# GROUND-BORNE VIBRATION ISOLATION CONCEPT FOR A PUMP AND TEST LOOP SUPPORT STRUCTURE

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**EXECUTIVE SUMMARY**

A test laboratory is constructing a centrifugal pump test loop support structure in their Test Facility. The support structure must satisfy certain dynamics criteria for ground-borne vibration isolation and avoidance of low-frequency modes. A conceptual design for the support structure is developed and the static and dynamics analyses required to demonstrate the expected performance of the structure. The concept design relies on a pseudo-rigid, wing-like steel-skinned deck suspended from two “isolation towers” supported on the existing Test Facility pit walls. The ground-borne vibration isolation system relies on suspension cables for horizontal isolation and pneumatic isolators, or an optional torsion-bar isolation assembly, for vertical isolation and satisfies the design requirements. The structural deck has a “weak” up/down warping mode at 14.5 Hz that can be mitigated effectively with a tunable tuned-mass damper The combination of the isolation system and the vibration-controlled deck satisfy the performance requirements.

1. BACKGROUND

A propulsion test laboratory is upgrading its centrifugal pump test loop (CPTL) evaluation capability. A conceptual design is developed for the CPTL support structure that provides vibration isolation from ground-borne vibration and minimizes the presence and severity of structural modes that could alter, or otherwise contaminate, the vibration measurements acquired near the centrifugal pump attachment point.

The test area is dominated by a 14.5-foot-deep test pit that measures 40 feet in the east/west direction and 28.5 feet in the north/south direction. An overhead crane with a lift capacity of 62.5 tons has access to most of the floor area. Site vibration measurements show that ground-borne vibration is highest on the slab-on-ground at floor level and lowest on the pit floor. The physical extent of the CPTL and the desire to support all of the elements on a single isolation platform led to the design decision to rely on the north and south pit walls for structural support of the CPTL support structure.

The pseudo-rigid deck structure is suspended from cables at the north and south ends to provide a very low sway-mode resonance frequency for lateral ground-borne vibration isolation. The top end of the suspension cables attach to a "floating" beam supported on pneumatic isolators[1] that provide the isolation in the vertical direction. The suspension cables and pneumatic isolators are supported on "isolation towers" that are supported directly on the test pit walls as shown in Figure 1. No new foundation elements are required, which conserves costs and avoids introducing new elements with an unknown ground vibration response. The suspended deck is constructed from built-up steel beams spanning in both directions and has a structural "skin" on top and bottom in most locations to maximize the rigidity of the structure—analogous to the design of an aircraft wing. The top-side plates serve as a convenient access platform and work surface. Bolt-on, removable sections are provided where necessary to provide the required stiffness, but may be removed during CPTL assembly and tear-down.

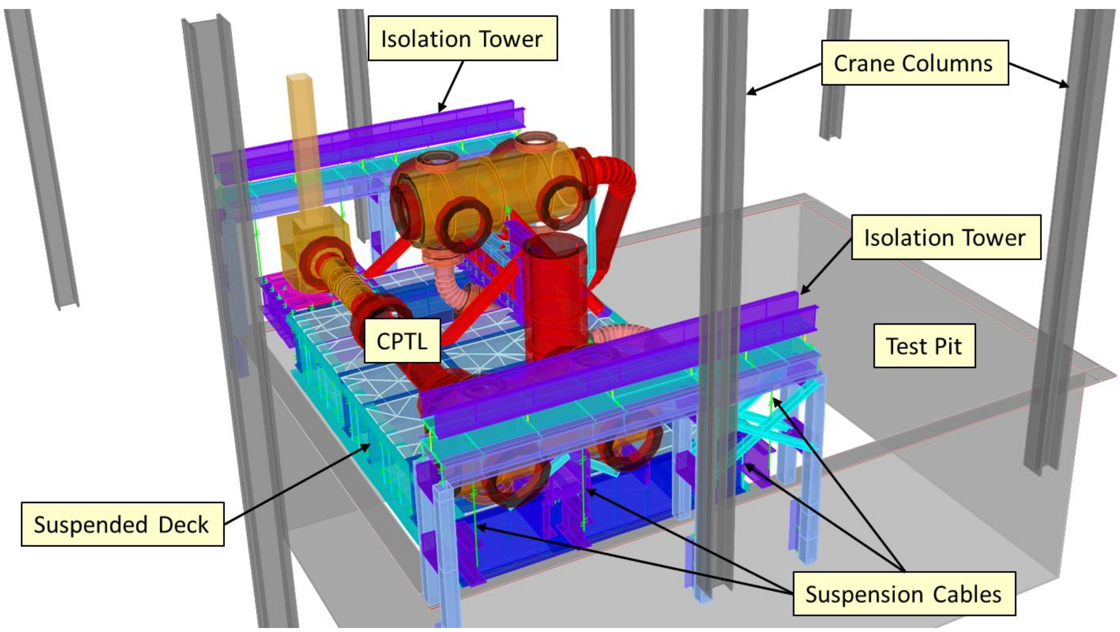



**Figure 1 SAP2000 Rendering of the Proposed CPTL Support Structure**

[1] An optional vertical isolation system based on a torsion-bar concept may be used in place of the pneumatic isolators and will provide improved performance via the lower damping that is achievable with all-steel construction.

## 2. CPTL PLATFORM DYNAMICS ASSESSMENT

The isolation system and self-excited dynamic responses are the critical challenges governing the design of the CPTL support structure. The isolation system prevents ground-borne vibration from adversely affecting the vibration measurements obtained at the pump base during operation. The Client defined the permissible level of ground-borne vibration as a function excitation frequency. A site vibration survey is performed as part of this effort to document the ambient ground vibration in three orthogonal directions at six locations. Aside from ground-borne vibration, there is also a risk that undesirable modal characteristics of the platform will distort the Client's vibration measurements during CPTL testing. Forced response analyses are performed to assess the structure's response.

### 2.1 SITE VIBRATION MEASUREMENT AND DATA ANALYSIS

The isolation system is designed to prevent ground-borne vibration from adversely affecting the vibration measurements acquired at the pump mounting location. The ground-borne vibration environment is not necessarily a constant from day to day, or even from hour to hour. The site vibration survey of the ambient ground-borne vibration environment in the Test Facility was conducted on 9 August 2016. The measurement locations mirrored those of an earlier survey conducted by the Client and are shown in Figure 2. In fact, the marks on the floor from the earlier survey were still present and were used for the current survey.

