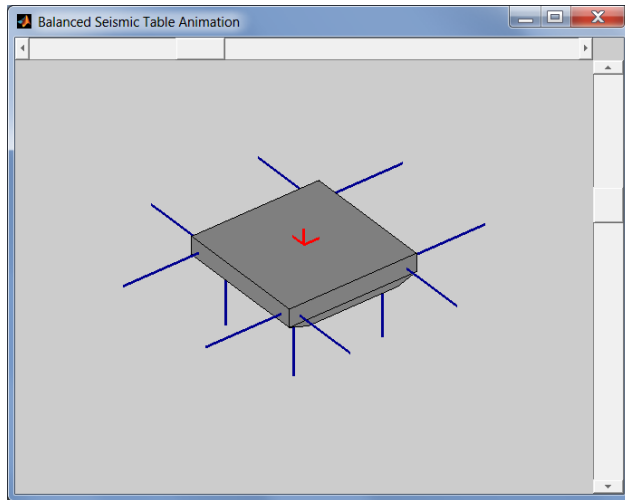


Crosstalk in Multi-Degree-of-Freedom Seismic Tables

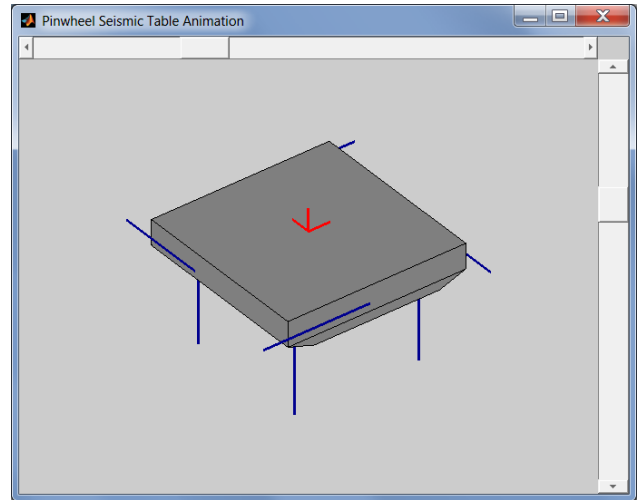
Brad Thoen, Staff Engineer
MTS Systems Corporation
Rev. 17-May-12

In this report, four multi-degree-of-freedom (multi-DOF) table configurations are analyzed and compared from a crosstalk standpoint:

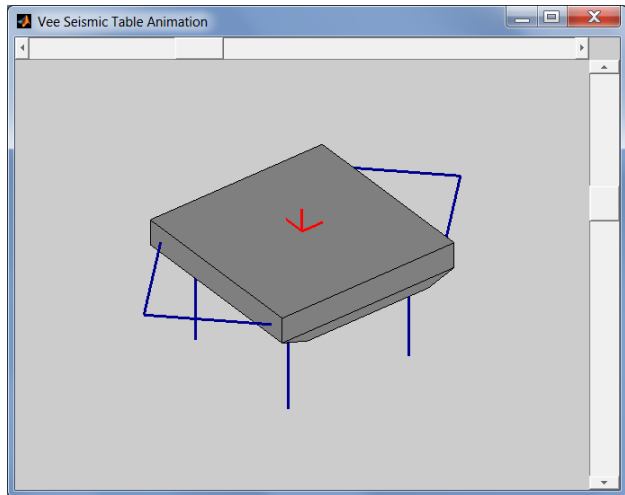
Balanced Configuration



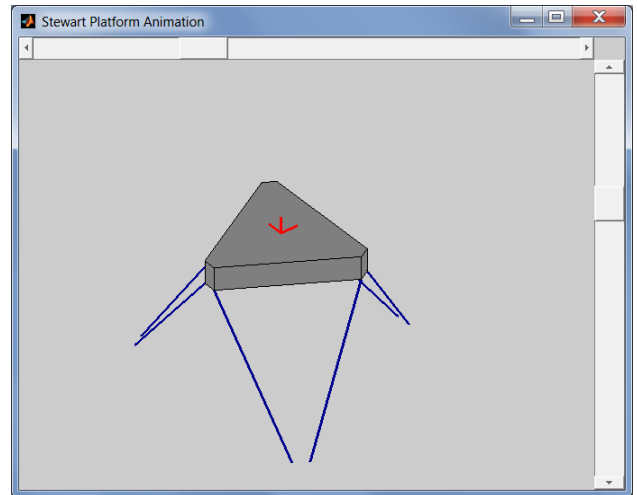
Pinwheel Configuration



Vee Configuration



Stewart Configuration



The *balanced* configuration, which represents the golden standard of seismic tables, is not only orthogonal in the X, Y, and Z directions, but also is symmetric with respect to all three Cartesian axes (hence the name “balanced”). The *pinwheel* configuration, which is very common in seismic tables, is orthogonal in the X, Y, and Z directions, but not symmetric (not “balanced”) with respect to X and Y axes. The *vee* configuration is relatively new to seismic testing, although the inverted vee configuration has been around for some time. The *stewart* (a.k.a. *hexapod*) configuration is an old design that has been used in motion simulators and fatigue test systems for many years, but has not been used in seismic applications due to a prevailing belief that (rightly or wrongly) it suffers from high crosstalk.

Factors that affect crosstalk

Crosstalk is influenced by factors other than the obvious one of actuator geometry: table dynamics, offset from home position, location of the center of gravity (CG), specimen dynamics, and closed-loop control also play significant roles.

To facilitate a meaningful comparison of the four table configurations, key physical properties such as natural frequency, maximum velocity, and maximum force were matched to the extent possible:

Natural Frequency

	Balanced	Pinwheel	Vee	Stewart	
X	13	13	13	13	Hz
Y	13	13	13	13	Hz
Z	23	22	26	22	Hz
Roll	21	21	21	20	Hz
Pitch	21	21	21	21	Hz
Yaw	21	21	21	21	Hz

Maximum Velocity

	Balanced	Pinwheel	Vee	Stewart	
X	2.3	2.3	2.3	2.3	m/s
Y	2.3	2.3	2.3	2.1	m/s
Z	1.8	1.8	1.8	1.7	m/s
Roll	60	60	60	68	deg/s
Pitch	60	60	60	65	deg/s
Yaw	63	50	29	78	deg/s

Maximum Force

	Balanced	Pinwheel	Vee	Stewart	
X	814	814	814	838	kN
Y	814	814	814	797	kN
Z	1279	1279	1279	1922	kN
Roll	2239	2239	2239	1639	kN-m
Pitch	2239	2239	2239	1452	kN-m
Yaw	3418	4232	3743	2425	kN-m

Each table's displacement controller was tuned for reasonable flatness and a magnitude peak of 1.10, using only displacement and force feedback gains. Resulting closed-loop bandwidths were remarkably similar:

Closed-Loop -3dB Bandwidth

	Balanced	Pinwheel	Vee	Stewart	
X	12	12	13	11	Hz
Y	12	12	13	11	Hz
Z	22	21	26	21	Hz
Roll	20	20	20	21	Hz
Pitch	20	20	20	21	Hz
Yaw	22	21	22	20	Hz

With regard to the influences of offset from home position, CG location, and specimen dynamics, there are an infinity of cases that could potentially be examined. Of these, seven cases were chosen as instructive:

	Position offset	CG offset
	{X Y Z}	{X Y Z}
Case 1: Home position, minimal OTM	{0 0 0}	{0 0 0}
Case 2: Home position, significant OTM	{0 0 0}	{0 0 1}
Case 3: X-only position offset	{0.2 0 0}	{0 0 0}
Case 4: Y-only position offset	{0 0.2 0}	{0 0 0}
Case 5: Z-only position offset	{0 0 0.1}	{0 0 0}
Case 6: X, Y, and Z position offsets	{0.2 0.2 0.1}	{0 0 0}
Case 7: Lightly-damped resonant specimen (100% of table mass, 5 Hz, 5% damping, 1m CG)		

The nonzero offsets above have units of meters, and represent the half-stroke displacement for each respective DOF. The CG location of each table, to which the CG offset is added, was chosen to be the “sweet spot”, i.e., the location that minimizes overturning-moment (OTM) effects. For the balanced, pinwheel, and vee configurations, this location lies in the plane of the attachment points of the horizontal actuators, and results in identically zero OTM. For the stewart configuration, there is no location that results in identically zero OTM, but there is a location where OTM is minimized.

