Geophysical Prospecting EAGE EUROPEAN ASSOCIATION OF GEOSCIENTISTS & ENGINEERS

Geophysical Prospecting, 2010, **58**, 33–40 doi: 10.1111/j.1365-2478.2009.00848.x

Developments in vibrator control

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Received February 2009, revision accepted October 2009

ABSTRACT

Hydraulic limitations, non-rigidity of the baseplate as well as variable characteristics of the ground constantly distort the downgoing energy output by vibrators. Therefore, a real time feedback control must be performed to continuously adjust the emitted force to the reference pilot signal. This ground force is represented by the weighted sum of the reaction mass and the baseplate accelerations. It was first controlled with an amplitude and phase locked loop system, poorly reactive and sensitive to noise. Later on, new vibrator electronics based on a digital model of the vibrator were introduced. This model is based on the physical equations of the vibrator and of the ground. During an 'identification' process, the model is adjusted to each particular vibrator. Completed by a Kalman adaptive filter to remove the noise, it computes ten estimated states via a linear quadratic estimator. These states are used by a linear quadratic control to compute the torque motor input and to compare the ground force estimated from the states with the pilot signal. Test results using downhole geophones demonstrate the benefit of filtered mode operation.

INTRODUCTION

A vibrator is intended to emit a frequency modulated signal (sweep) into the ground, whose duration and bandwidth can be selected. However, non-linear mechanisms within the vibrator system give rise to distortion that prevents the emitted signal from conforming with the predefined pilot signal. To limit this deformation of the sweep, vibrator control becomes mandatory. In 1961, the control was a simple analogue feedback loop to lock the phase of the baseplate as measured by an accelerometer (Laing 1989). In 1969, the first commercial phase controller was offered. In 1980, Rickenbacker patented peak force amplitude control to prevent the baseplate from decoupling from the earth. Later on, Lerwill (1981) demonstrated the benefit of measuring the reaction mass acceleration for controlling the signal emitted by the vibrator. Sallas (1984) showed that the most stable estimation of the downgoing force emitted by a vibrator is the weighted sum of the mass and baseplate accelerations (ground force), as previously proposed in Castanet and Lavergne (1965). With the advent of digital recording systems and signal generator, the first continuous ground force control was soon implemented (Schrodt 1987). In 1988 Sercel's VE416, a vibrator electronics based on a digital model of the vibrator that employed a Kalman filter (Kalman 1960), was marketed followed by VE432 (1998) and VE464 (2007). This article explains the vibrator model upon which these electronic controllers were based. After an explanation of the limitation of the previous vibrator controls, the parametrization of the model as well as the ways to perform quality controls are detailed.

FROM THE PHASE LOCK SYSTEM TO THE GROUND FORCE MEASUREMENT

The first control of the sweep was based on the control by the vibrator of the phase between the baseplate acceleration and the pilot transmitted by radio from the recorder. This type of control is limited by the noise coming from the accelerometer. Originally zero-crossing-phase comparators were used. As the phase evaluation only occurs at the zero-crossings, these are

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easily time shifted by any interfering noise; signal filtering becomes mandatory. Furthermore, phase measurement delay increases at lower frequencies slowing the feedback control. Another limitation is that the acceleration of the baseplate alone is not representative of the downgoing signal as it would have been measured by sensors placed into the ground below the vibrator.