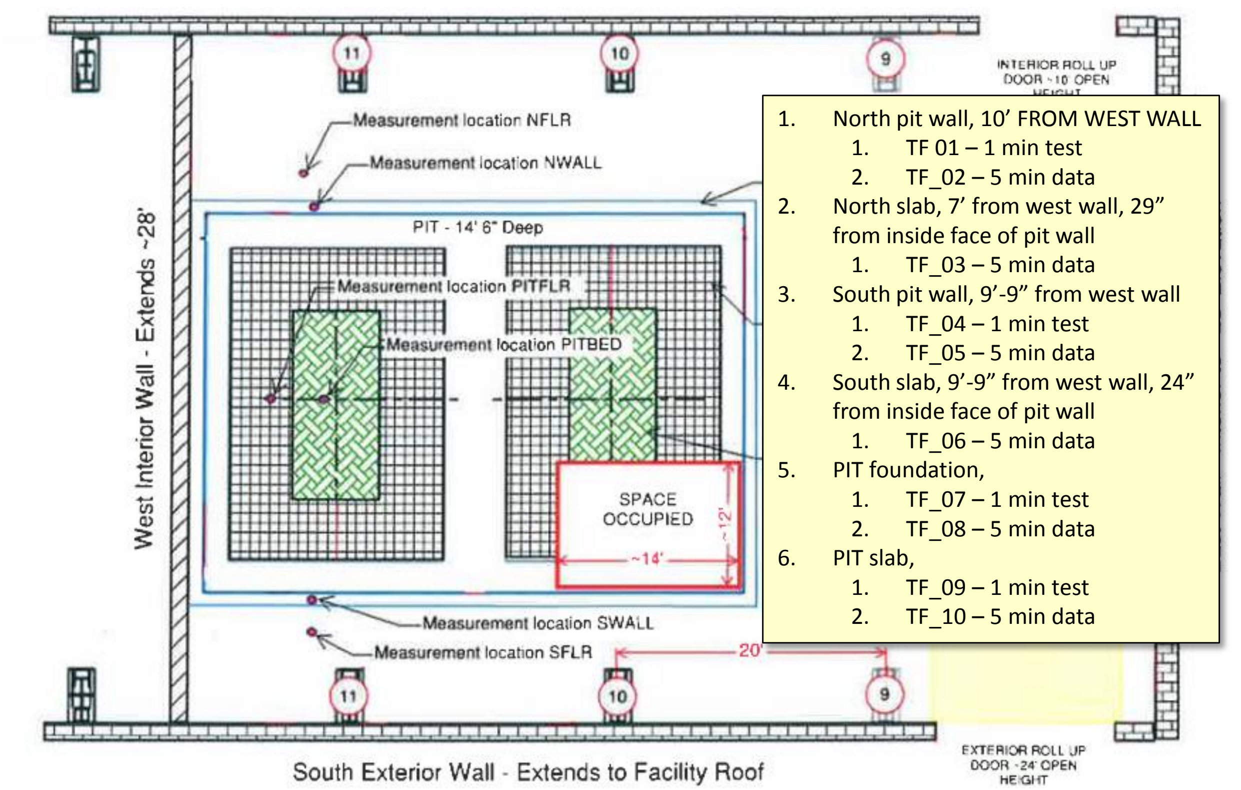



**Figure 2 Site Vibration Survey Measurement Locations**

The portable data acquisition (DAQ) system consists of a Windows-based laptop, a USB-powered four-channel 24-bit data acquisition module (Data Translation DT9837A), and the three single-axis accelerometers identified in Table 1. The DAQ module, accelerometers, and the steel block used to provide three mutually-orthogonal mounting surfaces and a stable platform are pictured in Figure 3. A sampling frequency of 5000 Hz is used to digitize the analog acceleration data stream, but the bandwidth of interest only extends out to 150 Hz. Also, three small viscoelastic pads are present on the steel block to provide three-point contact with the ground and to prevent high frequency vibration from contaminating the data.

Data were acquired for 5 minutes at each of the six (6) measurement locations. Each acquisition period produces an ASCII text file containing the raw time series data with one column of time values for each sample and three columns of acceleration values (in g's). Each column of acceleration data corresponds to the channels identified in Table 1. The time series data are then processed to determine averaged ground-borne vibration spectra for each of the three directions at each of the six locations. The time-averaged vibration spectra are provided in Section 4.

**Table 1 Accelerometers and Channel Assignments**

| Channel | (+) Direction | Accelerometer | S/N | Sensitivity |
|---|---|---|---|---|
| 1 | East | PCB 393B04 | 45802 | 0.994 V/g |
| 2 | North | PCB 393B04 | 45803 | 0.998 V/g |
| 3 | Up | PCB 393B04 | 32502 | 1.003 V/g |

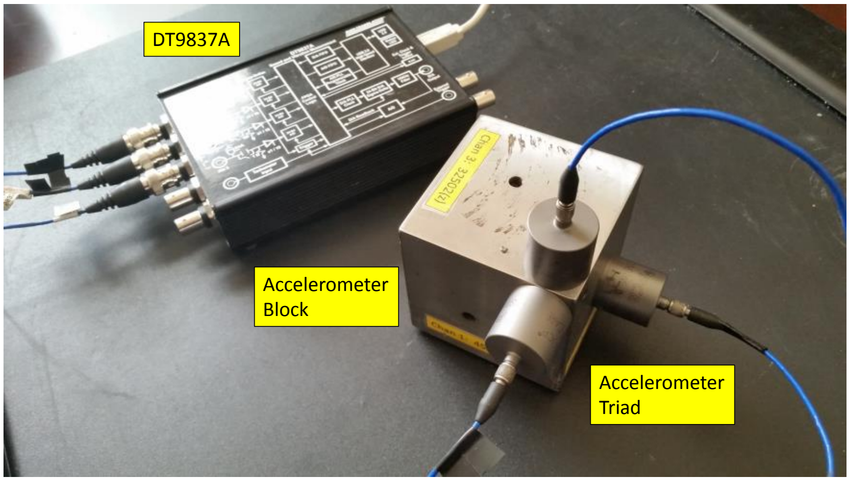



**Figure 3 Data Acquisition Module and Accelerometers**

The isolation towers are supported off of the south-side and north-side pit walls (NWALL and SWALL), so the vibration data acquired from the slab (NFLR and SFLR) and pit foundation (PITFLR and PITBED) are not directly applicable to the design concept. The NWALL and SWALL spectra are combined to provide an enveloped spectrum representing the ground plane environment and an enveloped spectrum representing the vertical vibration environment. These two enveloped spectra are plotted in Figure 4. The isolation system performance is evaluated based on these spectra.

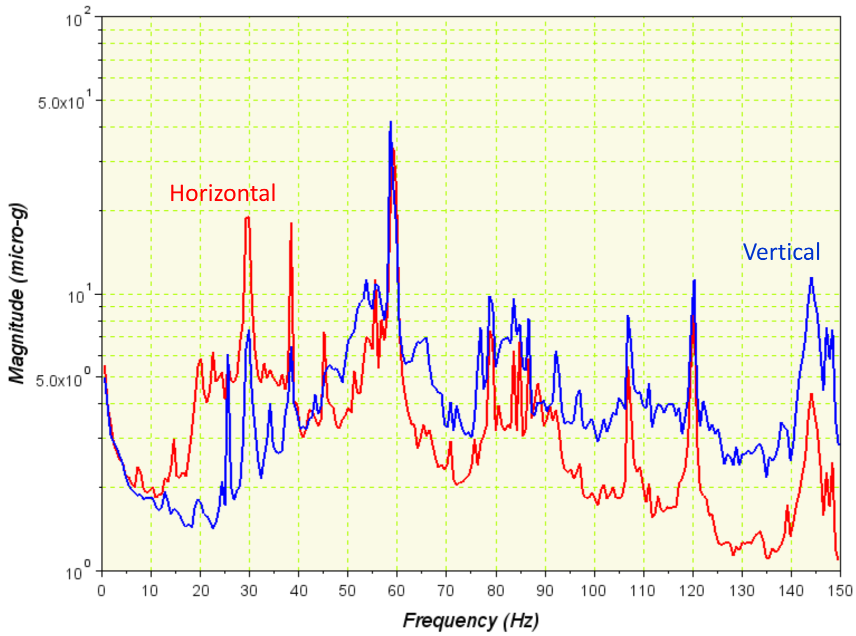



**Figure 4 Horizontal and Vertical Pit Wall Vibration Envelopes**

## 2.2 ISOLATION SYSTEM PERFORMANCE AND OPTIMIZATION

The isolation system consists of pneumatic isolators (baseline design) or a torsion-springs (optional design) that act in the vertical direction and suspension cables for the horizontal direction. The off-the-shelf pneumatic isolators provide a vertical isolation frequency of 1.5 Hz with 6% damping while the torsion springs can provide 1.5 Hz at about 1% damping. Lower-frequency pneumatic isolators can be specially-designed if better performance is needed. The lateral sway stiffness of a suspension cable is the cable tension divided by the length of the cable. The support structure platform is supported at eight (8) locations by the cables (four cables at each of the 8 attachment points); four on the north side and four on the south side. The lateral stiffness provided by each suspension cable can be adjusted by lengthening or shortening the suspension cable and provisions for this are included in the concept drawings. The optimal cable lengths and the vertical isolator locations required to balance the vertical static reaction forces on the pneumatic (or torsion bar) isolators will be determined during the final design phase. Once the isolation deck is installed, it is highly unlikely that any further adjustments will be required.