These seven cases were analyzed with the tables in closed-loop control. However, the amount of crosstalk in a closed-loop system depends greatly on the particular tuning, and because there are an infinity of tunings, comparisons require judgment.

Crosstalk plots for each of these seven cases are shown in the following pages. The plots are velocity frequency response functions (FRFs) from the on-diagonal DOF *output* to each off-diagonal DOF output. Note that the on-diagonal DOF *output* is used as the reference rather than the *input*, the reason being that relative output motion is a better indicator of crosstalk than absolute output motion. With this reference convention, on-diagonal FRFs are of course unity for all frequencies.

To reduce visual clutter, only FRFs that have at least one curve above 5% crosstalk are shown.

Also note that in the plots, R_x , R_y , and R_w are shorthand for *roll*, *pitch*, and *yaw*, respectively.

The units of the velocity FRF plots are *fraction of fullscale* so that crosstalk percentage values can be determined directly by inspection. For example, suppose that the X-to-Pitch FRF peaks at a value of 0.5. This means that for X motion at 100% of maximum X velocity, the peak crosstalk on pitch will be 50% of maximum pitch velocity. Because the FRFs are scaled according to DOF maxima, and to facilitate comparison, care was taken to assure that all four table configurations have approximately the same maximum velocity and force.

The mathematics used to compute the FRFs is described in *State-Space Formulation of Multi-DOF Dynamics.pdf*.

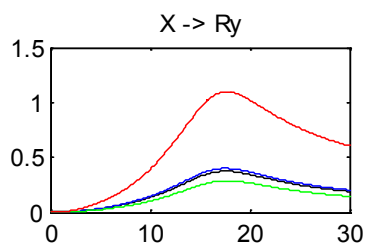
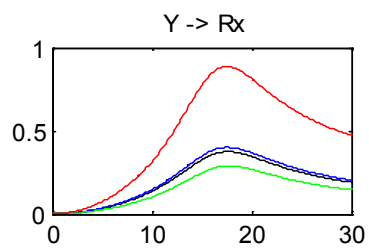
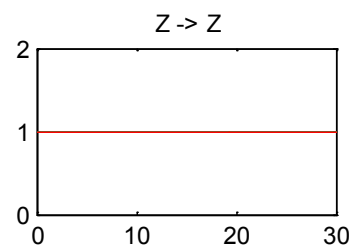
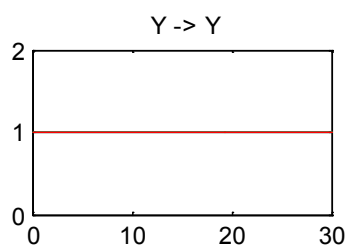
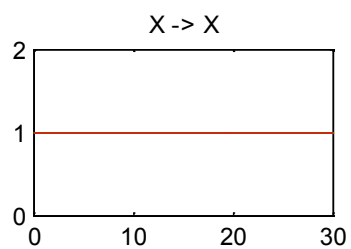
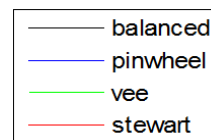
Observations

- There is no configuration that has uniformly better or worse crosstalk in all cases.
- However, the stewart configuration has worse crosstalk in most cases, particularly the OTM (X-to-Pitch and Y-to-Roll) crosstalk terms, which are greater than twice that of the other configurations.
- With simultaneous XYZ position offset (Case 6) the vee configuration has X-to-Y and Y-to-X crosstalk terms that far exceed that of the other configurations.
- The vee configuration has the most X-to-Z and Z-to-X crosstalk, while the stewart configuration has the least.