In 1965 an estimate of the downgoing signal that used source sensor measurements was proposed by Castanet and Lavergne. This is the ground force (GF), defined as the weighted sum of the baseplate and reaction mass accelerations ($\ddot{X}p$ and $\ddot{X}m$) multiplied by their respective mass (Mp and Mm) (Fig. 1):

$$GF = Mp\ddot{X}p + Mm\ddot{X}m. \tag{1}$$

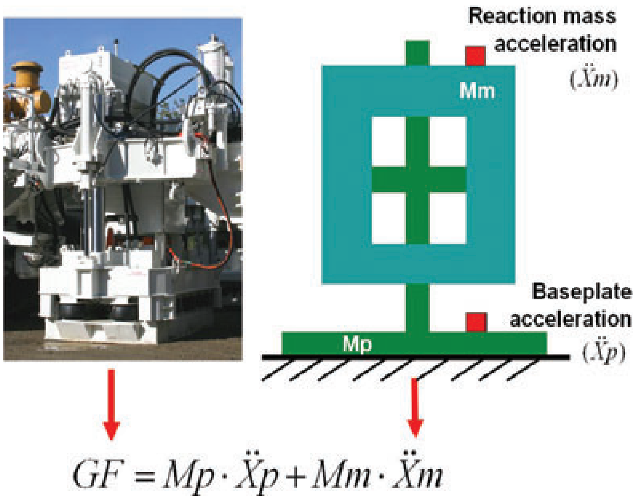

Figure 1 The measured ground force is equal to the weighted sum of the baseplate and reaction mass accelerations (Castanet and Lavergne 1965).

The validity of the weighted sum GF as a representation of the downgoing wave propagating into the ground has been discussed by many authors (Saragiotis and Scholtz 2008). Today this concept is widely accepted. Its main advantage is that it can be easily implemented in real time using just two analogue measurements. The first weighted sum GF vibrator electronics controlled the phase and the amplitude from these noisy outputs (Fig. 2). Not only the phase, still checked at zero-crossing, was an issue but also the amplitude measurement (what type of amplitude to control: absolute maximum, positive maximum, root mean square (rms) or fundamental?).

Comparisons between the weighted sum GF and more direct measures of downgoing signal using sensors (hydrophones, load cells) placed under the baseplate were performed during one of our field tests. They identified significant variations in phase (+25°) and amplitude (up to 40 dB) depending on the location of the sensor with respect to the baseplate and on the sweep's frequency. Above 150 Hz, the phase discrepancy may reach 100°. Different factors explain these discrepancies: the rocking of the reaction mass, a non-uniform hold-down weight, the flexure of the baseplate and the uneven coupling of the plate with the ground. From the experience gained after more than 40 years of vibrator manufacturing some of these deficiencies have been minimized. Today the reaction mass is better aligned with the piston axis and the baseplate is more rigid. It is also possible to better take into account these

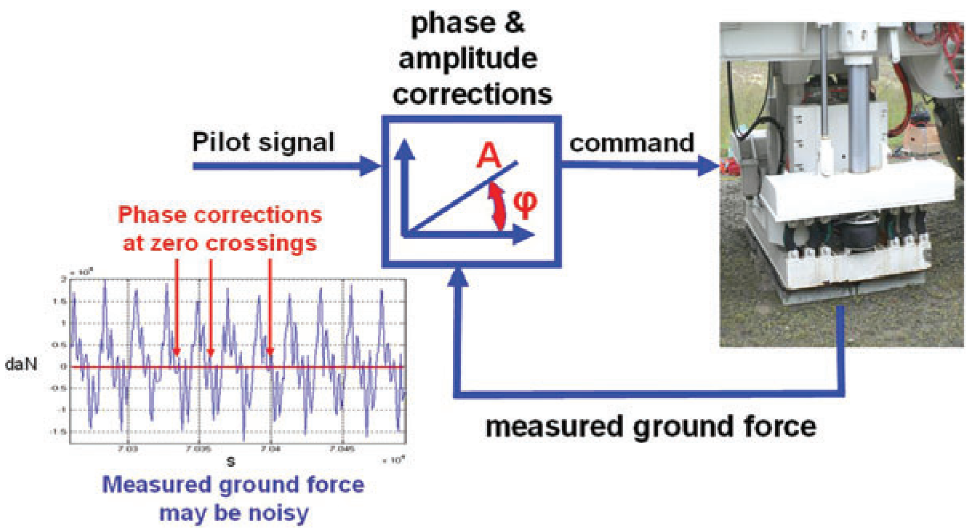

Figure 2 The classic feedback phase and amplitude control of the ground force. Phase correction at zero-crossing is sensitive to noise and becomes sparse at lower frequencies.

limitations by using more than one accelerometer on the mass and on the plate. Though this option has been made available it is seldom used.