The suspension system is modeled in SAP2000 using link elements as shown in Figure 5 for the south end of the platform. The cable links have an axial stiffness of 197 kip/in for the four cables and a lateral stiffness of 0.35 kip/in, which is the axial tension divided by the cable length. The six (6) pneumatic isolators at the north and south ends are represented with a link stiffness of 5.33 kip/in derived from the product literature. Self-equilibrating upward and downward forces are also applied to the pneumatic isolator links to represent the internal pressure in the isolator. This model of the isolation system is used for both forced-response analyses used to assess the pump-induced and ground-induced vibration.

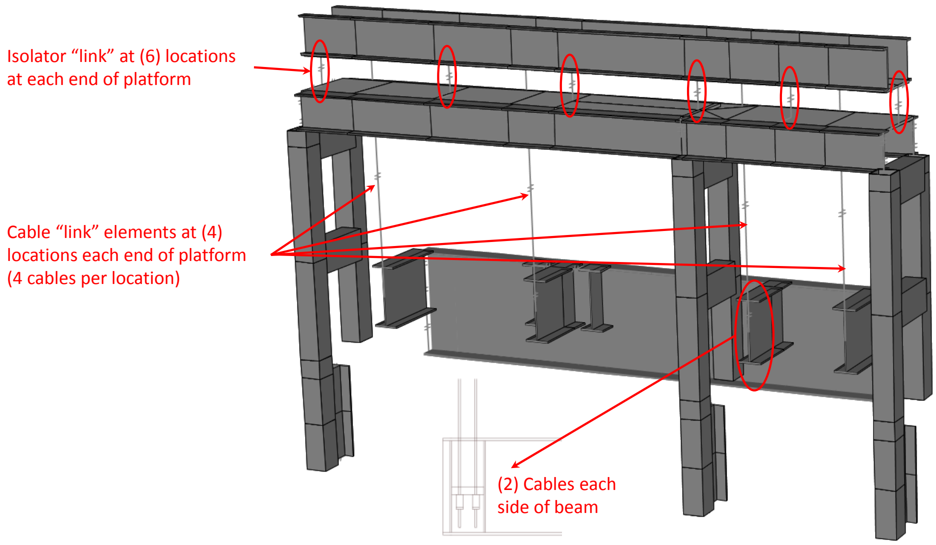



**Figure 5 Vertical and Lateral Isolation Elements at South End of Support Structure**

The measured ground-borne vibration envelopes shown in Figure 4 are treated as forcing functions for ground acceleration and a twelve-degree-of-freedom (12-DOF) model of the platform (6-DOF) and towers (3-DOF for each tower) is used to assess the ground-induced vibration environment transmitted through the isolation system to the platform at the pump mounting location.

A top view of the 12-DOF model is shown in Figure 6. The towers are represented as thin rectangles on the left- and right-hand sides. A gap is shown between the platform and the towers for graphical clarity. In reality, the points on the platform, $P_n$, and the corresponding points on the towers, $T_n$, represent the suspension cable attachment locations with the $P_n$ located directly below the $T_n$. Each tower can sway independently in the east/west and north/south directions and twist about the vertical axis. The platform is treated as a rigid body that can translate in all three directions and rotate (pitch, roll, and yaw) about the center of mass of the combined platform and piping loop system. Springs connect each pair of platform and tower points ($P_n$ to $T_n$) and any motion of the towers and the platform that separates these points from their initial relative positions results in a restoring force proportional to the separation distance. Springs also connect the towers at the column locations, $C_n$, to the ground. The SAP2000 model is used to determine the static spring stiffness for the columns: in the north/south direction, each pair of posts resists lateral forces per 128 kip/in, with cross-ties; and in the east/west direction provide 270 kip/in, with X-braces. A comparison of the twelve corresponding modes and resonance frequencies obtained with the SAP2000 model and 12-DOF model are provided in Table 2. There is very good agreement between the much more detailed model (SAP2000) and the reduced-order model (12-DOF).

The ground motion is transmitted to the platform through the attachment of the towers to the foundation. Time-dependent ground displacement, *s*(*t*), is applied in the north/south, east/west, and vertical directions at each of the six tower columns. The ground motion causes the towers to move, which, in turn, causes the platform to move. Relative offsets of the centers of mass and the centers of stiffness introduce some degree of rotation in the tower and platform motions as well.

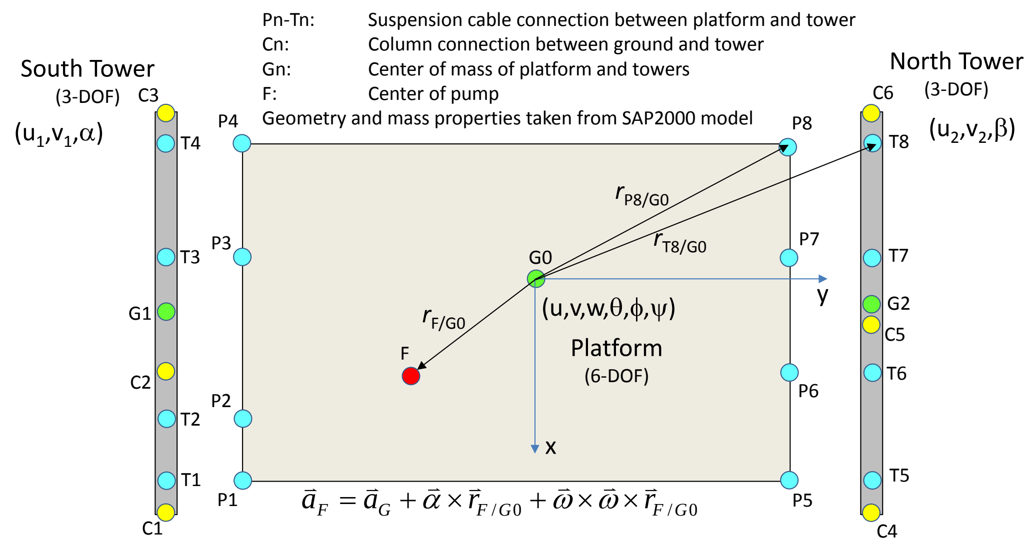



**Figure 6 Top View of 12-DOF Platform and Tower Model**

**Table 2 Comparison of Isolation and Tower Resonance Frequencies**

| Mode | $f_n$, SAP2000 | $f_n$, 12-DOF |
|---|---|---|
| Platform East/West Sway | 0.23 Hz | 0.32 Hz |
| Platform North/South Sway | 0.30 Hz | 0.32 Hz |
| Platform Rotation about Vertical | 0.47 Hz | 0.46 Hz |
| Platform Plunge | 1.46 Hz | 1.56 Hz |
| Platform Pitch about East/West | 2.36 Hz | 2.34 Hz |
| Platform Roll about North/South | 3.63 Hz | 3.45 Hz |
| North Tower North/South Sway | 19.3 Hz | 19.3 Hz |
| South Tower North/South Sway | 19.6 Hz | 19.3 Hz |
| South Tower East/West Sway | 27.9 Hz | 27.6 Hz |
| North Tower East/West Sway | 28.1 Hz | 28.2 Hz |
| North Tower Rotation about Vertical | 27.3 Hz | 28.2 Hz |
| South Tower Rotation about Vertical | 29.1 Hz | 28.2 Hz |

The acceleration at the pump mounting location (point F in Figure 6) is of particular interest in this study. Lateral base motion frequency response functions relating the ground acceleration to the resulting pump acceleration are plotted in Figure 7. The tower resonant modes reduce the isolation effectiveness at the tower's resonance frequencies (at about 19 Hz and 28 Hz). A potentially worst-case condition is represented here where the east/west tower sway modes have resonance frequencies very close to 30 Hz (highlighted in Table 2) which coincides with frequencies where the measured ground-borne vibration from operating mechanical systems is relatively high (see Figure 4) and can excite those sway modes. The tower modes can be adjusted relatively easily by adding/removing bracing elements. For example, if the X-braces are omitted, the tower sway mode frequencies drop from 28 Hz to 16.5 Hz. Neither the cross-ties nor the X-braces are required for structural integrity (*e.g.*, buckling strength) and therefore may be omitted or included based solely on isolation system performance objectives.

