

How good is the weighted-sum estimate of the vibrator ground force?

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Vibroseis sources are the principal nonimpulsive sources used in land seismic exploration. To achieve an improved image of the subsurface with higher accuracy and better resolution, it is necessary to take the true ground force as the reference in calculating the cross-correlation function with the far-field data instead of using the theoretical reference signal. The true ground force is defined as the total compressive force exerted by the Earth upon the vibrator baseplate. Theoretically, it can be calculated by integrating the compressive stress over the surface area that contacts the baseplate. In practice it is very difficult to quantify the true ground force accurately. As the vibrator shakes on highly variable surfaces such as desert sand dunes, the vibrator will generate more harmonic distortion. At the same time, the baseplate will flex and rock. This results in poor repeatability of source signatures. This means that the true ground force varies from place to place and becomes impossible to determine.

The vibrator ground force can be approximated by using a “weighted sum” of accelerations of the reaction mass and the baseplate. This method is based upon a rigid body assumption for both the reaction mass and the baseplate. Unfortunately, the baseplate is subject to flexural motions due to its low rigidity. Different locations within the baseplate have different motions so that the acceleration recorded by the single baseplate accelerometer cannot represent the baseplate motion. Therefore, the validity of the weighted-sum ground force becomes questionable. Load cells can provide a true measurement of the vibrator force output but are not yet robust enough for routine use. Designing the vibrator baseplate with sufficient stiffness is cost prohibitive. A combination of the relatively stiffer baseplate and the determination of the baseplate accelerometer position might provide a significantly better estimation for the true ground force.

Vibrator baseplate flexure and weighted-sum ground force

A modern seismic vibrator is essentially a hydromechanical system driven by a servovalve assembly that is controlled electronically. Figure 1 depicts a cross section of an ION (previously I/O) AHV-IV vibrator. The piston is rigidly connected to a top cross and a bottom cross. The top cross and the bottom cross are firmly joined with four tie rods that are mechanically integrated with a baseplate pad. The piston, the top cross, the bottom cross and the tie rods are linked together and called the baseplate stilt structure. The vibrator baseplate is formed by a baseplate pad and the baseplate stilt structure. The piston moves in a cylindrical bore inside the reaction mass and divides the cylinder into an upper chamber and a lower chamber. The high-pressure hydraulic oil flows out of the servovalve assembly and is fed alternately into the upper and lower chambers to drive the reaction mass up and down. The force acting on the reaction mass is equally and

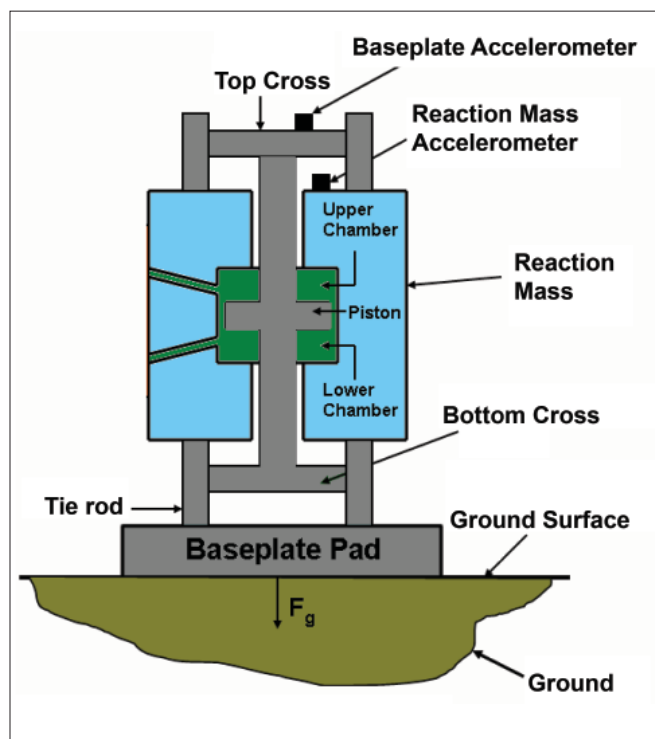


Figure 1. The schematic model of an AHV-IV vibrator.

oppositely applied to the piston. Eventually, the force is emitted into the ground by the vibrator baseplate. In general, the vibrator baseplate functionally acts like a transmitter, broadcasting a hydraulic force into the Earth.