THE DIGITAL MODEL OF THE VIBRATOR INSIDE THE VIBRATOR ELECTRONICS

The advent of a digital model of the vibrator made it possible to compare the raw analogue measurements from the accelerometers, to state values computed by the model and to use the estimation error to refine the model estimates. Modelling a vibrator means that we have been able to establish the physical equations of the vibrator and of the ground. In this case, the model is a set of coupled differential equations whose variables are the system states. This model is based on four physical relationships: the torque motor input that drives the servovalve spool; the spool position that controls the oil flow that moves the mass and the baseplate; the relative motion between mass and the baseplate that depends on ground characteristics; and the ground characteristics (Fig. 3). For example consider one of the servovalve describing equations, there is a square root (non-linear) relationship between the oil flow through a variable sharp-edged orifice, the pressure drop across that orifice ($\Delta \, Pressure$) and the spool position :

$$OilFlow = kSpool\ position \times \sqrt{Pressure\ Supply - \frac{Spool\ position}{|Spool\ position|} \Delta\, Pressure}. \quad (2)$$

The model uses four analogue measurements as input: the valve spool position; the mass acceleration; the baseplate velocity; the relative position of the mass and the baseplate. In order to tune the model parameters for each particular vibrator, installation and identification routines are executed when the controller is installed. First, vibrator characteristics such as maximum mass displacement (stroke), mass of the reaction mass and of the plate, hydraulic peak force and hold-down weight are input. Then, reaction mass and valve displacement electrical limits are measured. During the identification process, the same signal is sent to the torque motor stage of the pilot valve and to the model. Model parameters are adapted such that the vibrator and the model outputs fit after two successive steps: from torque motor input to valve position and from valve position to acceleration outputs (Fig. 4). During the sweeps, the model parameters are also constantly updated to take into account the ground characteristics that vary with frequencies and terrain conditions.

From those parameters and the input measurements, the model is able to compute ten states of the vibrator related together by physical equations: the reaction mass acceleration and velocity; the baseplate acceleration and velocity; the mass-baseplate relative displacement; the valve acceleration, velocity and displacement; the ground stiffness and viscosity. This reduced-order model (ten states) provides a good compromise between accuracy and complexity to provide robust and fast control.

THE LINEAR QUADRATIC GAUSSIAN CONTROL AND ITS BENEFITS

The vibrator control is based on a Gaussian linear quadratic error minimization procedure that has been modified to take into account the non-linearity of the servovalve. For

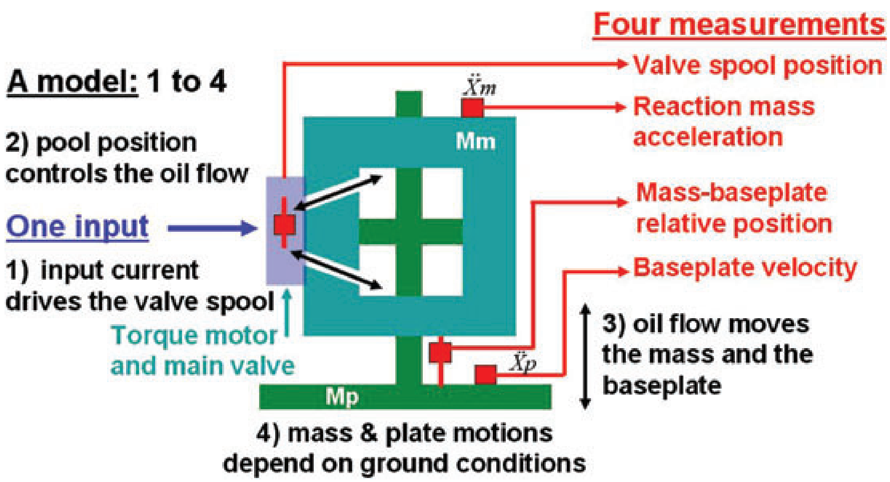

Figure 3 The model of the vibrator is established from the physical relationships between the input current and the plate and mass motions. It is based on four measurements.