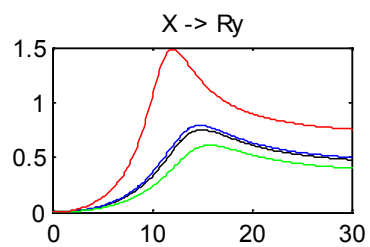
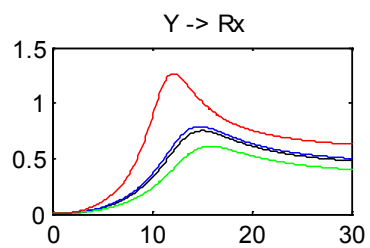
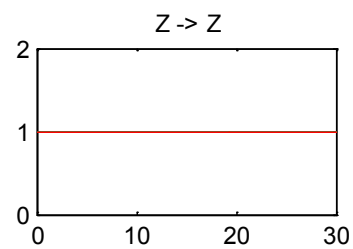
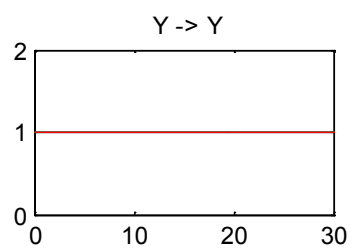
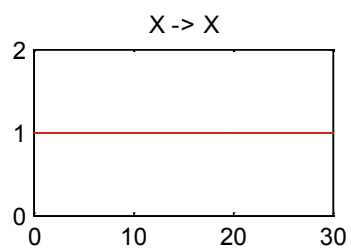
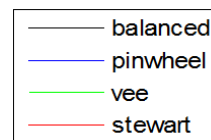
Discussion: Does the presence of a significant crosstalk term guarantee that a problem exists?

Not necessarily. Most earthquake acceleration records have frequency content under 10 Hz, where crosstalk is not significant. Seismic tests are centered at the home position, and only occasionally does the table move to a large nonzero position where crosstalk is significant. Also, these large excursions tend to be low-frequency events: because displacement is proportional to the inverse-square of frequency, only low-frequencies result in high displacements. As such, crosstalk generated by these occasional excursions tend to have low amplitude. Crosstalk due to CG offset is probably of more concern, since it exists at the home position where the table spends most of its time.

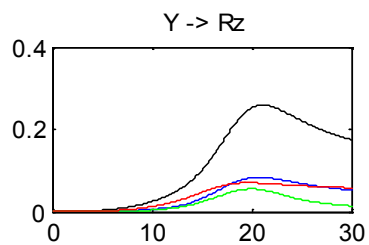
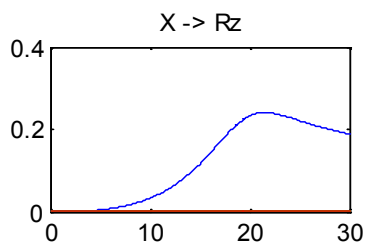
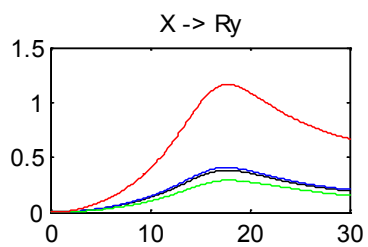
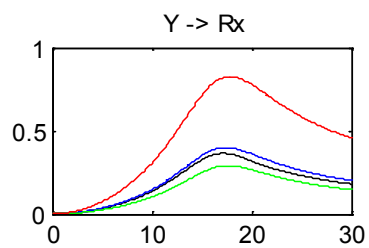
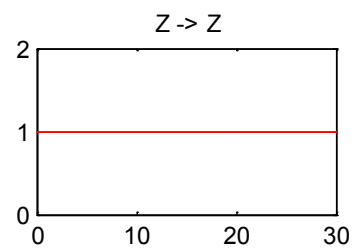
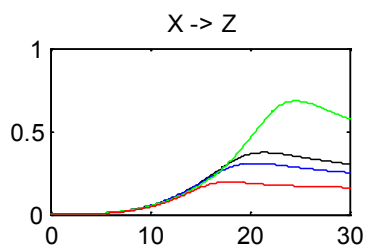
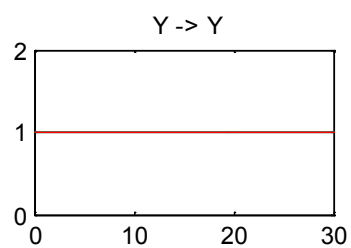
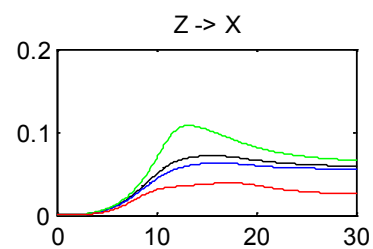
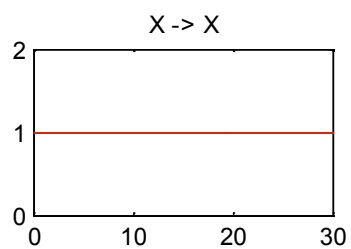
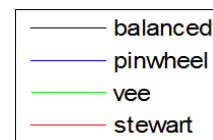
Case 1: Position offset = {0 0 0}, CG offset = {0 0 0}