Accelerometers are strategically mounted on the vibrator structure to record accelerations of the baseplate and the reaction mass. For an AHV-IV vibrator, the baseplate accelerometer is mounted on the top cross and the reaction mass accelerometer is installed on the top of the reaction mass as depicted in Figure 1. Sallas (1984) presented a weighted-sum method to approximate the true ground force (F_g). This method assumes that the baseplate acts as a rigid body, and a full coupling of the baseplate and the ground is achieved. Under these assumptions, the weighted-sum ground force is obtained by summing weighted baseplate and reaction mass accelerations. In this case,

$$-F_g = M_r A_r + M_b A_b \quad (1)$$

where M_r , M_b , A_r , and A_b are the mass of the reaction mass, the mass of the baseplate, the reaction mass acceleration, and the baseplate acceleration, respectively.

Due to its low rigidity, the baseplate is subject to flexural vibrations at higher frequencies. The modes of the flexural vibration are diverse and depend on ground conditions. When the baseplate is on very uneven surfaces, the flexural vibration can be described as the baseplate wobbling and jumping up

and down. Often this flexural vibration leads to full decoupling or severe partial decoupling, and the vibrator performance is significantly degraded. When the baseplate is on a flat surface, the flexural vibration can be described as a bird flapping its wings. In this situation, the partial decoupling will occur, but the decoupling area is small. For an AHV-IV vibrator, the hydraulic force is more concentrated on the central area of the baseplate pad than the side area of the baseplate when the baseplate is pushed downwards. In this case, the portion of the baseplate at the four corners moves upwards opposite to the downward direction of the forces. When the baseplate is pulled upwards, the baseplate deforms in the shape of an arch with the center of the baseplate at the top of the arch. A partial decoupling occurs at the central area. Generally, different locations within the baseplate will produce different motions. Placing accelerometers in different places on the baseplate will measure different accelerations. It is very difficult to determine the exact vertical acceleration of the baseplate using a single accelerometer. It also becomes difficult to determine how much baseplate mass participates in the vertical motion.

The vibrator ground force can be estimated by using a “weighted sum” of accelerations of the reaction mass and the baseplate. Because of the flexing of the baseplate pad and very complicated rocking of the baseplate stilt structure at higher frequencies, the weighted-sum method can approximate the true ground force only in a narrow frequency band. In general, the weighted-sum approximation overestimates the actual force output of the vibrator. Many researchers have verified this by making comparisons between the weighted-sum ground force and the direct-force measurement using load cells (Sallas et al., 1985; Baeten and Strijbos, 1988; Baeten and Ziolkoski, 1990). Figure 2 shows an experimental setup. The AHV-IV vibrator sits on load cells. The load cell is a sensor that can directly measure the true ground force. Eight load cells are firmly mounted on concrete and placed evenly under the baseplate. There are two pieces of rubber pad on the top of each load cell to protect the load cells from metal-to-metal contact. Under this loading condition, the baseplate is well coupled with the load cells. However, the contact area is small. Obviously, a severe decoupling is formed between the baseplate and the concrete. Figure 3 depicts a top view of the baseplate pad where magnetic accelerometers are positioned. The locations are grouped on the driver’s side (A, B, E, H, and J) and passenger’s side (D, C, G, I, and K) with sensor F in the middle. The positions of A, D, J, and K are 6 inches away from the corners in the X and Y directions. B, C, H, and I are chosen to be at the leg tube positions. The positions of E and G are located on the centerline in the X direction and midway between the edge and stilt tubes. F is at the center of the baseplate pad. Six magnetic accelerometers were used to measure the motion of the baseplate pad. They were placed on driver’s side first to record accelerations of the baseplate pad, and then they were moved to the passenger’s side to record accelerations of the baseplate pad. In general, the data from the driver’s and passenger’s sides are very similar. Thus, we only present the driver side’s data here.

