Vibrator force control: How simple can it get?

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The introduction of *groundforce amplitude control* (force control) in 1980 made a great contribution to the vibroseis technique. However, the improvements don't always make life easier in the field. Someone must decide how much force the vibrators should produce, and that decision isn't always as simple as a rule of thumb. Consequently, determination of the force level set point during field set-up tests may prove more reasonable than to specify it in a contract. This is due to the vibrator's interaction with the earth, and its design limitations. This article will attempt to provide a basic understanding of both.

The following definitions will apply:

Vibrator refers to parts meant to vibrate (the reaction mass, baseplate, and stilt structure, and everything firmly attached to them).

Vibrator truck refers to a complete vibrator and vehicle, and everything on the vehicle.

Mass is often used to refer to the "reaction mass," and "weight" is often used in place of the more correct physical concept of "mass" to avoid confusion with the reaction mass, and to correspond to actual practice.

Force control improves vibrator performance because it goes a long way toward solving some problems which plagued the technique for a generation. Basically, force control is designed to:

1) prevent decoupling (i.e., separation of the baseplate from the earth),
2) allow maximum use of vibrator power over a wide frequency range, and
3) generate repeatable power spectra on various earth surfaces.

These are big improvements. But they came at a cost; they brought some new problems and highlighted some old ones we didn't recognize before. The problems include:

1) Need for accurate reaction mass and baseplate weights.
2) Vibrators fail to produce as much ground force as their rated "peak force" on some types of ground, at some frequencies.
3) Servovalves and other parts sometimes fail, even within rated torque motor current.
4) Distortion may increase when the power spectrum changes.

Before further examination of these problems, I think it will be helpful to consider the interaction between a vibrator and the earth. Some simple imagined or actual experiments will help describe what actually happens.

Experiment 1: Decoupling from a hard surface. Imagine that you jump straight up from a hard surface. You pressed down on the floor with enough force to accelerate your body more than the acceleration of gravity (1 G); your legs ran out of stroke or stopped pushing; and you lifted off. On a vibrator, this is called decoupling.

There is another way to decouple. It's a little harder. Lift your feet and knees at an acceleration greater than 1 G without jumping, and then put your feet back down. Your weight was temporarily removed from the floor. This is the decoupling mechanism we traditionally think of with vibrators.

Experiment 2: Decoupling from a soft elastic (springy) surface. Imagine a standing jump on a trampoline. Do it with a single motion, not by bouncing. The frequency at which you bounce after your jump attempt is the natural resonance frequency of a spring/mass system in which you are most of the mass, and the trampoline provides the springs. It's hard to decouple without bouncing at the natural resonance frequency of the system. As you press down to accelerate your body, the surface moves away. You can't build up as much force under your baseplate (pressure on your feet times area) as you could on the hard surface, because this surface gives way at too little force. You feel that if your legs were four times longer or stronger, maybe you could decouple; but you run out of stroke before your acceleration is adequate under current system limitations. A trampoline has a low spring constant. By Hooke's law, force divided by elastic surface displacement is the spring constant, also known as stiffness coefficient.

Now for the second method of decoupling on the trampoline. The weight a vibrator baseplate applies to the ground while at rest is called its "hold down" weight. Lift your feet and try to remove all your hold down weight temporarily from the surface. Again, it's hard to do. Your weight depressed the surface and stored potential energy in the springs. When you lift your feet, the surface follows, returning the stored energy. You must accelerate your feet at much more than 1 G to decouple. Again, having longer or stronger legs would help. A fast stroke much longer than the original deformation of the surface would succeed.

OK, go ahead and bounce at the natural resonance frequency of the trampoline and mass system. You deserve it. Notice that you can build up plenty of pressure under your feet now. You are part of a highly tuned (high Q) resonant system. At the system's natural resonance frequency, you are very efficient. The trampoline's energy storage ability, its long stroke, and its low stiffness help you gain enough velocity to fly high.

Experiment 3: Decoupling from a soft elastic surface with damping. Imagine that you are making a standing jump on a mattress. One with cotton or feathers inside should do nicely. The mattress is a compromise between the two surfaces tried previously. It's easier to accelerate and decouple than on the trampoline, but harder than on the floor.

