Orientation of Power Equipment in Seismic Qualification Testing

Anshel Schiff

[1] *Principal, Precision Measurement Instruments, Los Altos Hills, CA, USA*
Email:Schiff@stanford.edu

ABSTRACT:

IEEE 693, "IEEE Recommended Practice for Seismic Design of Substations," is used to seismically qualify electrical power equipment in the United States. It requires equipment operating at or above 161 kV to be seismically qualified by shake-table testing. Input test motions are specified by the Required Response Spectrum (RRS). The response spectra of theoretical shake-table input records are typically within 5% of their target values. The Test Response Spectra (TRS), which are derived from table-mounted accelerometers, are typically within 25% of the RRS. Some power equipment is structurally simple and modes of vibration can be estimated, however, small variations in the method of installation can cause a large change in the mode shape orientation. When equipment is tested it is generally assumed that the modes of vibration are aligned in the directions that the table motions have been optimized. If the actual mode shapes are aligned along different axes, the equipment can be over or under test by as much as 60% when using theoretical analysis and deviations in actual table motions may be larger. Thus, minor changes in the method of installing the equipment on the shake table can cause large variations in the degree of over or under testing. For complex systems the modes of vibration can have different orientation for each mode so that it is not possible to orient the equipment to conform to the directions for which the TRS has been optimized. This demonstrates that even when testing is done correctly qualification results may not meet qualification objectives.

KEYWORDS: testing, qualification, equipment, orientation

1. BACKGROUND

The orientation of the modes of vibration of an item of equipment are primarily determined by the equipment, but can be influenced by the support structure and equipment are secured to the shake table. Details of the construction of an item of equipment, which may not be obvious by looking at the equipment, may also influence the orientation of the modes of vibration. The Test Response Spectra (TRS) are typically optimized to conform to the Required Response Spectrum (RRS) along the primary directions of excitation, say X, Y, and Z directions. In tests of an instrumentation transformer, it was observed that the modes of vibration of the equipment installed on the support structure were orientated at 45 degrees to the X and Y directions. This was controlled by the anchor bolt pattern that secured the support structure to the shake table.

To explore what affect this may have on the test results three sets of table motions were analyzed. Two sets are the motions suggested in IEEE 693, Motion 1 (CERL) and Motion 2 (Landers) are evaluated. These are theoretical motions that would be used as input to the shake table. A third set are the actual table motions recorded, Motion 3 (MCEER), from tests on the shake table used to qualify the instrument transformer mentioned above. Each record was normalized to conform to the High Performance Level, that is, a 1.0g RRS. Projecting the original motions on axes at 45 degrees to the original axes generated a new set of motions. These are referred to as the XX and YY records. The 2% damped TRS were then calculated for the transformed records.

2. TRANSFORMATION OF THE RECORDS

The horizontal components of each set of records have been evaluated to determine the variation in the TRS along axes different from the direction for which the TRS have been optimized. The motion from the two horizontal table motions was projected on axes orientated at 45 degrees using the equations given below to generate a new set of records.

The X and Y are the original records and the new records are defined by the following equations.

$$XX = X * \text{Sin}\ (45^0) + Y * \text{Cos}\ (45^0)$$
$$YY = X * \text{Sin}\ (45^0) - Y * \text{Cos}\ (45^0)$$

3. EVALUATION OF TABLE MOTION 1

Figure 1 shows the X and Y records for Motion 1 and the corresponding TRS. Note that the TRS in the 1.1 Hz to 8 Hz range is relatively flat, as required by the RRS. Figure 2 shows the transformer Motion 1 records, XX and YY, and the corresponding TRS. Note that the character of the accelerations shown in Figures 1 and 2 are similar, however, the character of the TRS in the 1.1 Hz to 8 Hz range are very different with the Transformed Motion 1. The transformed TRS show much larger variations. For a direct comparison Figure 3 shows all of the TRS on a single plot. In the 1.1 Hz to 8 Hz range the RRS is 3.25, and the Motion 1 TRS should envelop this value, a condition that is satisfied. While the largest variation is in the low frequency range below about 3 Hz, there are significant variations in the frequency range corresponding to most substation equipment. Equipment that use composite insulators and 500 kV-equipment will typically be in the lower frequency range. In addition, Figure 3 shows that when one of the transformed components has a low spectral amplitude, the other component mirrors this with a high spectral amplitude.