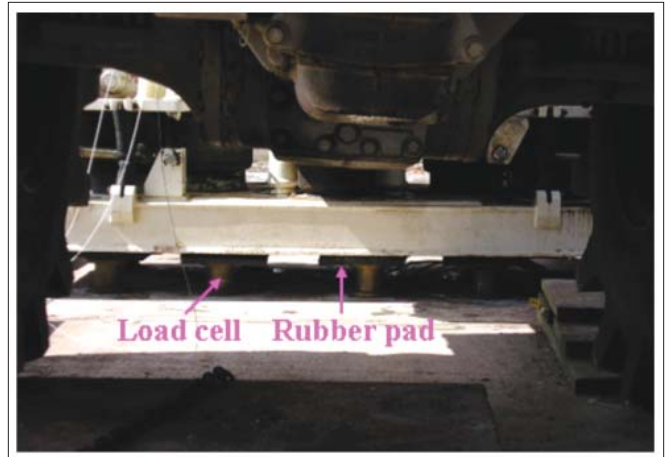


Figure 2. The vibrator is on load cells.

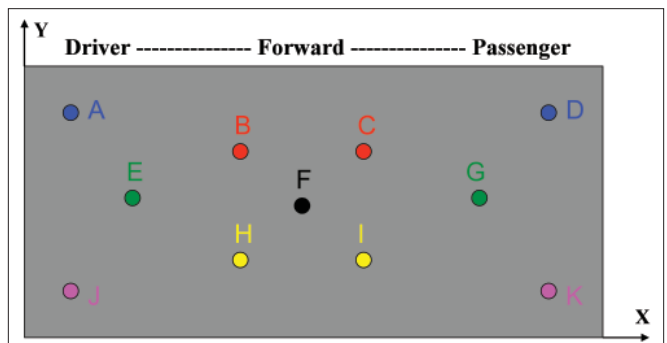


Figure 3. Magnetic accelerometer positions on the baseplate pad.

To compare the weighted-sum ground forces and the true ground force, a linear sweep with a length of 20 s from 1 Hz to 201 Hz was used to run the vibrator. The target force is set at 70% of hold-down weight (60,000 lbs). Figure 2 shows this experimental setup. The baseplate stilt structure of this vibrator is about 6 inches shorter than that of the production AHV-IV vibrator. Figure 4 shows the frequency response of the weighted-sum ground forces against the true ground force. The weighted-sum ground forces were calculated by using different baseplate accelerations recorded with magnetic accelerometers on different positions, and the true ground force was measured by load-cell sensors. The magnitude ratio and phase spectra were plotted by using the load-cell ground force as the input and the weighted-sum ground force as the output. Theoretically, the magnitude ratio spectrum and the phase spectrum should remain constants at 0 dB and 0°, respectively, if the weighted-sum and measured ground forces are equal. Figure 4 clearly demonstrates that none of weighted-sum ground forces are in agreement with the load-cell ground force in the 200-Hz frequency range. The broken line marked as FBK in Figure 4 is the weighted-sum ground force calculated by using the Pelton accelerometers against the true ground force. The Pelton baseplate accelerometer is often placed on the top cross of the baseplate stilt structure.

The measurements from positions F and H are extremely anomalous. The ground forces estimated by the weighted-sum method from these positions are completely different than the true ground force. The trend of this discrepancy in-

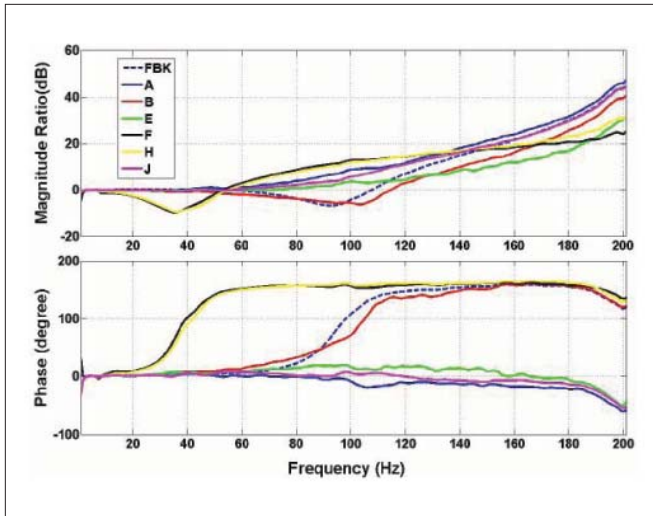


Figure 4. Comparison in frequency response of weighted-sum ground force versus load-cell force in frequency range from 1 to 201 Hz.