Lift your feet to decouple. You have to significantly exceed 1 G because the mattress will follow your feet. It follows more slowly than the trampoline though, so you may be able to succeed.

In these experiments, your body substituted for a vibrator. I hope you got a feel for the force interaction between your baseplate (soles of your feet) and the different surface types. Instead of doing sweeps, you performed impulse functions except in the latter part of experiment 2 where you did a monochromatic (single frequency) sweep. The word "sweep" doesn't correctly apply to a single frequency, but it is normally used anyway.

The surface types made a big difference in the feel and in the results. Impedance can help describe surface types. It is the vector sum of an energy dissipating (damping) load, and a reactive (spring or mass) load. The floor is a hard (high impedance) surface. On a hard surface, you can generate your maximum ground force with a short stroke, and the primary limitation is the energy source. You probably wouldn't notice whether it was a stiff spring, or a stiff damper, or both. It just feels hard.

The trampoline is a low impedance, springy surface, a reactive load. When you push on it, energy is stored for later return. It dissipates little energy as heat. The only easy way to develop dynamic ground force on it is to operate at the natural resonance frequency of the spring-mass system. When you push on the surface, it gives way. Ground force requires cooperation. You or a vibrator push on a surface, and you want the surface to push back.

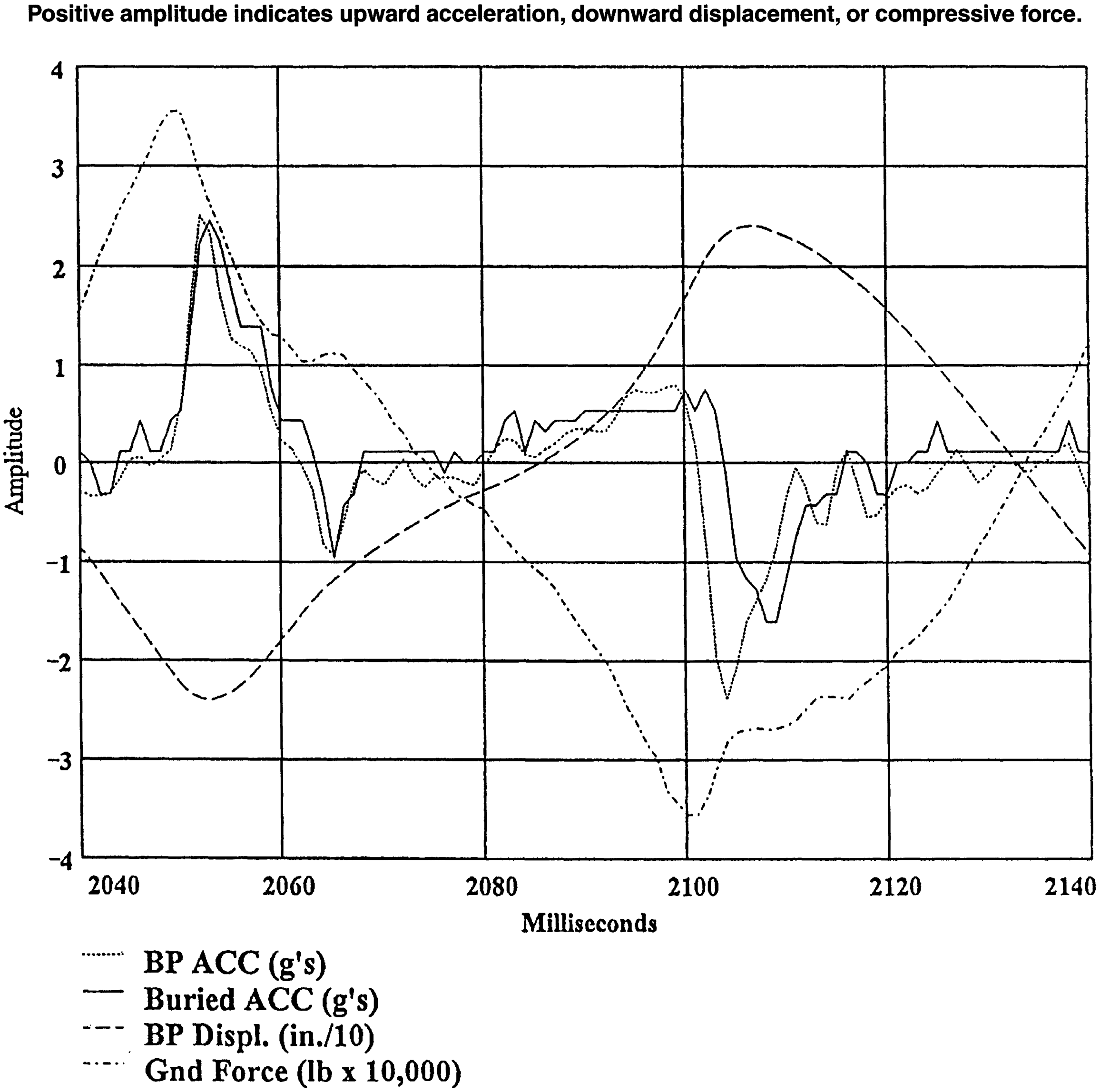

Figure 1. Accelerometers on and under a vibrator baseplate, baseplate displacement, and ground force. One cycle of a constant 10 Hz signal.

Several important points arise from the trampoline experiments:

1) A pure spring load returns all energy, permanently accepting none.
2) On a soft surface, a large stroke and a lot of effort may be required to achieve the desired ground force.
3) If a vibrator baseplate operates at peak accelerations greater than 1 G (the usual case), it depends upon the spring characteristic (elasticity) of the ground to prevent decoupling.
4) When you operate at the natural resonance frequency of a system, you have maximum efficiency. You or your vibrator can burn less fuel and expend less effort, and develop maximum force.

Vibrators can develop even more than their rated force when they are in highly tuned resonance with a surface. At resonance, the ground helps the energy source by returning some of its energy at just the right time in each cycle.

