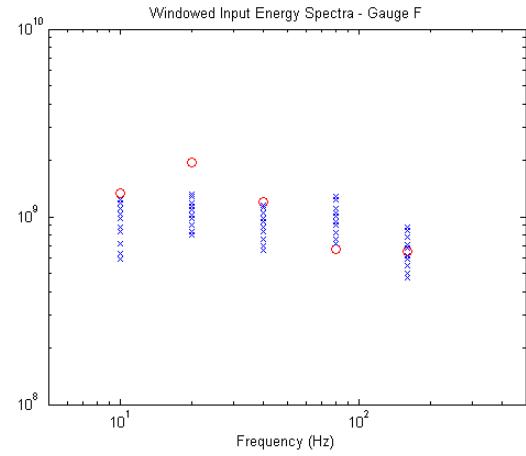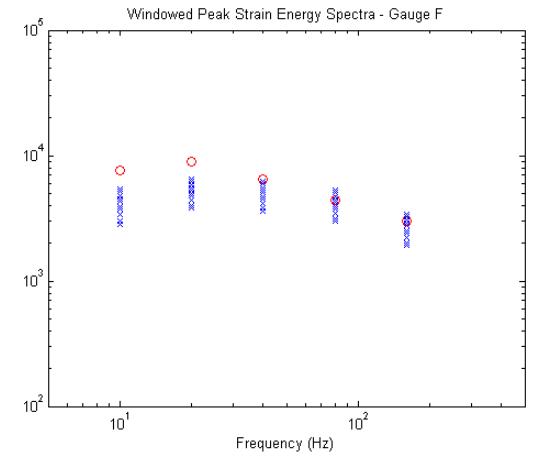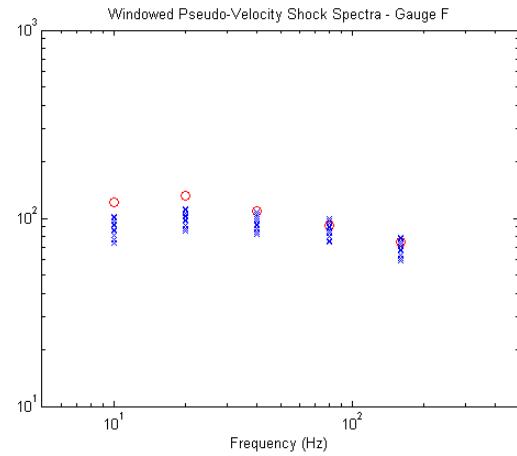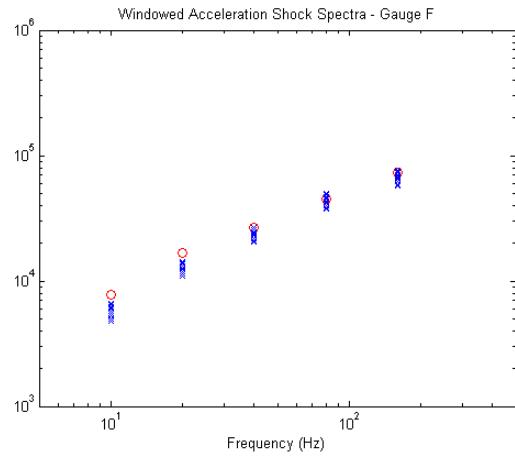
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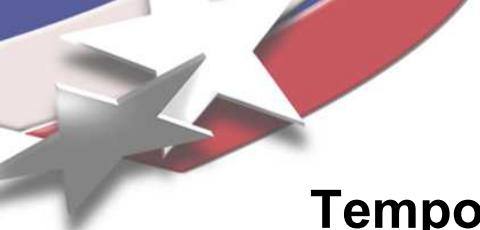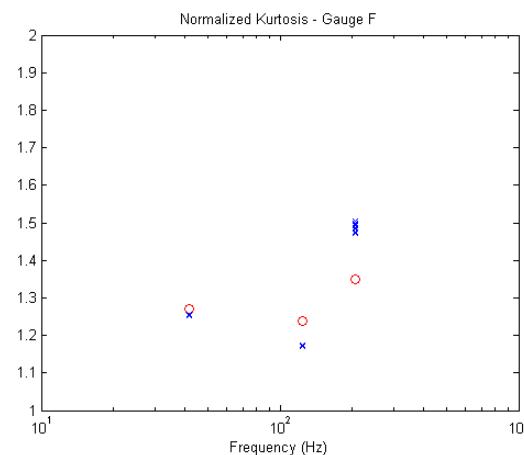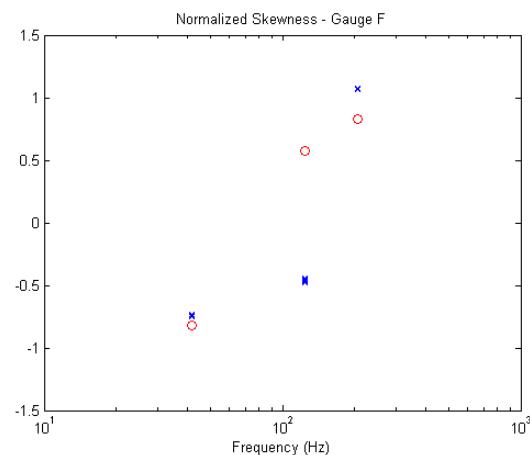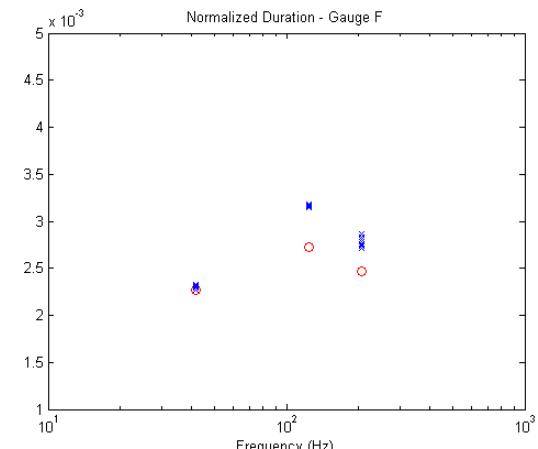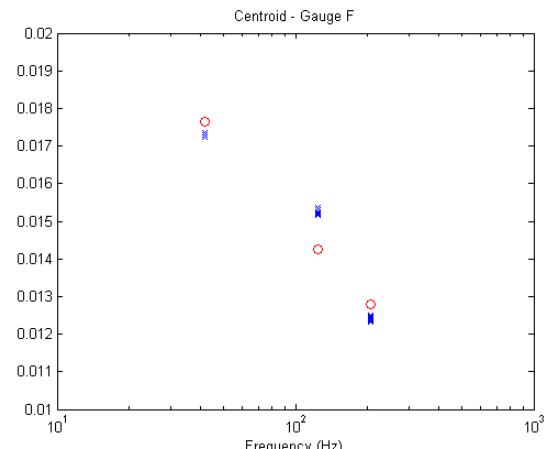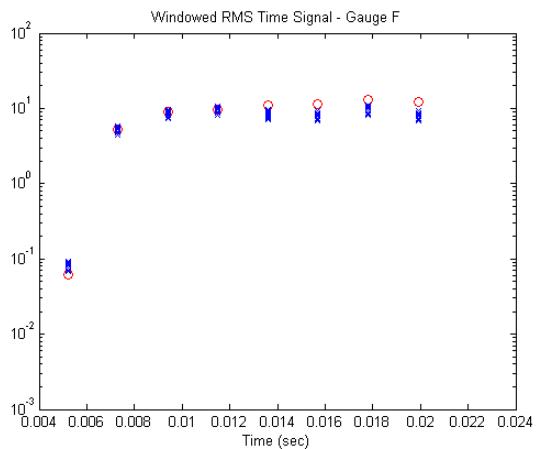
# Observations