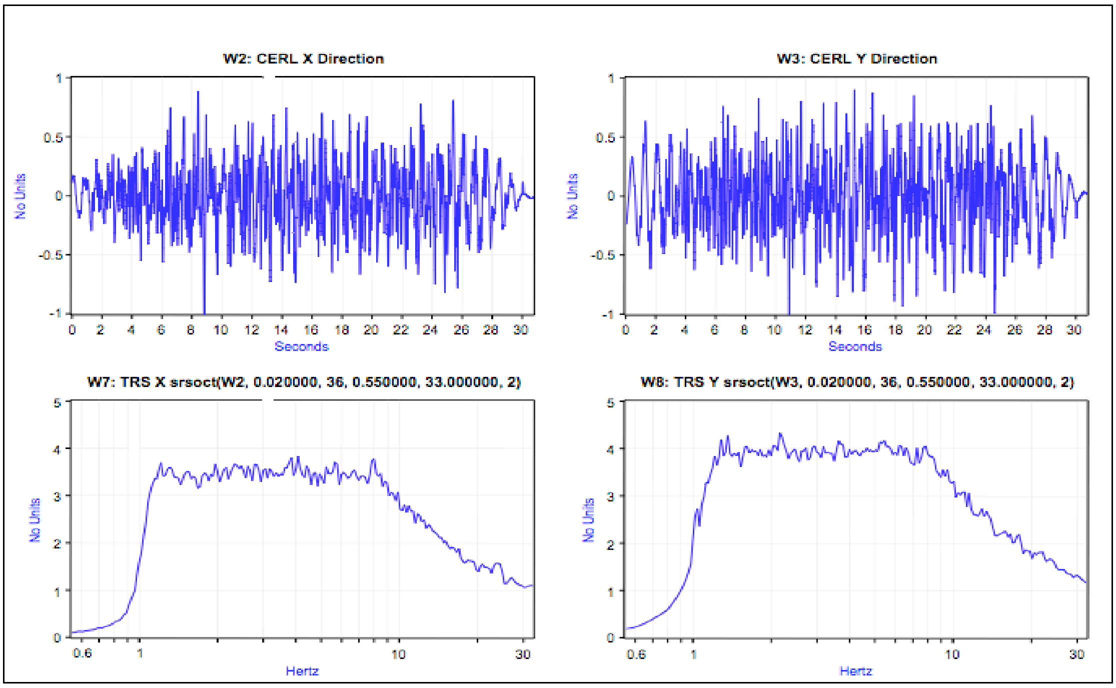

Figure 1 Records and TRS for the table input Motion 1

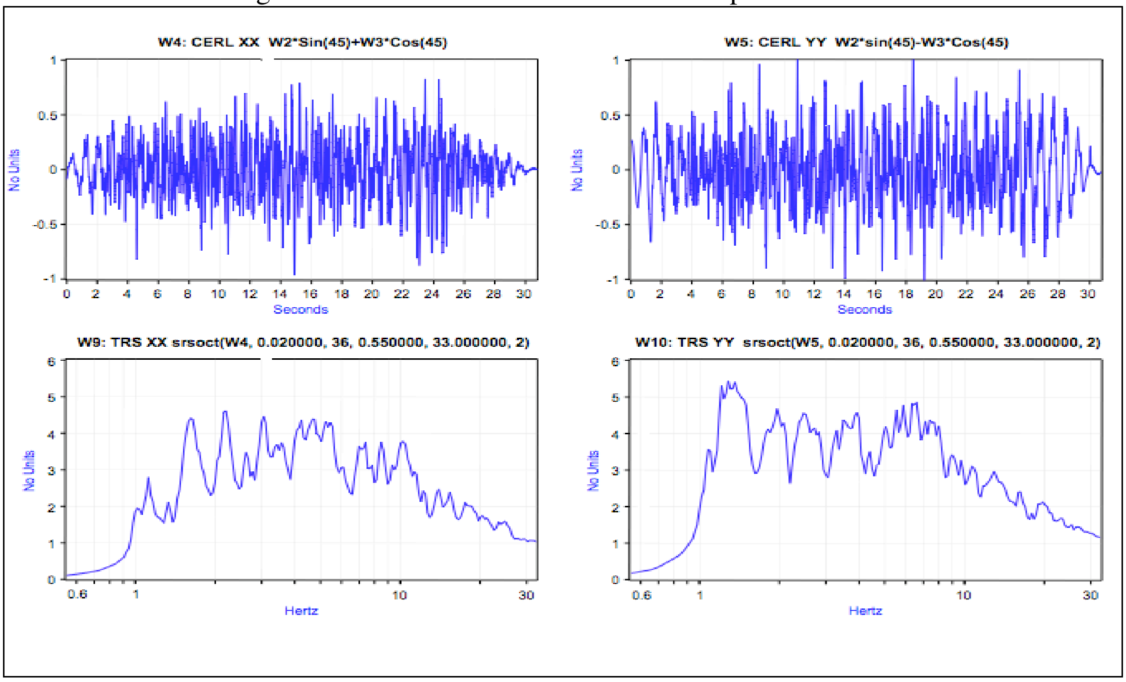

Figure 2 Records and TRS for the Transformed Motion 1 records

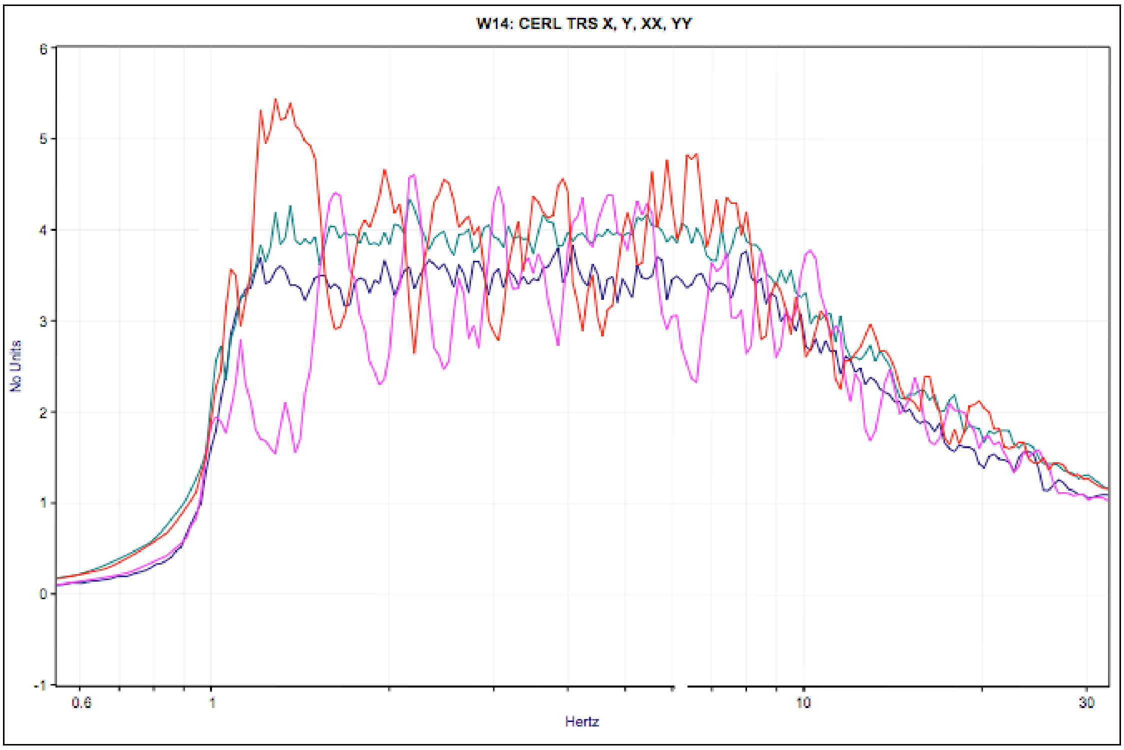

Figure 3 TRS for the Motion 1 and Transformed Motion 1

Major peaks and valleys of the TRS in the 1.1 Hz to 8 Hz frequency range are given in Table 1. For the original records only the minimum and maximum values are shown. These records correspond the Performance Level excitations, that is, they have a TRS that envelopes twice the 0.5g RRS. Thus, the value of the RRS in the 1.1 Hz to 8 Hz range would be 3.25. Note that the minimum X value is 3 % below the target level and the maximum is 16% above the target value. The minimum XX TRS is 29% below the target value and the maximum is 38% above the target value. Motion 1 is an-input table acceleration. Had they been measured table motions, the TRS would have exhibited much large variations so that the equipment would have experiences significant over and under testing.