A mattress is a low impedance surface with both spring and damping characteristics. Damping dissipates power by changing mechanical energy into heat energy, and also by radiating energy through the earth in the case of a vibrator. Damping tends to reduce the velocity of an object. (Force applied by a damper = damping coefficient multiplied by velocity.) Shock absorbers on cars are dampers. An energy source must have some damping in its load in order to permanently transfer energy. If the load is only reactive (mass or spring), all energy applied to the load is later returned to the source.

Damping moderates the effects of resonance in a spring/mass system, and makes control easier. It reduces the Q or tuning of a system. Damping also reduces the earth's ability to follow and stay in contact with the baseplate when its direction is upward and its acceleration exceeds 1 G.

The above experiments sample hard and soft surfaces, springs, and dampers. A vibrator encounters a wider variety of surfaces. It must also operate on nonlinear surfaces, on which the spring and damping characteristics change not only with frequency, but also with compression. Some soils must be thixotropic (changes viscosity with agitation). Some are prone to permanent (plastic) deformation, and you and/or a vibrator leave foot prints.

Measurements with a real vibrator. A vibrator experiment was made in Ponca City using a constant frequency of 10 Hz, with "absolute value peak force" set at 90% of hold down force. One accelerometer was bolted to the top and center of the baseplate's steel "pad" which contacts the ground. A similar device was touching the bottom and center of the baseplate pad. The bottom accelerometer was partially buried in a flat soil surface such that its top was flush with the soil surface. It was a light-weight piezo-resistive device in a plastic package. Several sweeps were taken on location before a record was made. The soil was dry and cracked after weeks without rain.

Refer to Figure 1. Upward acceleration produces positive voltage from the accelerometers, and is shown as positive Gs. The baseplate accelerometer signal was integrated twice to show baseplate displacement. Positive amplitude indicates downward displacement. Ground force is shown with positive amplitude representing compression, and negative, rarefaction. The static hold-down force is 10% greater than dynamic peak ground force, so there is no decoupling as we traditionally define it. The time window is 100 ms. All signals were measured using AC coupling.