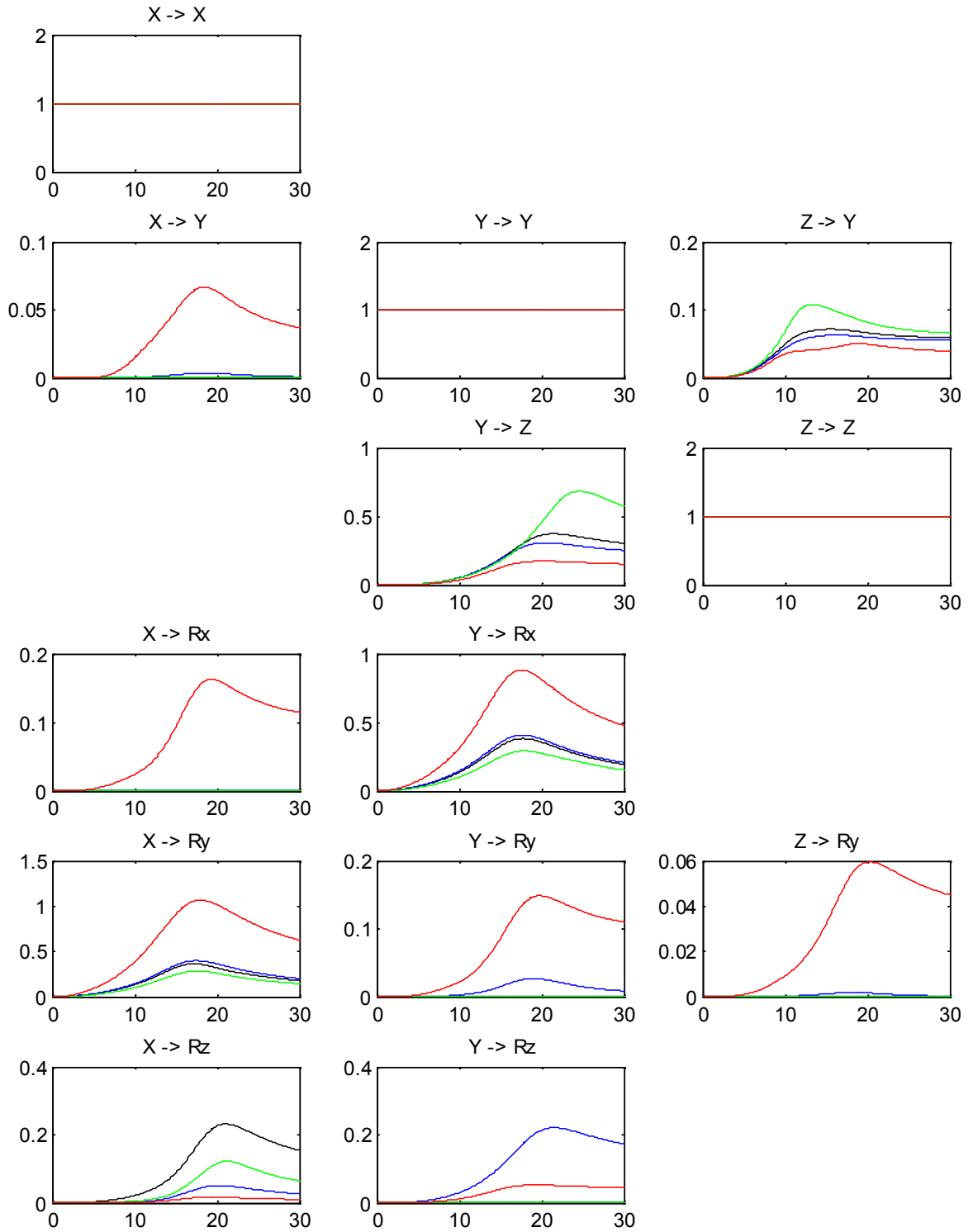
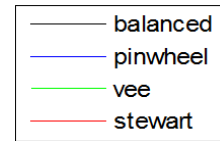
Case 2: Position offset = {0 0 0}, CG offset = {0 0 1}