Table 1 Motion 1 TRS Values in the 1.1 Hz to 8 Hz Frequency Range

X		XX		Y		YY	
Extreme	Amplitude	Frequency	Amplitude	Extreme	Amplitude	Frequency	Amplitude
Minimum	3.16	1.62	4.4	Minimum	3.61	2.2	2.64
Maximum	3.77	1.92	2.3	Maximum	4.34	2.47	4.56
		2.47	2.47			3.05	2.79
		3.05	4.47			3.92	4.57
		3.85	2.73			4.57	2.84
		4.23-5.43	4.29			6.59	4.84
		6.59	2.32				
The value of the RRS in the 1.1 Hz to 8 Hz range should be 3.25 and the TRS should closely envelop this value.							

5. EVALUATION OF TABLE MOTION 2

Figures 4 to 6 show similar plots for Motion 2. Note that the minimum TRS of X is 19 % below the target level and the maximum is 6% above the target value. The minimum TRS of XX is 30% below the target value and the maximum is 32% above the target value. The transformed Motion 2 have larger variations at higher frequencies so that more substation equipment would experience over or under testing. Also, the adjacent peaks and valleys are larger than in the other records. The lack of the flat character of the TRS in the 1.1 Hz to 8 Hz range of the transformed plots is striking. Major peaks and valleys of the TRS in the 1.1 Hz to 8 Hz frequency range are given in Table 2.