The positive (downward displacement) peaks of the accelerometers are nearly in phase; but the buried accelerometer lags the baseplate accelerometer, and has lower amplitude at the negative peak.

Was the baseplate decoupling? Not by the normal definition, but it's hard to describe a difference between this and decoupling. Another accelerometer (not shown) was buried 6.5 inches below the baseplate. It showed similar results except for greater delay. There is clearly a nonlinearity in the earth/baseplate coupling and in the radiation impedance.

The baseplate can push both accelerometers down equally, and it can rise without limitation by the earth; but the earth's surface is raised only by the damped spring characteristic of the earth. The negative peak (upward displacement) of the baseplate acceleration is 2.35 Gs, and the earth evidently can't accelerate the buried accelerometer upward that fast. If baseplate acceleration is greater than 1 G then we can only hope earth impedance will allow the surface to rise at similar accelerations and stay in tight contact with the baseplate during upward displacement.

The earth's damping characteristic retards both upward and downward velocity of the surface. Because of nonlinearity though, the velocities may not be the same in both directions, even when dynamic force is symmetrical. The earth's nonlinear nature works against the hope of tight baseplate coupling during upward displacement. In the extreme, the earth may undergo pure plastic (permanent) deformation, in which case the surface doesn't move upward at all. Then the baseplate settles into the ground during a sweep, and will decouple any time it exceeds 1 G during upward displacement. Normally, we have a mixture of plastic and elastic deformation.

Coupling is complicated further by the fact that baseplate bending causes some regions of a baseplate to accelerate more than others. Further, the earth's surface isn't necessarily homogenous or flat.

More force control terms and why you can't get brochure results. A vibrator's dynamic force, "ground force," is measured by the "weighted sum" method. One accelerometer is mounted on the baseplate, and another on the reaction mass. Each one's signal is multiplied by the weight of the structure it's on, and the sum of the two is ground force.

To make the system practical, the weighted sum method assumes that the reaction mass and baseplate are rigid bodies, and that they move only along the desired axis (Sallas, GEOPHYSICS 1984). Any baseplate flexing or motion in undesired directions causes errors in measurement. Up to maybe 80 Hz, the weighted sum is reasonably accurate, but at higher frequencies, the errors may become as large as the signal itself. A device to accurately measure ground force without a need for those assumptions exists, but it adds cost, and is not widely used.

Vibrator brochures specify "peak force." This is a static rating obtained by multiplying the supply pressure by the piston area. It is commonly but erroneously interpreted as "peak ground force." It should be interpreted as "static peak actuator force," sometimes called "reaction mass force." The only reason a vibrator can sometimes achieve ground force equal to or greater than its peak force rating is because the earth's elastic properties assist the vibrator near the earth/baseplate resonance frequency, as the trampoline assisted you at the spring/mass resonant frequency.

The actuator is the hydraulic cylinder consisting of the reaction mass, its piston, and piston rod. The product of the piston area and the difference in pressure across the piston is the "actuator force," also known as reaction mass force (force = pressure x area). Equal and opposite actuator force is applied to the reaction mass and the baseplate. To directly measure actuator force, multiply mass acceleration by the weight of the reaction mass (force = mass x acceleration). The computer software you use to check vibrators probably does this already. Check actuator force to see whether a vibrator is performing well. Check torque motor current, servovalve displacement, and reaction mass displacement, as well. Remember that a vibrator's rated "peak force" is a static rating.

Fluid leakage and flow resistance (dampers) and fluid compressibility (spring) reduce the amount of actuator force which can be developed. Compressibility is more important at high frequencies simply because it happens more often.

Losses associated with the baseplate make up the difference between actuator force and ground force. Some of the actuator force is expended to accelerate the baseplate by overcoming its inertia and friction, some couples from the baseplate into the vehicle frame, and some bends the baseplate structure. The remainder is ground force. Don't be surprised when you are working on soft ground and you can't achieve as much ground force as the vibrator's specified "peak force." A rubber pad under the baseplate may accentuate the problem.