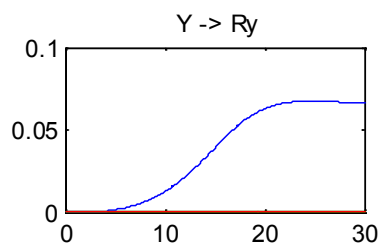
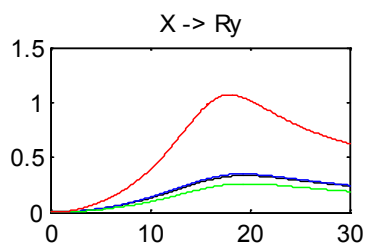
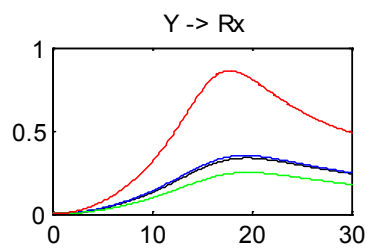
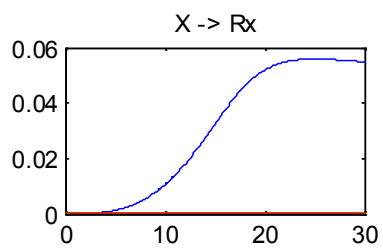
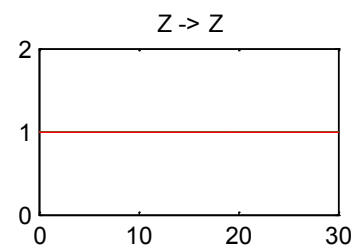
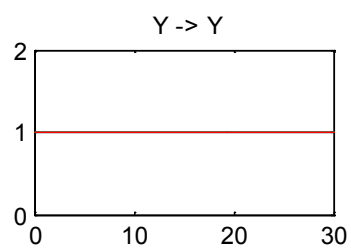
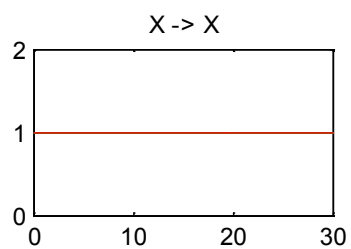
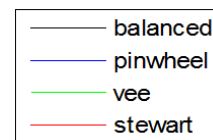
Case 3: Position offset = $\{0.2 \ 0 \ 0\}$, CG offset = $\{0 \ 0 \ 0\}$