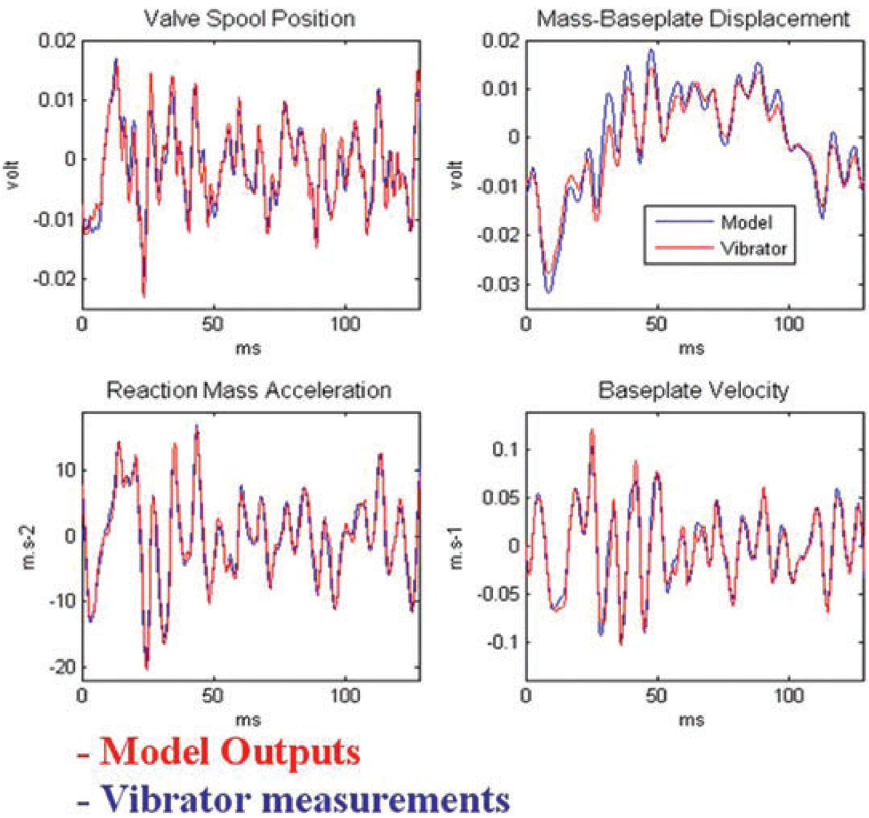

Figure 4 Comparison between model outputs and vibrator measurements with the random stimuli input during the identification process.

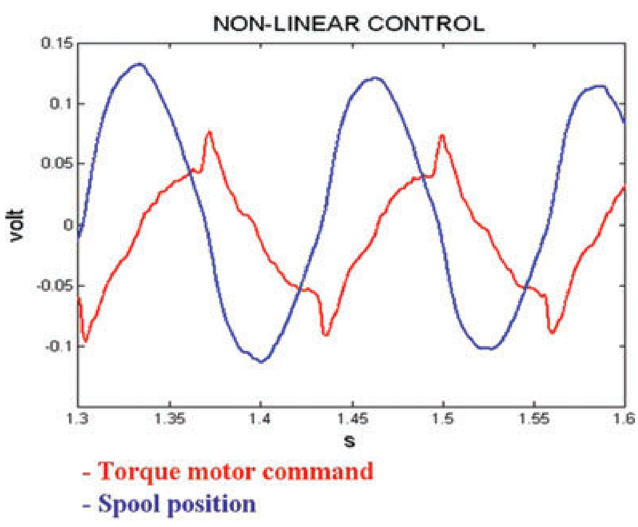

Figure 5 Standard equations of the linear quadratic estimator have been specifically adapted to take valve non-linearity into account.