- **Windowed RMS time signal provides best correlation with the visual assessment**
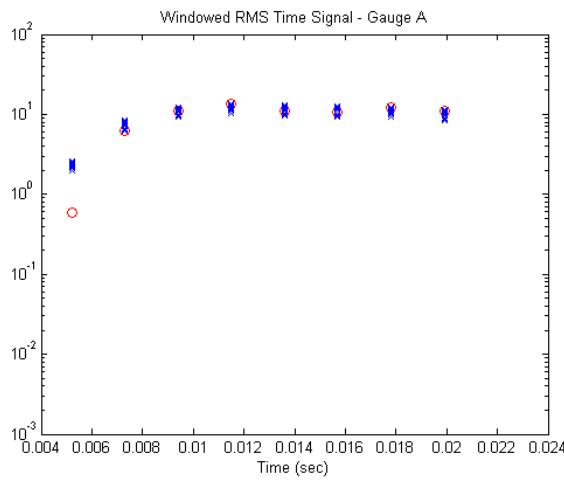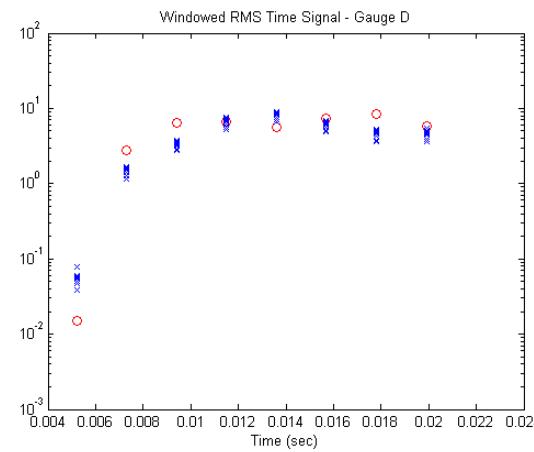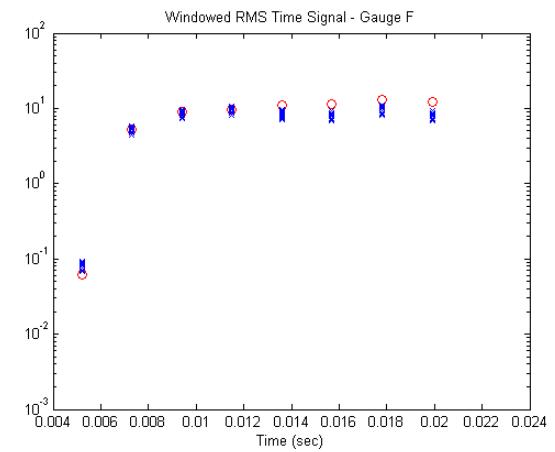
| Good | Bad | Questionable |

- **The trend of windowed RMS correlation holds for the remaining gauge locations**
- **The correlation at early times dominates the judgment**

Conclusions

- The QoIs examined in this paper provide discrete measures of system response that can be used to quantitatively compare test and analysis results

- The validation process can be formalized by applying test-of-hypothesis to compare experimental and analytical response measures and make an assessment of model validation

- Sensitivities of the QoIs must be further examined to establish acceptable tolerance limits for hypothesis testing

- The QoIs discussed in this work do not consider spatial variation or ranking

- Assuming all gauges have equal importance for the above sample problem, it would be concluded that the model is not validated due to bad and questionable correlation constituting five out of eight gauge response measures