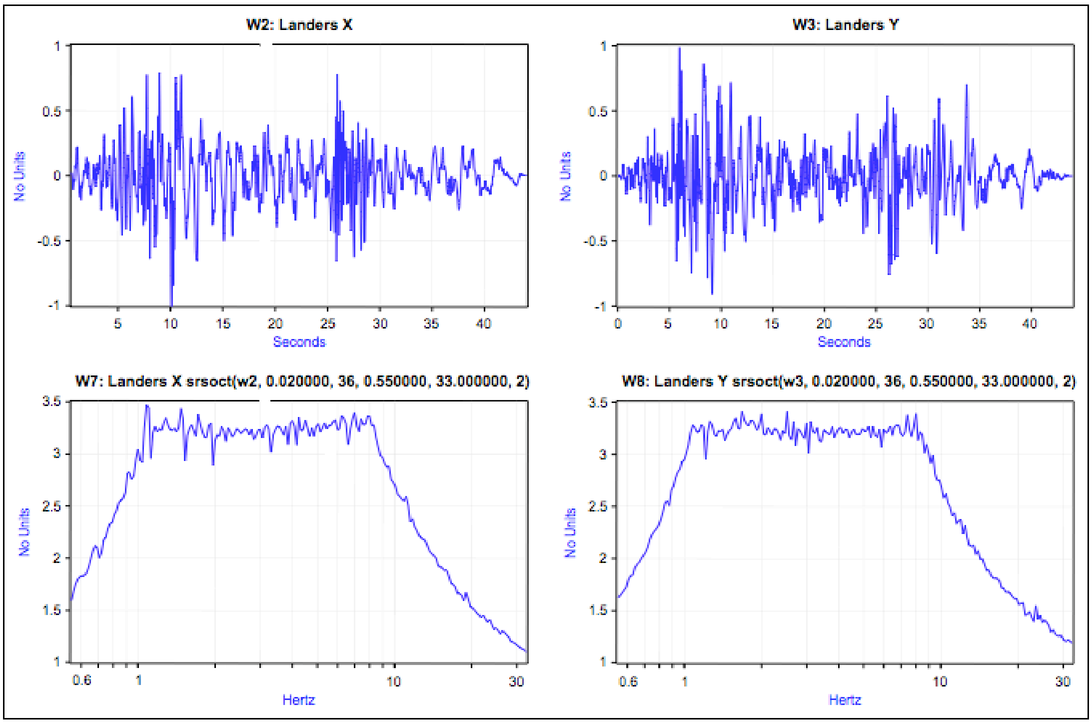

Figure 4 Records and TRS for the horizontal Motion 2 theoretical table motions

Figures 7 to 9 show similar plots for the Motion 3 table motions. Note that the minimum TRS X is 1 % below the target level and the maximum is 31% above the target value. The minimum XX TRS is 6% below the target value and the maximum is 105% above the target value. Larger variations would be expected from the Motion 3 data as it was based on actual test data recorded on a shake table rather than theoretical table motions.

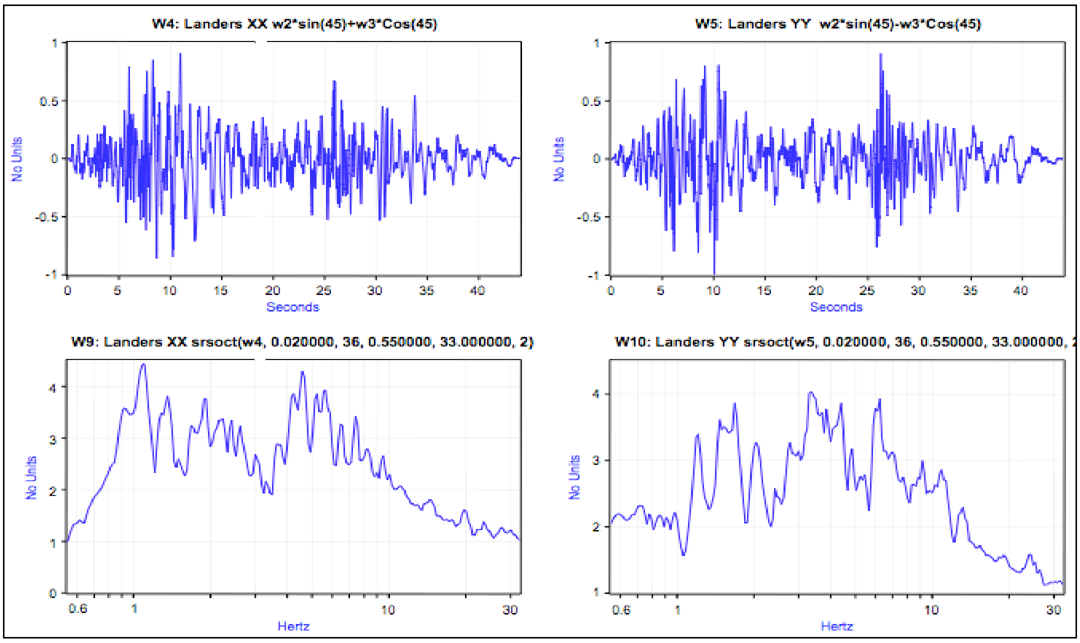

Figure 5 Records and TRS for the horizontal transformer Motion 2 theoretical table motions