example in Fig. 5, we can see the action of the controller. In effect the torque motor current and subsequently the valve main stage spool displacement are pre-distorted to compensate for the aforementioned non-linear relationship between spool displacement and resulting differential actuator pressure used to accelerate the reaction mass. In this case we are trying to output a sine wave but in order to accomplish this the controller has modified the spool motion to compensate for this non-linearity. This control approach is composed of two main parts; the linear quadratic estimator and the linear quadratic control. Linear quadratic estimator includes the vibrator model integrated with a Kalman filter, which is useful for estimating inaccessible states in a dynamic system with additive noise. It estimates the ten states from the four measurements and the torque motor input as defined from the model. When comparing measured inputs (baseplate velocity/acceleration) to the same parameters computed by the model we may observe that the linear quadratic estimator acts as a zero-delay adaptive filter that removes noise (Fig. 6). This effect is related to the gain defined by the Kalman filter: when the consistency is high between the measurements and the estimates of the model, more weight is given to the inputs; if one analogue measurement is different from the corresponding model value, its weight drops. Even if one of the four analogue measurements does not respect the physical relationships established in the model, the low gain applied by the Kalman on this input will

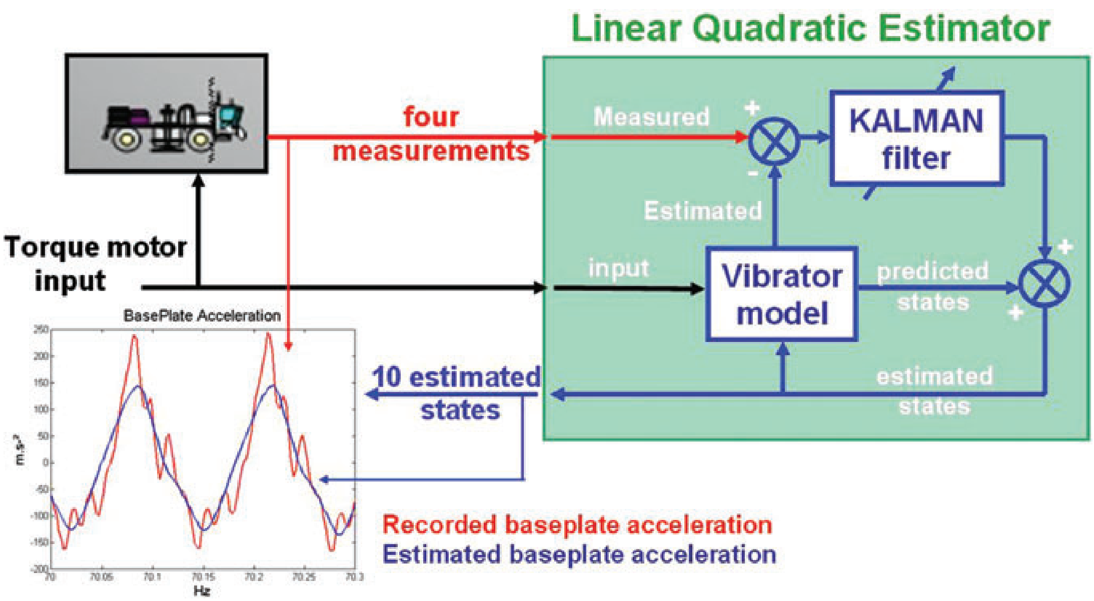

Figure 6 The linear quadratic estimator computes from the vibrator model ten estimated states using torque motor and four analogue measurements as input. The Kalman adaptive filter removes noise.

preserve the consistency of the computed states with the model and with the other measurements. Thus, this digital model of the vibrator is able to remove the noise and inconsistencies between the input analogue measurements. The linear quadratic estimator is also able to estimate the two parameters (ground stiffness and viscosity) that vary with ground nature and sweep frequency. When mapped, these two parameters have proved to be consistent with the terrain type and associated noise (Girard *et al.* 2008) and can provide useful information for estimating near-surface velocity and associated static values (Al-Ali *et al.* 2003).