Common force control problems. A few years, ago, the most commonly reported force control problems were on hard surfaces, such as limestone outcrops. Hard surfaces aren't so often a problem now because of recent technology (Reust, *Geophysical Prospecting* 1993). We still hear of occasional problems though, on soft surfaces with certain characteristics (maybe springy with little damping).

Remember the trampoline experiment. Occasionally we encounter soft reactive ground surfaces which remind us of that. There may be a ground force amplitude notch. A vibrator computer analysis system may show that both actuator force and weighted baseplate acceleration are at or above the vibrator's rated maximum peak force, and that the phase angle between them is 130" or more. The vector sum of the two will be low, even though the vibrator is shaking very hard. The results look uncomfortably similar to those of an "air shot." If you operated an ideal vibrator with the baseplate in mid air (don't try this!), the weighted baseplate and mass accelerations would be equal and opposite, and the sum would be zero.

When the ground has a low impedance and little damping, the force control circuit must drive the torque motor hard to achieve the desired ground force amplitude, except at the earth/baseplate resonance frequency. When the vibrator is driven very hard, several bad things can happen. Perhaps the least obvious but most damaging is degrading the data quality by producing excessive harmonic distortion. If you exceed a certain force level, you add more distortion than fundamental to the vibrator's output. Unfortunately, that cross-over force level is different for every surface type, vibrator model, and frequency. In fact, moving a vibrator as little as one meter sometimes changes results dramatically.

Equipment reliability often suffers on surface types which require large valve openings to maintain the desired force level. Cavitation erosion inside the actuator and servovalve increase, and various parts break more frequently. The pilot servovalve is especially prone to early failure at high drive levels. Its design allows the flapper to hit the nozzles at 1/3 rated torque motor current under some load (ground impedance) conditions and over some frequency bands. You may hear a distinct hammering noise in the valve. It can quickly degrade the gain, offset, stability, and noise of the servovalve. It can also crack the flexure tube, allowing oil to leak from the top of the valve.

Lowering the force set point a little often solves problems. In one example, total harmonic distortion was reduced from 75% to 25% by reducing the peak ground force amplitude setting from 90% to 60% of hold down force. The signal-to-noise ratio in the seismic data may have increased, because harmonic distortion decreased much more than the fundamental.

Fundamental, harmonic distortion, and the correlation wavelet. The "fundamental" is the desired component of a vibrator's output signal, excluding any harmonic distortion or noise. It should look like the reference sweep. Harmonic distortion is energy at multiples of the fundamental frequency. Harmonics at integral multiples of the fundamental may be further classified as ultraharmonics, and harmonics at fractional multiples are called subharmonics. With upsweeps, ultraharmonics appear as "precursors" to events in correlated seismic records, and subharmonics appear as a following second set of events. Noise is disturbance on the output signal which is not related to the reference frequency. The meaning of terms changes somewhat whenever we refer to signal-to-noise ratio. In that context, signal means "fundamental," and noise means "noise plus harmonic distortion."

Harmonic distortion is caused by nonlinearities in the vibrator, the earth, and the coupling between the two. Nonlinearities may be further classified as overlinear and sublinear. The earth's impedance is typically sublinear. That is, it appears increasingly soft with increasing compression. This is documented in civil engineering texts, such as *Vibrations of Soils and Foundations* by Richart et al. (Prentice-Hall 1970). Sublinearity is extreme on rock surfaces. The relationship between baseplate displacement and ground force on rock may include a square law term. Sublinearity is similar to positive feedback.

A vibrator's servovalve is nonlinear because the flow through an orifice is proportional to the square root of the pressure drop across the orifice. With small valve openings, the nonlinearity may not be noticed, but for large openings, the effect is very apparent. This nonlinearity is nearly symmetrical about valve center if the valve is adjusted well.

Symmetrical nonlinearity causes odd harmonics (third, fifth, etc.) and nonsymrnetrical nonlinearity causes even harmonics. Earth coupling nonlinearity is responsible for most of the even harmonic distortion in a vibrator's signal. Servovalve nonlinearities and mismatch of the earth's and vibrator's impedances are responsible for most of the odd harmonic distortion. Percent Total Harmonic Distortion (THD) usually increases with drive level. Fortunately, frequencies outside the sweep bandwidth are attenuated by correlation; and some by recording system filters. Look at background noise in the correlation of the reference with ground force to see the effects.