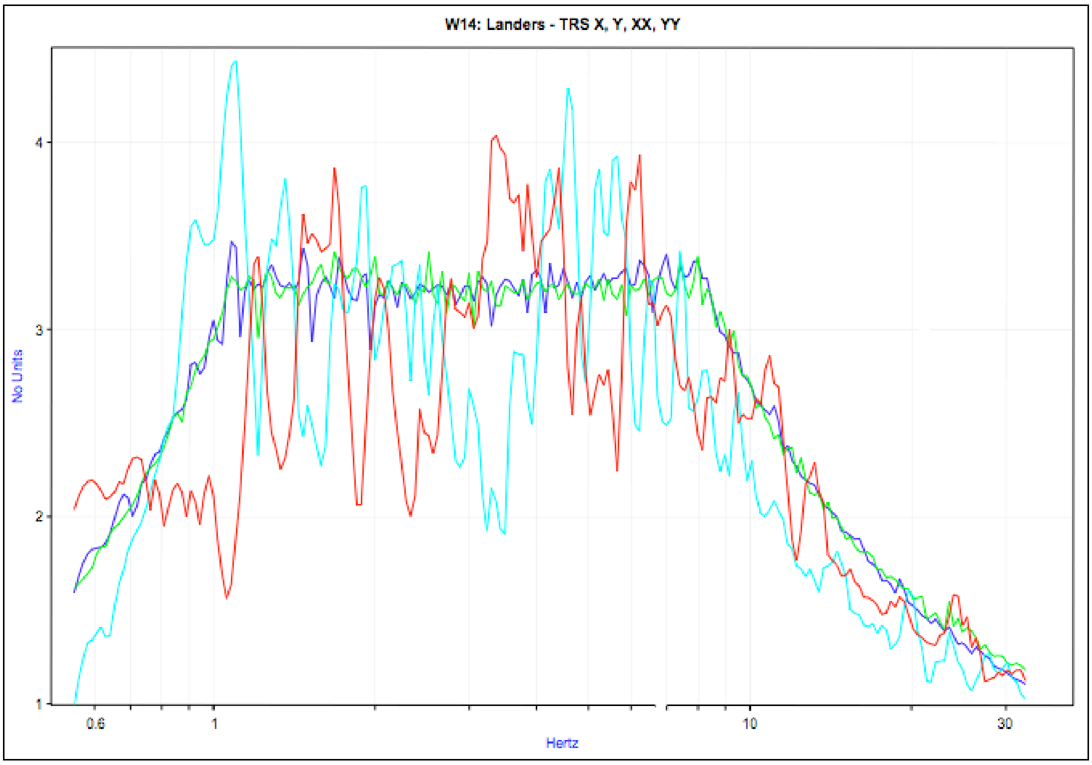

Figure 6 TRS for the Horizontal Motion 2 theoretical table motions

Table 2 Motion 2 TRS Values in the 1.1 Hz to 8 Hz Frequency Range

X		XX		Y		YY	
Extreme	Amplitude	Frequency	Amplitude	Extreme	Amplitude	Frequency	Amplitude
Minimum	2.89	1.1	4.44	Minimum	2.96	1.21	3.39
Maximum	3.44	1.21	2.33	Maximum	3.41	1.33	2.25
		1.36	3.81			1.68	3.86
		1.59	2.27			1.85	2.06
		1.92	3.77			2.04	3.28
		3.49	1.91			2.33	2.00
		4.57	4.29			3.36	4.04
		4.94	2.72			4.40	3.87
		5.65	3.93			5.65	2.24
		6.22	2.46			6.22	393
		7.40	3.42				
The value of the RRS in the 1.1 Hz to 8 Hz range should be 3.25 and the TRS should envelop this value							