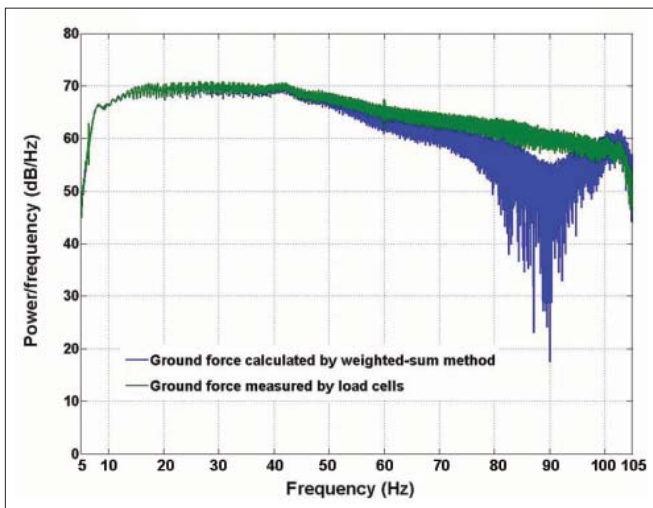


Figure 5. Comparison in power-spectrum density of weighted-sum ground force versus load-cell force in frequency range from 5 to 105 Hz.

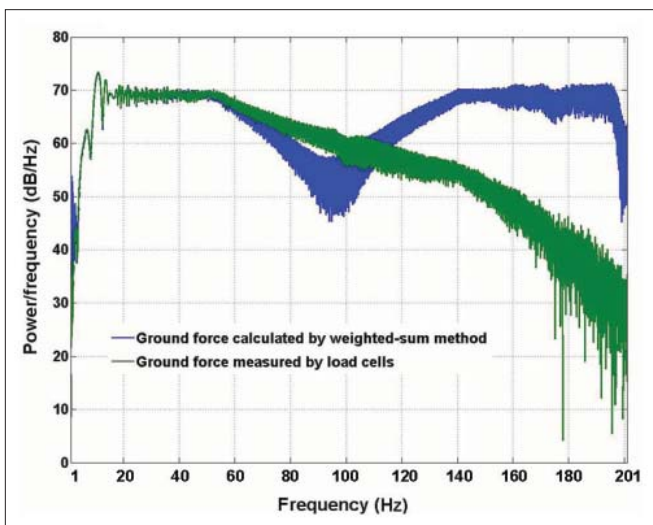


Figure 6. Comparison in power-spectrum density of weighted-sum ground force versus load-cell force in frequency range from 1 to 201 Hz.

indicates that the central area of the baseplate has experienced severe partial decoupling for a substantial amount of the time. Conversely, the ground forces estimated by the weighted-sum method using accelerations on the positions of A, B, E, and J agree to the true ground force in the frequency range below 50 Hz. For frequencies above 50 Hz, the measurements demonstrate that the weighted-sum method is no longer valid to approximate the vibrator true ground force output. This finding is also applied for the FBK cases. Actually, this has been observed as well on other types of vibrators by Sallas et al. (1985) and Allen et al. (1998).

Figure 5 shows one example of power-spectrum density to compare the weighted-sum ground force and the true ground force. The experiment used a 20-s linear sweep in the frequency range of 5–105 Hz. The weighted-sum ground force is computed by using the Pelton baseplate accelerometer data. As stated earlier, the Pelton baseplate accelerometer is mounted on the top cross of the stilt structure. The weighted-sum ground force is shown in blue, and the ground force measured by load cells is shown in green. Both forces are in good agreement below 50 Hz, but at 50 Hz the forces start to diverge. As the frequency goes up, the discrepancy becomes larger. Obviously, the weighted-sum ground force can not fully represent the true ground force. It underestimates the true ground force in this case. Figure 6 shows another example of power-spectrum density comparison between the weighted-sum ground force and the true ground force. The test was run using a 20-s linear sweep in the frequency range of 1–201 Hz. Once again the weighted-sum ground force is calculated by using the Pelton baseplate accelerometer data. As in Figure 5, the weighted-sum ground force is shown in blue and the ground force measured by load cells is shown in green. In the frequency range below 100 Hz, Figure 6 shows similar behavior to Figure 5. When the frequency goes above 80 Hz, the weighted-sum ground force is a poor estimation of the true ground force and it overestimates the true ground force. Traditionally, most of these discrepancies are attributed to the baseplate flexural vibration. However, the complexity is increased by the relationship between the weighted-sum ground force and the true ground force, which is variable due to different ground-coupling conditions. In practice, the ground force is not known exactly and varies from place to place. For the case of the AHV-IV vibrator on load cells, the weighted-sum approximation underestimates the actual force output of the vibrator between 50 and 100 Hz, but it overestimates the actual force output of the vibrator beyond 100 Hz. Direct force measurement such as using load cells is needed to measure the real ground force, but load cells are not yet robust enough for routine use.