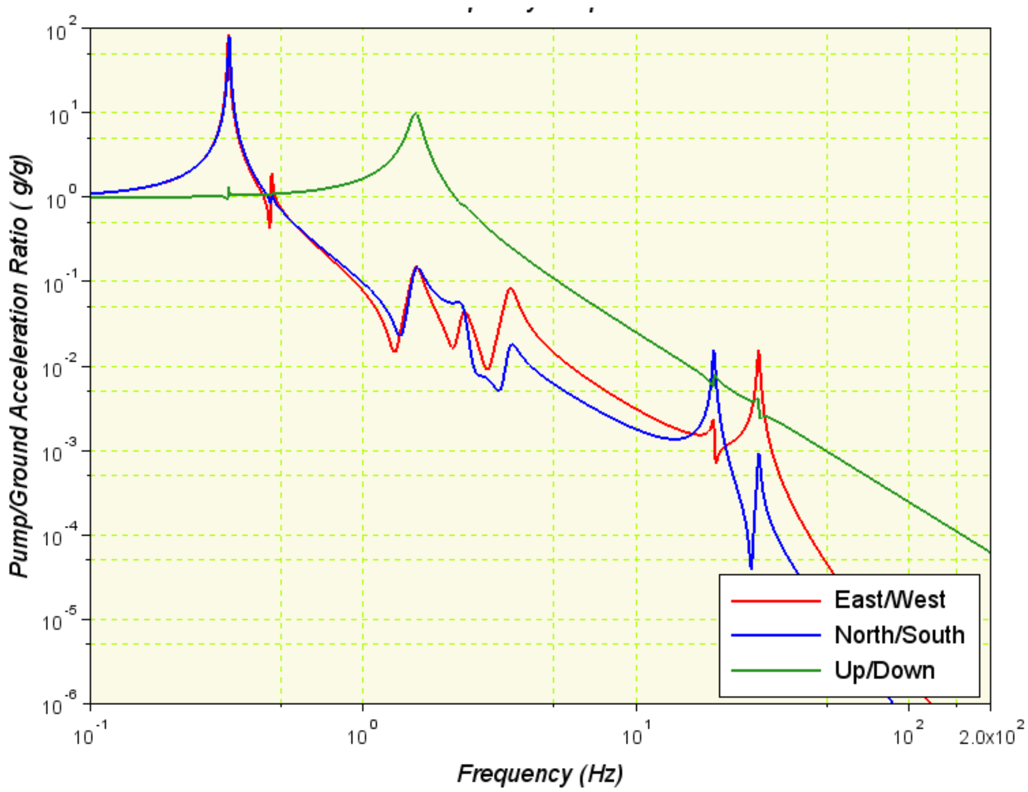



**Figure 7 12-DOF Ground-Borne Vibration Frequency Response Functions**

The ground-borne vibration envelopes shown in Figure 4 are multiplied by the transfer functions to obtain the predicted response of platform to the measured ground-borne vibration environment and the resulting curves are plotted in Figure 8 along with the Client's limit curve. The motion in each of the three directions satisfies the criterion. The peaks in the north/south and east/west spectra near 19 Hz and 28 Hz correspond to the tower modes in Table 2. Note that the 28-Hz tower sway modes amplify the ground-borne vibration at 30 Hz in the east/west direction; however, the resulting motion still satisfies the performance requirement for the isolation system. The point of closest approach for the vertical motion is at 5 Hz.

The off-the-shelf pneumatic isolators deliver a sufficiently low resonance frequency (about 1.5 Hz) to provide a 10-dB margin relative to the criterion; however, lower damping and improved isolation system performance is achievable with the optional torsion-bar isolation system. The concept design for the torsion-bar vertical isolation system is shown in Figure 9 and is designed to be compatible with the isolation towers so that the pneumatic isolation system can be replaced with the torsion-bar isolation system with minimal effort.

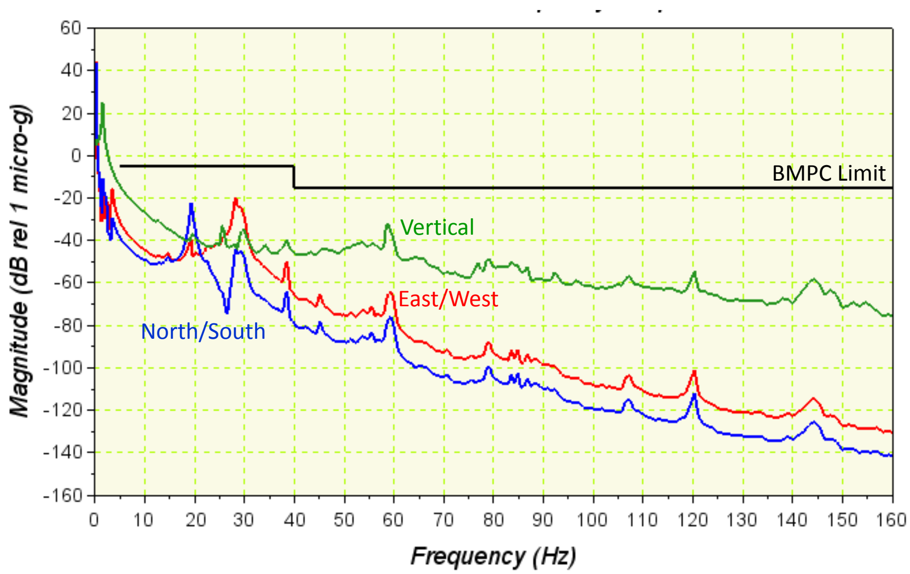



**Figure 8 Predicted 12-DOF Platform Response to Measured Ground-Borne Vibration**

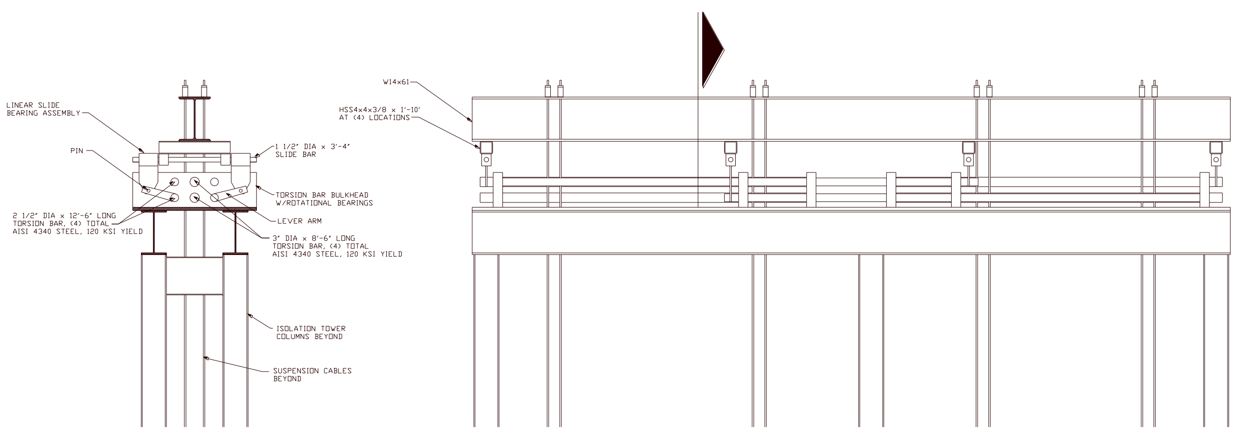



**Figure 9 Optional Torsion-Bar Vertical Isolation Assembly**

The torsion bar isolation system allows the top end of the suspension cables to move up and down at a nominal frequency of 1.5 Hz (similar to the pneumatic isolators). The concept design relies on eight (8) high strength steel (AISI 4340, 120-ksi yield stress) steel bars that are caused to twist about their axes through the action of lever arms. The suspension cables deliver the vertical loads to the lever arms through a stiff beam (W14x61 in the current design). Four (4) of the bars are 3 inches in diameter and 8.5 feet long. The other four (4) bars are 2.5 inches in diameter and 12.5 feet long. The bars are welded at one end and free to rotate at the lever arm end. Rotational bearings provide vertical support (thereby eliminating flexural stresses) while permitting nearly friction-free rotation to minimize damping. As the torsion bars twist, a linear bearing slides horizontally along a 1.5-inch diameter slide bar. The torsion bar isolation system does not have the self-lifting capability of the pneumatic isolation system and will require the overhead crane or integrated lead screws to slightly raise each end in order to remove or insert the mechanical stops used to by-pass the vertical isolation system.