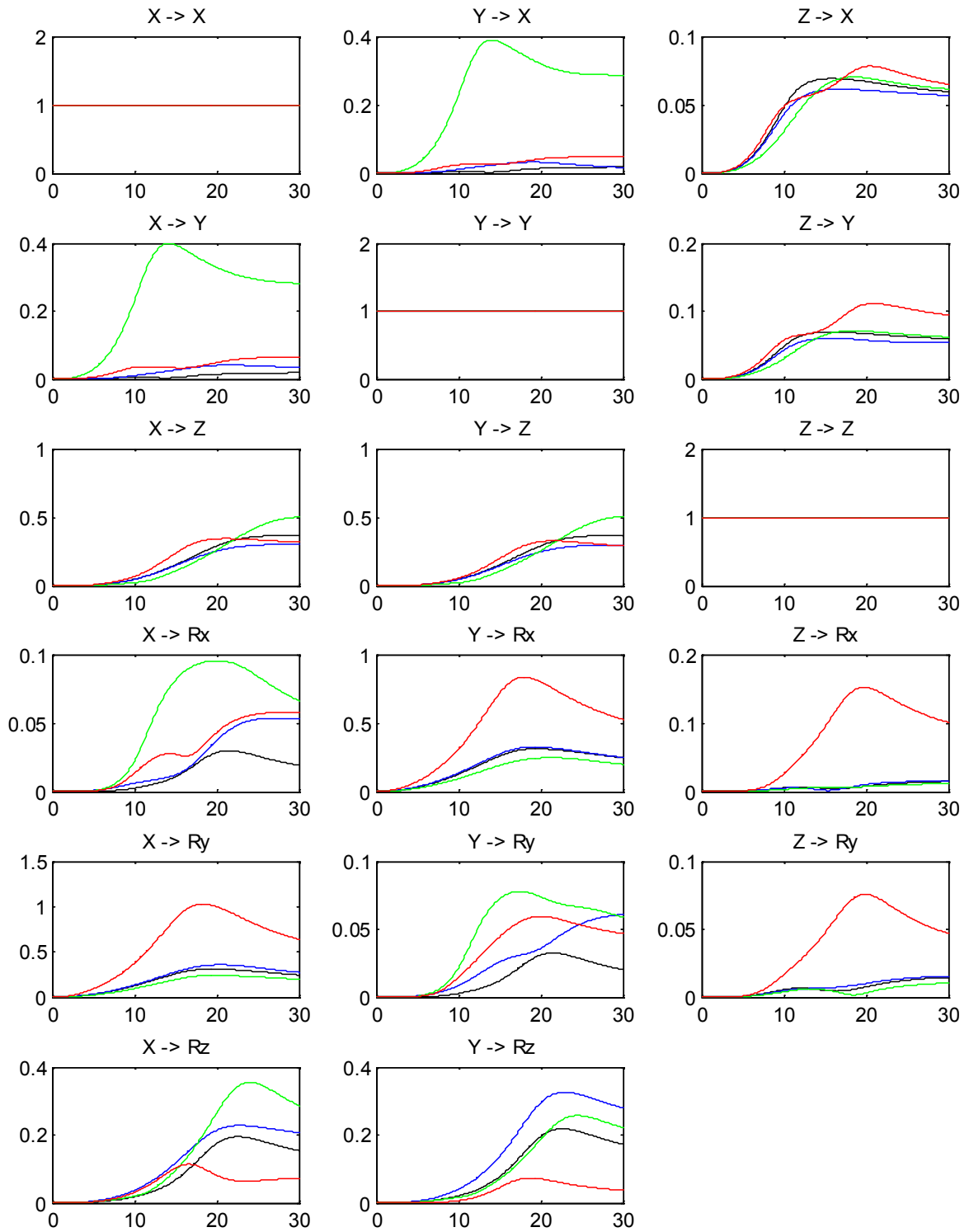
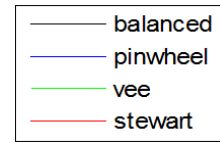
Case 4: Position offset = $\{0 \ 0.2 \ 0\}$, CG offset = $\{0 \ 0 \ 0\}$



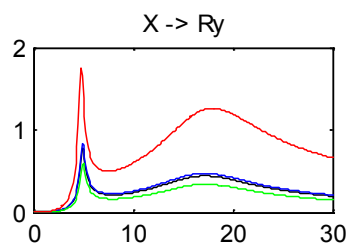
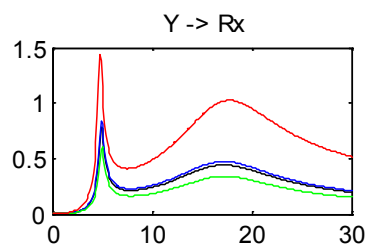
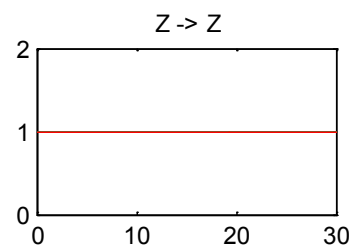
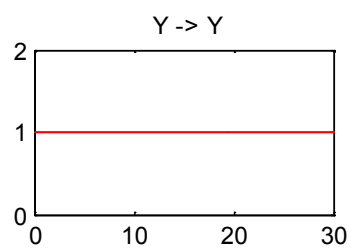
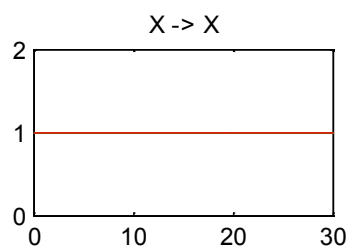
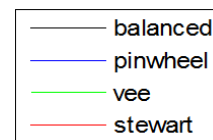
Case 5: Position offset = $\{0\ 0\ 0.1\}$, CG offset = $\{0\ 0\ 0\}$