New stiffer baseplate and weighted-sum ground force

The weighted-sum of the accelerations of the baseplate and the reaction mass provides a means for measuring the true ground force. The advantage of this method is that it only requires measuring accelerations of the baseplate and reaction mass. In practice, the accelerometer is easy to install, maintain, and troubleshoot. The disadvantage of this method is that it assumes the baseplate behaves as a rigid body

and that the baseplate is fully coupled with the ground. In real world applications, we know it is impossible to achieve a rigid-body baseplate. Full coupling can never be achieved either because the ground is never flat. As stated earlier and demonstrated in Figure 4 and Figure 5, the baseplate is not a rigid body and is subject to flexural vibrations. Placing accelerometers on different positions within the baseplate will measure different accelerations. Weighted-sum ground forces formed by using these baseplate accelerations agree with the ground force measured by load cells in a very narrow-frequency bandwidth. When the frequency goes above 50 Hz, the discrepancy occurs and grows larger. Eventually, this discrepancy causes the validity of the weighted-sum ground force to become questionable.

The inaccuracies in the weighted-sum ground force estimation, stemming from both baseplate flexure and the limitations of accelerometer placement on the baseplate, call for improvements in vibrator design. Theoretically, the flexural vibrations of the baseplate can be reduced by stiffening the baseplate structure. The resultant reduction in flexure allows the dynamic motion of the baseplate to be simplified and characterized more accurately. Having characterized the baseplate motion accurately, an optimal location or “sweet spot” can then be found for the accelerometer placement where the vertical motion of the baseplate and ground can be measured more precisely. This two-fold approach allows the weighted-sum ground force estimate to be far more representative of the true ground force.

Stiffness is the resistance of an elastic body to deformation by an applied force. It is a material property and extensively controlled by both the Young’s modulus of the material and the geometry of the elastic body. For modern seismic vibrators, the baseplate is made of steel. Enhancing the stiffness by using materials with a high Young’s modulus (such as composite materials) will significantly increase capital costs of the vibrator. The only option left is to change the geometry of the baseplate. Through experimental tests and finite-element modeling and analysis, a new stiffer baseplate was designed. This new baseplate design involved extensively changing the structural shape of its mechanical components. Experimental results show that the new design significantly increases the stiffness of the baseplate and dramatically reduces its flexure. The new baseplate is 2.5 times stiffer than the standard baseplate but has only an 8% increase in weight. With the new baseplate, the coupling of the baseplate and the ground is improved under various loading conditions, and the vibrator performs robustly. In general, the vertical motion of the baseplate can still be described as a bird flapping its wings. For the new stiffer baseplate, an optimal spot was found to use as the baseplate accelerometer location.

Figure 7 compares the weighted-sum ground force and the load-cell ground force in the power spectrum density in blue and red, respectively. A 20-s linear sweep from 5 to 105 Hz was chosen for the experiment. The weighted-sum ground force is computed using the optimal location baseplate accelerometer data. Figure 7 shows that both forces are in very good agreement throughout the entire frequency band. Only