## 2.3 PUMP-INDUCED RESPONSE CHARACTERISTICS

Ground-borne vibration is one source of undesirable vibration that can contaminate the vibration measurements obtained at the pump base during CPTL testing. The pump is an imperfect mechanical system with internal moving components, manufacturing tolerances, and wear will produce harmonically-varying forces related to the pump's speed and impeller geometry. These forces are of primary interest to the Client and must be extracted from the dynamic response of the support structure. The key point here is that there *must* be pump-induced motion—a perfectly fixed pump would provide no insight into the forces it generates. The ideal support structure would have low mass (low inertia and, hence, more accurate measurement of pump-induced forces) and no structural modes that would amplify or attenuate the response caused by pump-induced forces. In the real world, however, a low-mass system is more flexible (*i.e.*, will have many modes in the frequency range of concern) because stiffening elements that push those modes to higher frequencies have mass. No real structure is a perfect null transfer function (even though that is the design objective) and tuned-mass dampers may be incorporated into the structure to improve the dynamic response if necessary.

The centrifugal pump is assumed to be the dominant source of self-excited vibration. The objective of the CPTL measurement and characterization effort centers on measuring the dynamic response of the support structure and then analytically removing the dynamic contribution of the support structure to determine the dynamic forces generated by the pump. These forces can then be analytically applied to the actual structure that will host the pump in service to evaluate the vibration of the host structure caused by the pump's operation. In the ideal world, the support structure would not contribute to, or otherwise alter, the vibration created by the pump. In reality, the support structure cannot help but contribute to the measured vibration. The issue is the extent to which the support structure vibration characteristics affect the vibration measurements and what options are available to minimize their contribution.

Steady-state forced-response analyses are performed in SAP2000 to evaluate the response of the support structure to harmonic time-varying forces applied at the pump center of gravity (CG) as illustrated in Figure 10. The corresponding acceleration response is obtained at the center of the pump base support (point *P* in the figure). Three steady-state analysis are performed in sequence with a 1-kip amplitude force acting in the X-Direction (east/west), then in the Y-Direction (north/south), and finally in the Z-Direction (up/down). The real pump may tend to produce higher-amplitude forces in the vertical direction than the horizontal direction, or vice versa. In any event, the response is presented as a ratio of the acceleration magnitude at the pump base (in g units) to the applied force (1 kip) for frequencies ranging from 5 Hz to 50 Hz. The SAP2000 model (see Figure 1 and Figure 5) used for these analyses includes elastic links representing the cable supports and the pneumatic isolators and all of the coupled elastic modes of the support structure, isolation towers, and the CPTL.

The thermal expansion is assumed to have taken place at the time the steady-state vibration is recorded. The slip interfaces modelled for the slip plates and pillow blocks are fixed for the dynamics analyses. The basis for this modeling assumption is that the magnitude of the vibration-induced forces is much lower than the thermal expansion-induced forces that the slip surfaces are intended to accommodate. In essence, the natural friction in these surfaces is assumed to be higher than the vibration-induced forces and therefore these locations will appear to be fixed for the purposes of the dynamic response. There is no direct experience with this system to validate this assumption; however, the role of normally-negligible friction forces has been observed in many other measurement/validation efforts the author has led when dealing with civil and aerospace structures. Should the actual performance of CPTL and support structure indicate that slip does in fact occur, the interfaces can be clamped together during the performance measurement phase following the transient thermal expansion phase.

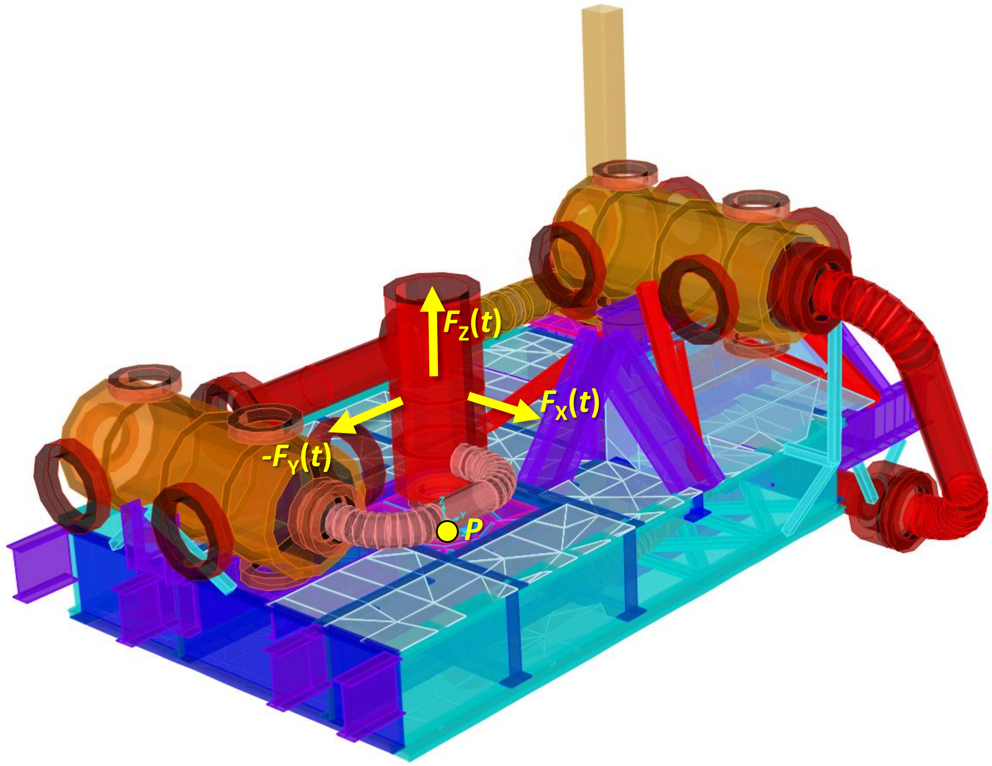



**Figure 10 Steady-State Forced Response Model**

The transfer functions obtained between the CG-applied force and the acceleration at the pump mounting surface are plotted in Figure 11. The design objective is have no structural modes below 25 Hz. There are several modes in this keep-out bandwidth, but their contribution is extremely low and can be effectively "eliminated." The truly "significant" modes are around 45 Hz and are associated with east/west motion of the discharge take support. Additional stiffening of this support could possibly push these modes beyond 50 Hz if necessary.

The mode of greatest concern in the "keep-out" zone occurs at about 14.5 Hz and is associated with a predominantly vertical warping motion of the deck structure. The warping motion of the 14.5-Hz mode is visualized in the Z-direction deflection contour map shown in Figure 12. Numerous alternate design configurations (*e.g.*, deep truss structure) were investigated as part of this study in an attempt to push this mode beyond 25 Hz, however, the slight improvement observed does not justify the significant increase in cost and weight of the support structure given that more cost-effective vibration control strategies are available.