Case 6: Position offset = {0.2 0.2 0.1}, CG offset = {0 0 0}



Case 7: Lightly-damped resonant specimen
(100% of table mass, 5 Hz, 5% damping, 1m CG)

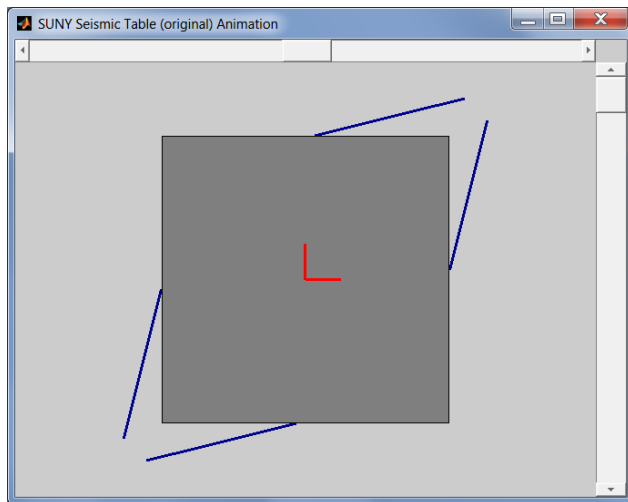


Appendix: The SUNY Seismic Table

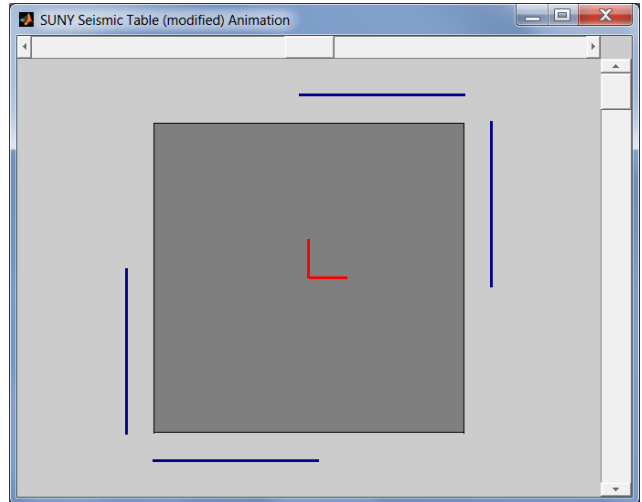
Severe crosstalk can result in an unusable system. This section discusses one such system, the SUNY seismic table. The figure on the left below shows the original actuator configuration, with horizontal actuator pairs 62 degrees apart. The crosstalk plots shown in the following pages predict significant (>50%) X-to-Y and Y-to-X crosstalk. Unlike the other table configurations discussed in this report, this crosstalk occurs at the home position, and at low frequencies too, within the 10 Hz bandwidth of typical earthquake acceleration records.

These severe crosstalk predictions were borne out during system commissioning. At great expense, the actuator configuration was modified in the field, made even more expensive by the fact that there were two tables requiring modification. The actuators angles were expanded to 90 degrees, as shown in the figure on the right below, and wings added to the table (not shown in the figure) to provide clearance between the actuators and the table. The modified configuration is in essence a pinwheel configuration.

Original Configuration



Modified Configuration



The plots shown in the following pages compare the original and modified configurations for Case 1 (zero position offset and zero CG offset). After the modifications, X-to-Y and Y-to-X crosstalk is virtually nonexistent.

SUNY Case 1: Position offset = {0 0 0}, CG offset = {0 0 0}