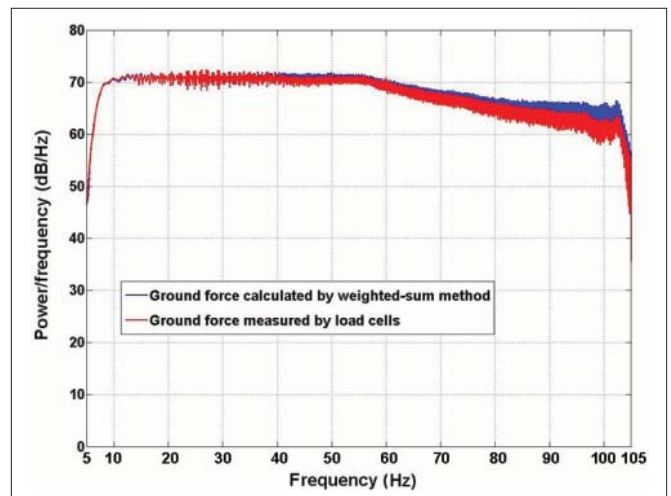


Figure 7. Comparison in power-spectrum density of weighted-sum ground force versus load cell force in frequency range from 5 to 105 Hz.

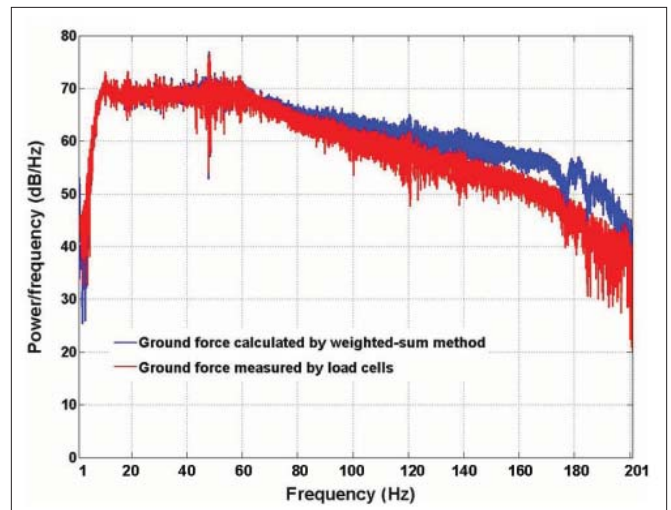


Figure 8. Comparison in power-spectrum density of weighted-sum ground force versus load-cell force in frequency range from 1 to 201 Hz.

a slight discrepancy is observed between 90 and 100 Hz. The weighted-sum ground force calculated using the baseplate acceleration on the optimal location estimates the true ground force very well. Figure 8 shows another comparison in power-spectrum density. In this case, the experiment was performed using a 20-s linear sweep from 1 to 201 Hz. Once again the weighted-sum ground force is calculated using the optimal location baseplate acceleration. Figure 8 demonstrates that the weighted-sum ground force overlaps the true ground force very well up to 120 Hz. For the frequencies above 120 Hz, the weighted-sum ground force slightly overestimates of the true ground force. However, compared to Figure 6 the weighted-sum ground force estimated using the baseplate acceleration on the optimal location is a significant improvement.

Figure 9 compares ground forces measured by load cells. Green represents the true ground force output from the standard baseplate and red represents the true ground force output

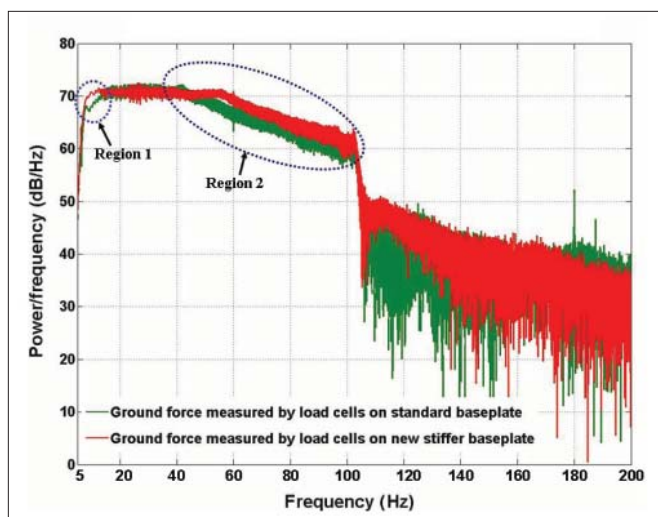


Figure 9. Comparison in power-spectrum density of load-cell forces in frequency range from 5 to 201 Hz.