The small amplitude of motion seen in the frequency response function at 14.5 Hz can be effectively eliminated by "re-locating" the nodal line (zero displacement contour) shown in the figure so that it passes though the measurement location. The addition of strategically-placed mass could achieve this goal; however, recent studies suggest that significant added mass may be required and, therefore, may not be a practical solution. Altering the placement and stiffness of the supporting beams will be investigated as part of the final design effort. An alternative approach is to introduce a tuned-mass damper as discussed in the next section.

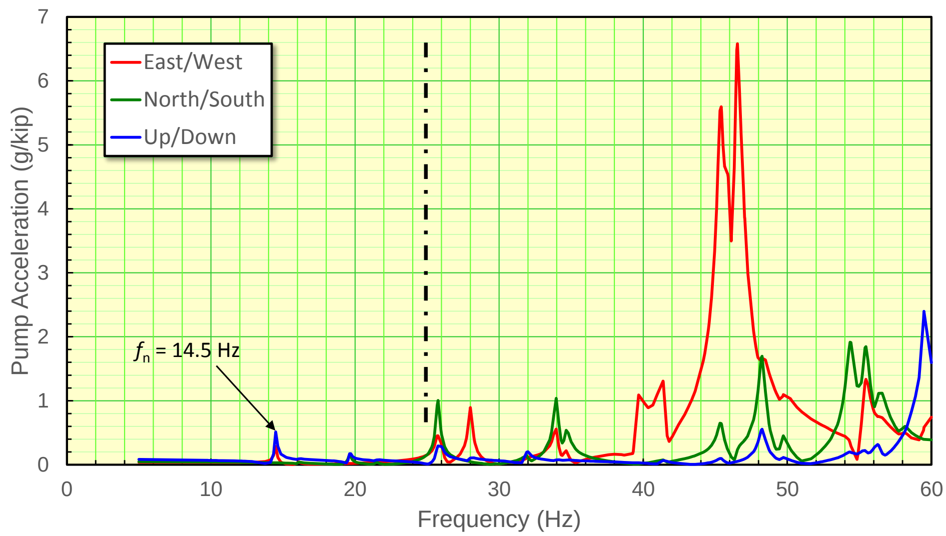



**Figure 11 Steady-State Response for 1-Kip Harmonic Force at Pump CG**

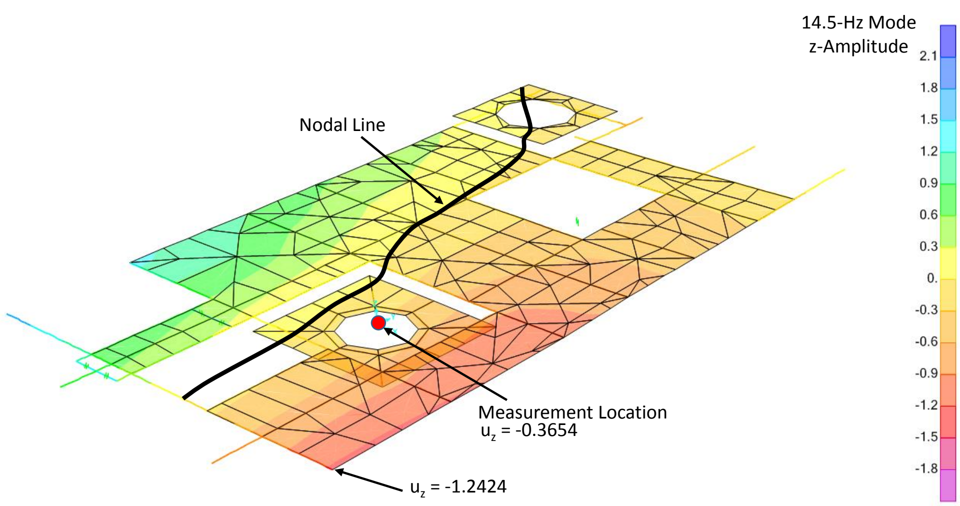



**Figure 12 14.5-Hz Mode Z-Contour Map and Zero-Response Nodal Line**

The objective of the Client's test activity is to measure the acceleration of the CPTL support platform as a means of estimating the dynamic forces produced by the centrifugal pump(s), then the critical platform response is represented as the pump force-to-platform acceleration transfer functions such as those plotted in Figure 13 based on the 12-DOF model discussed above (Figure 6). A rigid platform yields a constant-magnitude acceleration within the measurement bandwidth of interest (with a slight deviation near 5 Hz) that is directly proportional to the force generated by the pump at a given frequency. Deviations from the ideal rigid platform caused by the coupled elastic modes of the platform/CPTL structure are shown in Figure 11 and can be mitigated with tuned-mass dampers. Finally, it is worth noting that the isolation tower resonant modes do not affect the quality of the lateral acceleration measurement (*i.e.*, there are no peaks at 19 Hz or 28 Hz).