Interpretation of seismic data is based on the central lobes of correlation wavelets. Side lobes interfere. Normal vibroseis data processing involves correlating recovered energy with a pilot sweep. Nearly all the recovered fundamental energy from vibrators shows up in the central lobes of cross correlation wavelets. For practical purposes, fundamental energy is contained in the central lobe. Harmonic distortion and noise show up in the side lobes. Maximizing the fundamental and minimizing harmonic distortion and noise improves record quality.

In order to control the power spectrum of the fundamental, you need to control fundamental force. It's good to use a peak force limit when you “se fundamental force control. The limit is needed because the fundamental doesn't indicate decoupling, but peak force does, in the traditional way we think of decoupling. If a vibrator produces more force when the peak force limit is removed, the force set point is too high. The limiter does what it must to prevent decoupling.

Decoupling is bad. Each time the baseplate strikes the ground, it makes a” impulse. Impulses correlate with sweeps and look like reflections. Decoupling also degrades the ability to measure and control amplitude and phase. When the baseplate is off the ground, the weighted sum method doesn't work well. Some of the energy measured as ground force actually goes into the vehicle rather than the ground. That energy doesn't help record quality at all, “or does it help equipment reliability. It's best to keep the baseplate on the ground.

It's important to understand that a vibrator's output is an unpredictable mixture of fundamental signal, harmonic distortion, and noise. Controlling fundamental doesn't make harmonic distortion and noise disappear. It only moves them outside the control loop. We must still allow for distortion and noise by setting the fundamental amplitude well below the peak force rating of a vibrator. Settings of 50.75% of the hold down weight may be optimum, depending on the amount of harmonic distortion and noise.

Now I understand, but what should I do? If you write specifications for exploration contracts, choose the force co”trol method you prefer (fundamental. absolute value peak force, etc.), and say that ground force is to be controlled to a desired level except in the following limiting conditions:

1) peak actuator force: 90% of rated max.
2) peak ground force: 90% of hold-down weight
3) torque motor current: manufacturer's rating
4) servovalve flapper: should not strike nozzles
5) servovalve main stage: 90% of rated stroke
6) reaction mass stroke: 90% of working stroke
7) total harmonic distortion: limit set after sweep tests

Make it clear that the client representative may select a new force set point to ensure that the limiting conditions will seldom be reached. This will improve repeatability.

Be aware that the maximum fundamental force without decoupling is typically 70% of hold-down weight, and that total harmonic distortion measurements will vary considerably with the measuring equipment. There are good reasons for this. First, digital measuring equipment must have antialias filters, which attenuatr some distortion and noise by design. Also, there is more than one documented way to measure THD. One method includes all noise.

Conclusions. No single rule of thumb determines the optimum vibrator amplitude for all conditions. The earth's impedance has a profound impact on a vibrator's ability to generate force. A vibrator cannot produce ground force equal to its rated actuator force on all surface types and at all frequencies.

The earth's impedance. impedance nonlinearity, and vibrator coupling arc the main causes of harmonic distortion.

Moving a vibrator a short distance may have a dramatic effect on performance.

A similar effect to decoupling can occur, eve” when ground force is less than the hold down force, since baseplates normally accelerate at more than 1 G, and also since they bend. This effect depends upon the spring and damping characteristics of the earth's surface, and it increases harmonic distortion.

If you want constant ground force, you must choose a set point within the vibrator's demonstrated capability on site.

We want to maximize fundamental energy (signal) from a vibrator and minimize harmonic distortion and noise. but we cannot expect simultaneously, a lot of force and only a little distortion. There's a trade-off between the two.

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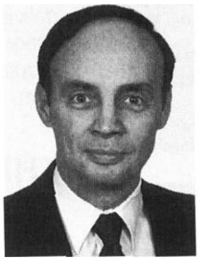

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