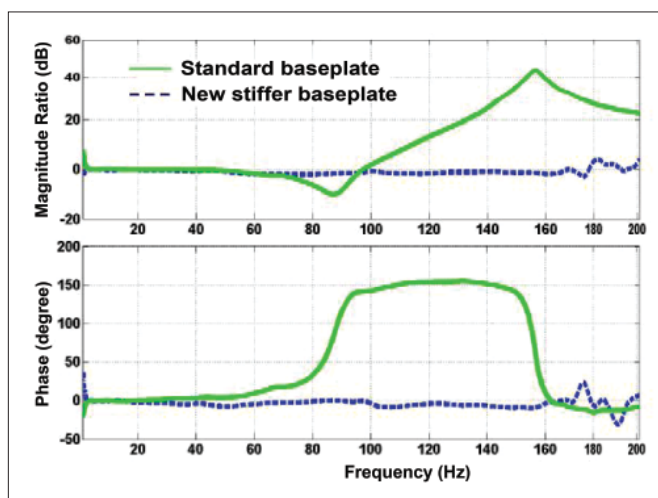


Figure 10. Comparison in frequency response of weighted-sum ground force versus load-cell force in frequency range from 1 to 201 Hz.

from the new stiffer baseplate. These load-cell ground forces were presented in Figure 6 and Figure 7. The new stiffer baseplate provides more ground-force energy than the standard baseplate does in region 1 from 5 to 10 Hz and region 2 from 40 to 105 Hz. This is because the new stiffer baseplate reduces the baseplate rocking and flexural vibrations so that the force loss is minimized. Both load-cell forces decline at higher frequencies. The ground force at these high frequencies indicates that there are some limitations in the vibrator hydraulic and mechanical system; for example the weight of the baseplate, the limits of the torque motor current on the pilot servovalve, and the hydraulic supply pressure. These limitations eventually prevent the vibrator from achieving its target force.

Figure 10 shows the ratio of the ground force frequency response calculated by the weighted-sum method against the ground force measured by load-cell sensors, in similar manner to Figure 4. The comparison was made between the new stiffer baseplate and the standard baseplate. The dashed blue line

uses the new stiffer baseplate with the baseplate accelerometer on the optimal location. The solid green line, however, uses measurements from the standard baseplate with the baseplate accelerometer mounted on the top cross of the stilt structure. A zero-dB and zero-phase response will be seen in the ground force frequency response plots if the baseplate is acting as a rigid body and the baseplate accelerometer records the vertical motion of the plate and the ground. As illustrated in Figure 10, the weighted-sum ground force provided by the new baseplate provides a more accurate depiction of the weighted-sum ground force when compared to the true ground force experienced by the load cells. Figure 10 also shows that the weighted-sum ground force under the standard baseplate can approximate the ground force measured by load cells below 40 Hz. With the new baseplate, the weighted-sum method can accurately estimate the measured ground force up to 160 Hz.

Conclusions

Ideally, a vibrator used in vibroseis data acquisition should produce ground force as a known spatially-invariant wavelet such that any variations in reflection data can be attributed to variations in geology. In reality, we don't even know the true ground force being output by the vibrator. Experimental data show that the popular method of weighted-sum only works in a narrow-frequency band on current production vibrators. With the new stiffer baseplate and the optimal location for the baseplate accelerometer, the weighted-sum ground force can be used to approximate the true ground force and will remain valid up to 160 Hz. Meanwhile, more ground force energy produced by the new stiffer baseplate is observed.

Suggested reading. "Seismic vibrator control and the down-going P-wave" by Sallas (GEOPHYSICS, 1984). "Ground force control of a P-wave vibrator" by Sallas et al. (SEG 1985 seismic field techniques workshop). "Wave field of a vibrator on a layered halfspace: theory and practice" by Baeten et al. (SEG 1988 *Expanded Abstracts*). *The Vibroseis Source* by Baeten and Ziolkowski (Elsevier, 1990). "High-fidelity vibratory seismic (HFVS) method for acquiring seismic data" by Allen et al. (SEG 1998 *Expanded Abstracts*). **TLE**

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