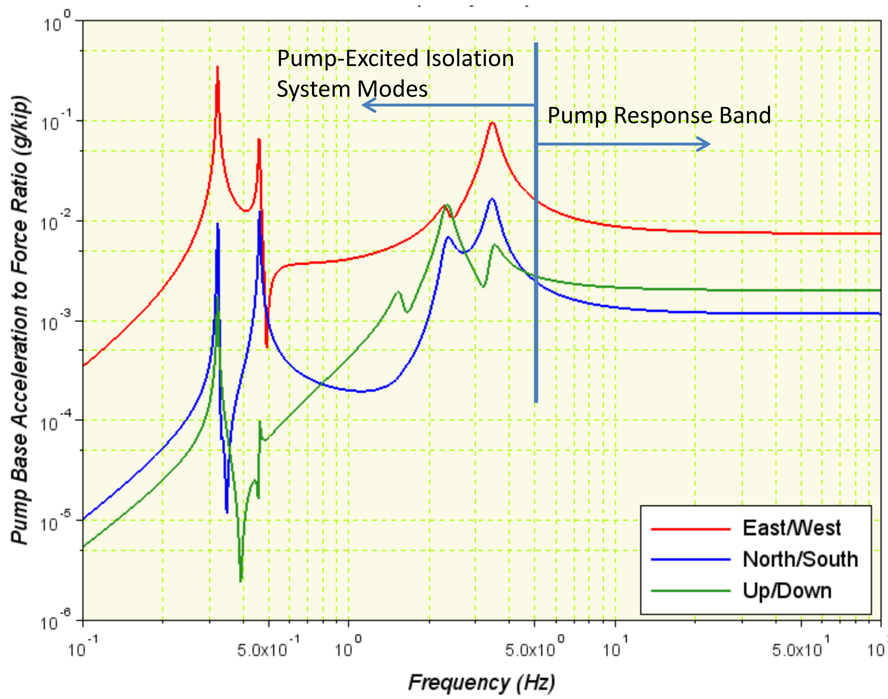



**Figure 13 12-DOF Model Transfer Functions for Pump-Excited Vibration (Rigid Platform)**

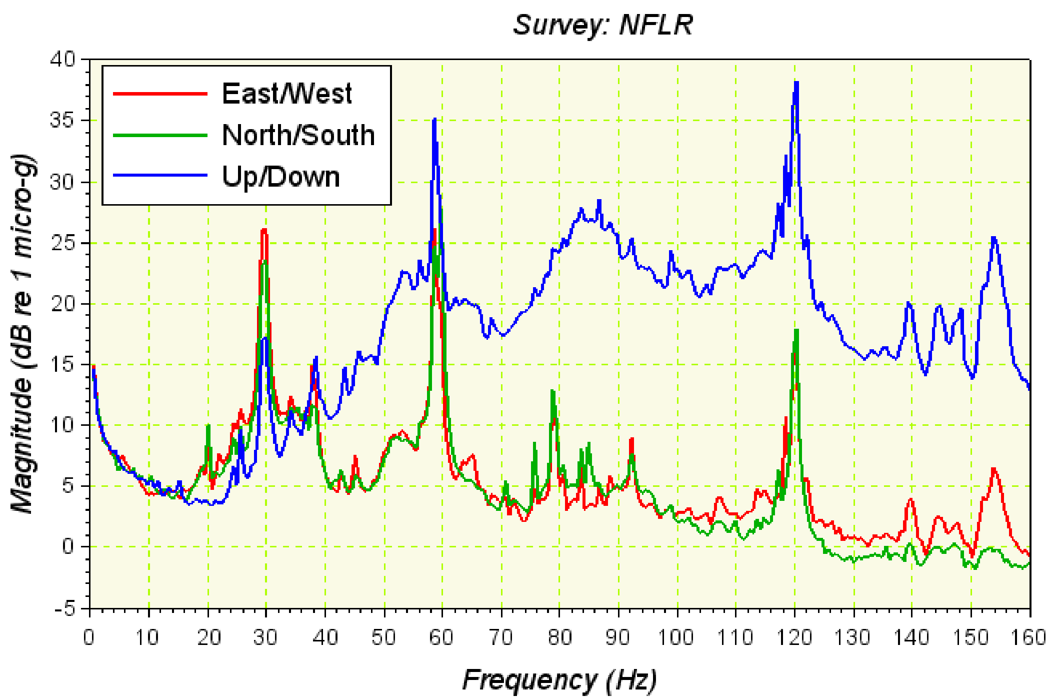
## 3. OBSERVATIONS AND WATCH ITEMS

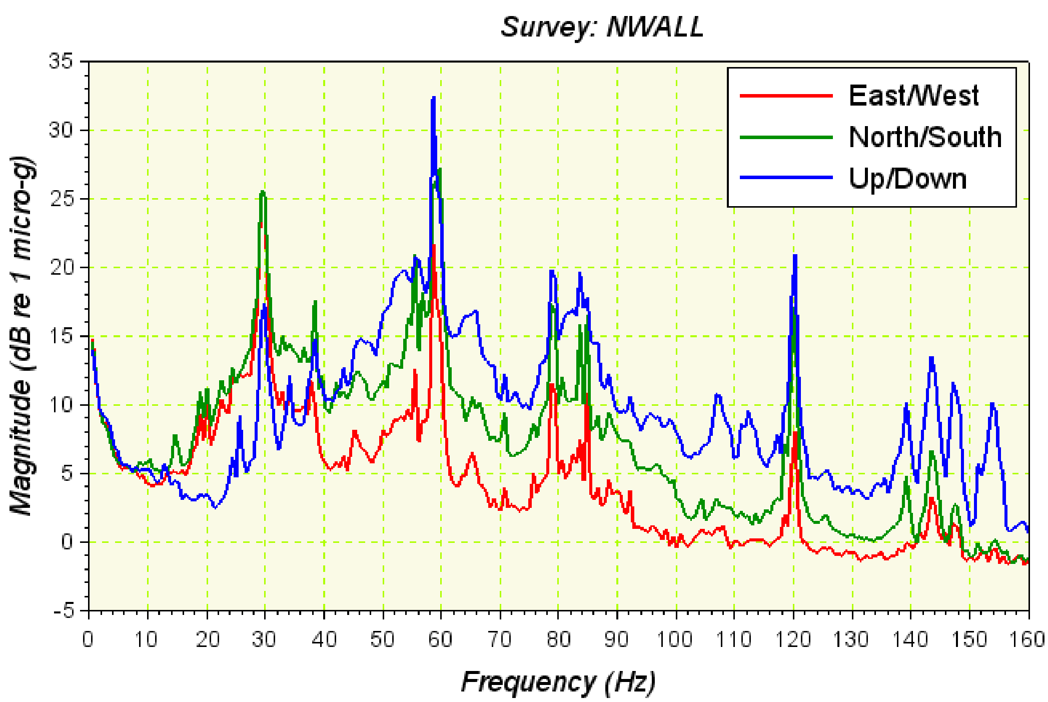
The conceptual design of the CPTL support structure satisfies the ground vibration isolation objectives. The isolation system consists of a length-adjustable cable-suspended deck for excellent horizontal isolation and employs twelve off-the-shelf pneumatic isolators for the vertical isolation. Client personnel have experience using these or similar pneumatic isolators. The isolation systems can be locked out when necessary to prevent platform motion during CPTL assembly, tear-down, and maintenance and then “floated” when test operations resume.

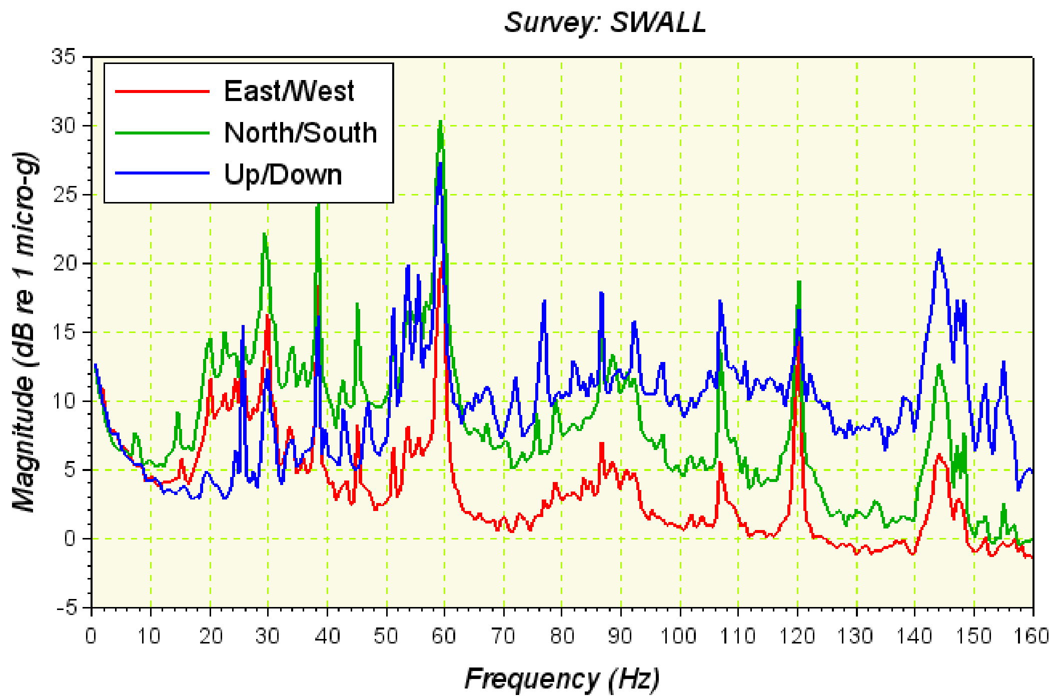
The ideal design provides an isolation system with consistent and known dynamics properties supporting a rigid platform. True rigidity is impossible to achieve; however, every attempt is made to design a practical pseudo-rigid platform. There is one structural mode (a warping-like mode) that persists within the 5 Hz to 25 Hz frequency range (estimated to be around 14.5 Hz) that primarily affects the vertical response of the deck and is therefore most problematic for vertical forces generated by the pump. Tuned-mass dampers provide a means for essentially eliminating this mode to the point where its presence will have no measurable impact on Client test data and.

The Client may alter the main CPTL configuration and test a variety of pumps with different overall mass properties during their follow-on testing. The alternate configurations are not addressed explicitly in the present analysis as experience gained modeling and analyzing the primary configuration provides the insight necessary to address these alternate configurations “by inspection.” First, pump weight variation is not an issue. If necessary, additional weight can be added under the platform to maintain the same total mass and the slight changes in pump mass will not have a measureable effect on the platform CG or overall mass properties. The much simpler alternate loop exchanges the S-curved 14-inch pipe segment that spans between the suction tank and the pump with a U-shaped 20-inch pipe segment. The as-designed platform can accommodate this pipe segment without any conflicts and the pipe stress analysis performed for the main loop suggests there will be no structural issues with the simple loop. The Client has also suggested that one or both of the tanks may be replaced with straight pipe segments. An additional roller support can be bolted in place to the existing tank supports to support these pipe segments. This small add-on feature falls in the category of miscellaneous metals as far as the overall construction budget is concerned. In summary, the current design should be very tolerant of CPTL variations.