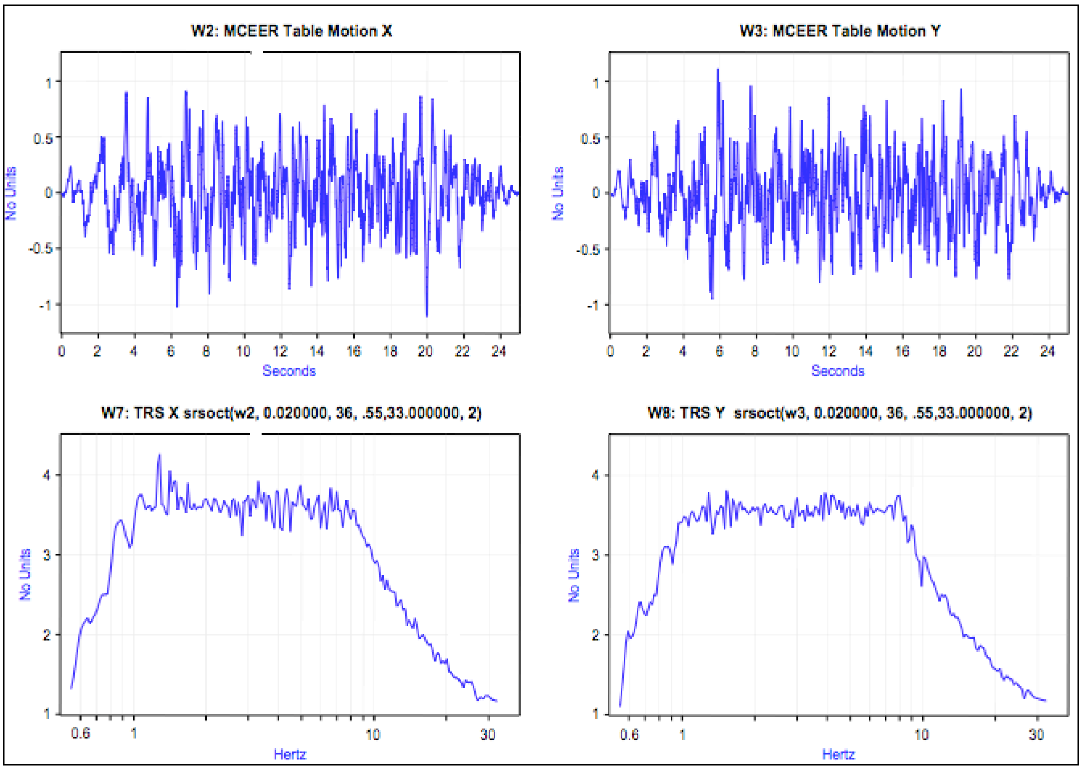

Figure 7 Records and TRS for the horizontal Motion 3 table motions

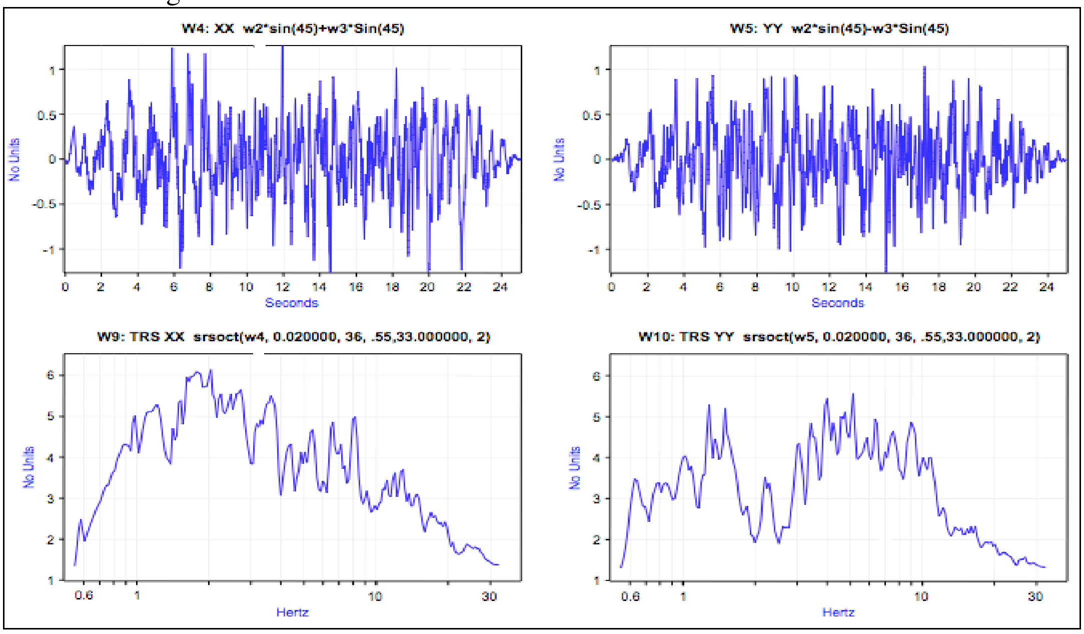

Figure 8 Records and TRS for the horizontal transformer Motion 3 table motions

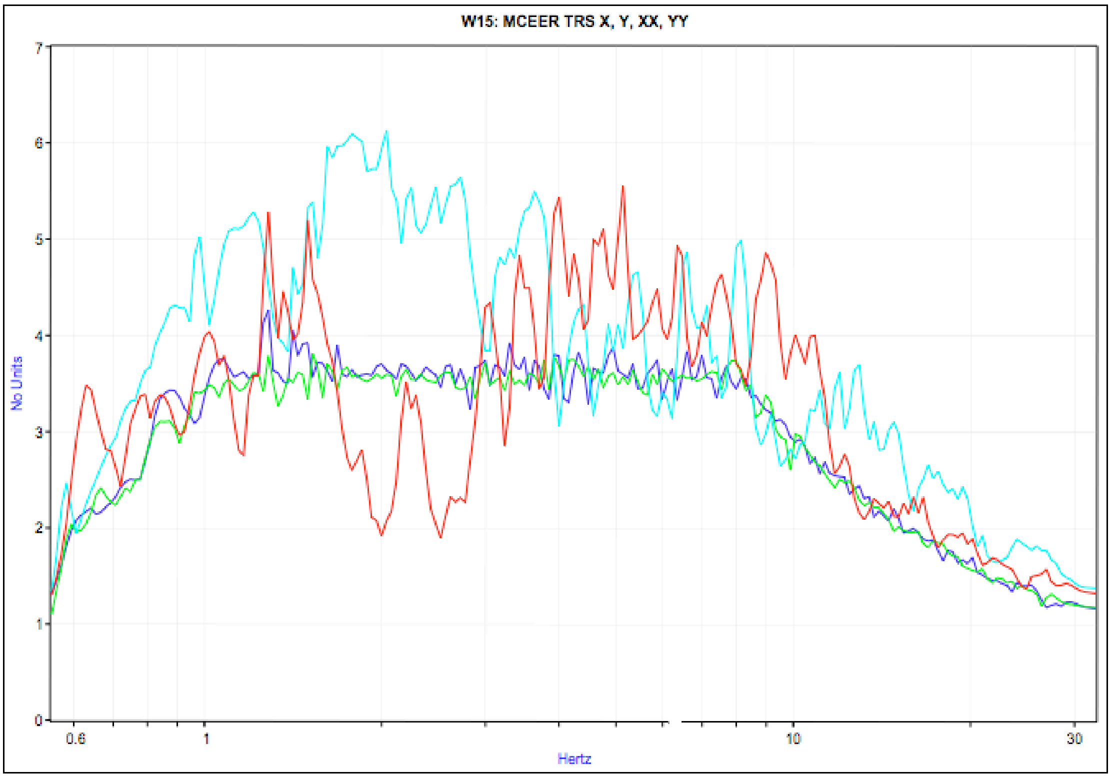

Figure 9 TRS for the horizontal Motion 3 table motions

Table 3 Motion 3 TRS Values in the 1.1 Hz to 8 Hz Frequency Range

X		XX		Y		YY	
Extreme	Amplitude	Frequency	Amplitude	Extreme	Amplitude	Frequency	Amplitude
Minimum	3.23	1.2	5.28	Minimum	3.26	1.16	2.75
Maximum	4.25	1.39	3.83	Maximum	3.81	1.28	5.28
		1.78	6.09			1.41	3.95
		2.04	6.13			1.49	5.20
		2.99	3.84			2.00	1.92
		3.63	5.50			2.20	3.52
		3.99	3.06			2.52	1.90
		4.40	4.32			3.05	4.34
		4.57	3.17			3.23	2.86
		5.44	6.66			3.43	4.83
		6.22	3.14			4.00	5.44
		6.59	4.87			5.16	5.56
		7.54	3.36			6.34	4.99
						7.54	4.64
The value of the RRS in the 1.1 Hz to 8 Hz range should be 3.25 and the TRS should envelop this value.							

3. OBSERVATIONS AND RECOMMENDATIONS

The orientation of equipment modes of vibration relative to the principal directions of the shake table can cause significant over or under testing. The precision of qualification methods are probably less that assumed by many test engineers. The equipment modes should be aligned with the principal table motions where the TRS have been optimized to reduce the potential for over or under testing. Some records that have been suggested in IEEE 693 standard have more severe variations in directions not aligned with the principal axes and their use is questioned. Methods for optimizing the TRS that improve off-axis TRS should be explored.

The TRS of the transformed records were significantly different from target RRS. Where one component exceeds the RRS, its counterpart will be approximately an equivalent amount below the RRS, resulting in over or under testing. The variations in the transformed records can be much larger and appear to be different for different record sets.

These results have at least two implications. First, while it would be desirable to align modes of vibration with the principal shake table axes, for may systems this will not be possible so that the precision that may have been assumed associated with testing may have been overly optimistic. Second, the large variation in the TRS for some records suggests that these records may be inappropriate to use for testing.

4. ACKNOWLEDGEMENTS

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