4. SITE SURVEY VIBRATION DATA

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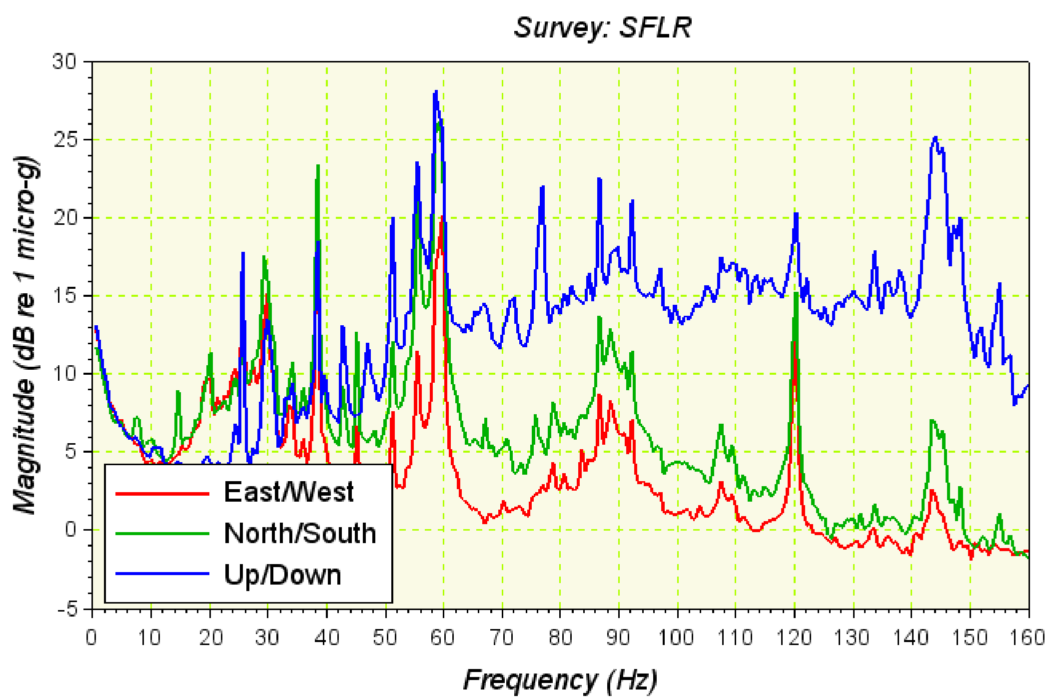
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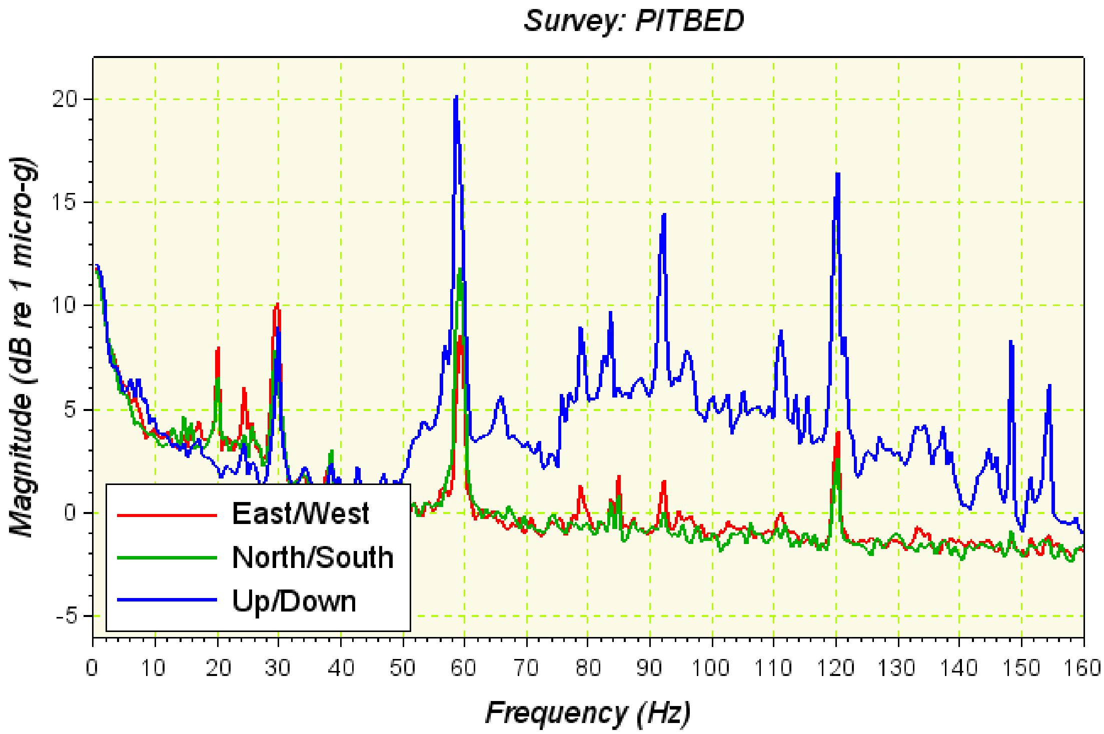
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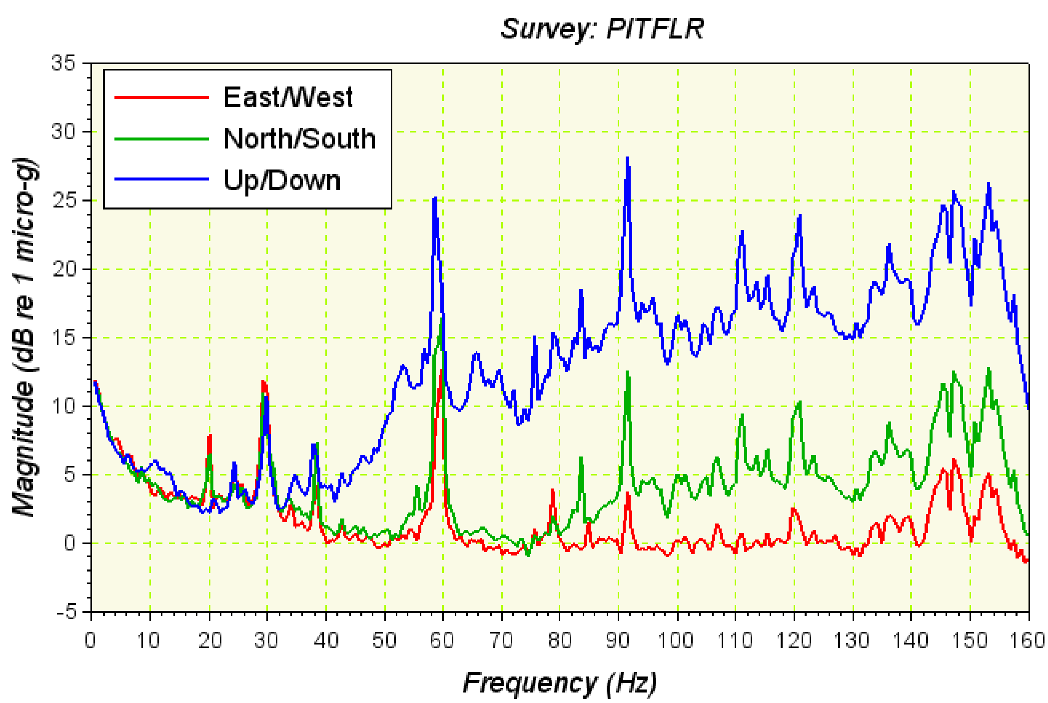
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