The ten estimated state values are then input in the linear quadratic control that computes the torque motor command every 0.25 ms with respect to the pilot (Fig. 7) in order to minimize a quadratic criterion (J):

$$J = \sum_k Ru(k)^2 + Qe(k)^2, \tag{3}$$

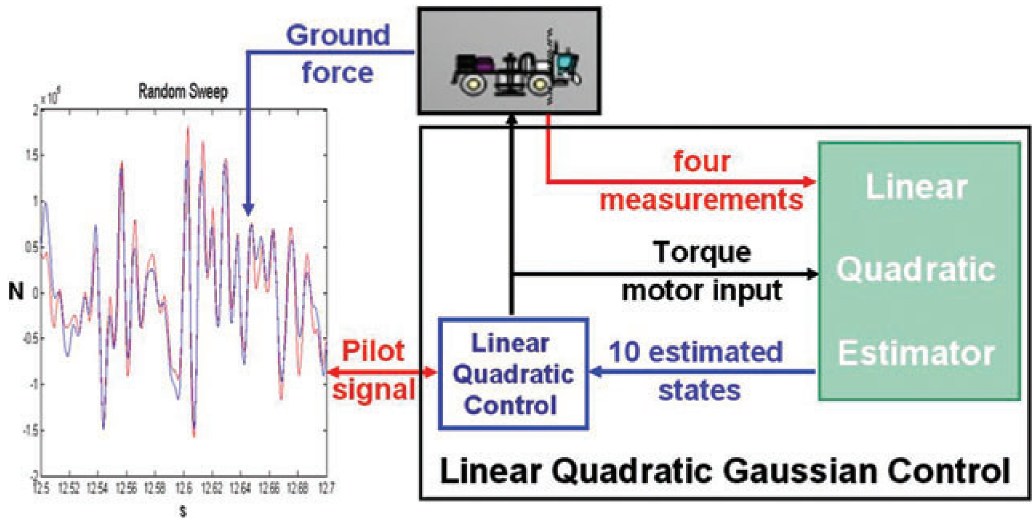

Figure 7 The linear quadratic control computes the torque motor input every 0.25 ms, using the ten estimated states.

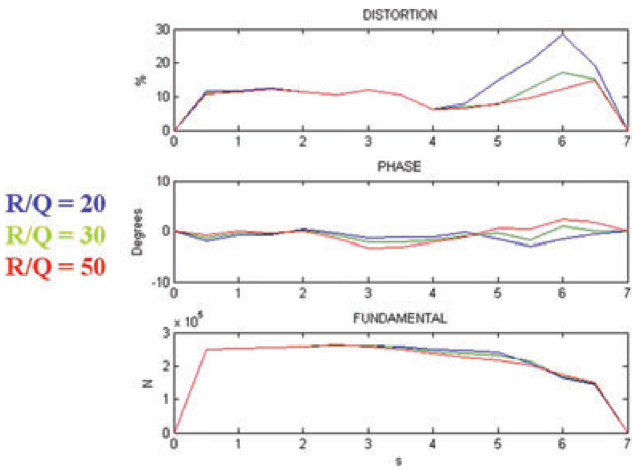

Figure 8 Influence of the R/Q parameter on the distortion between the measured ground force and the pilot signal. The phase and the fundamental amplitude remain stable (linear sweep: 7 s, 100–250 Hz, 80% drive).

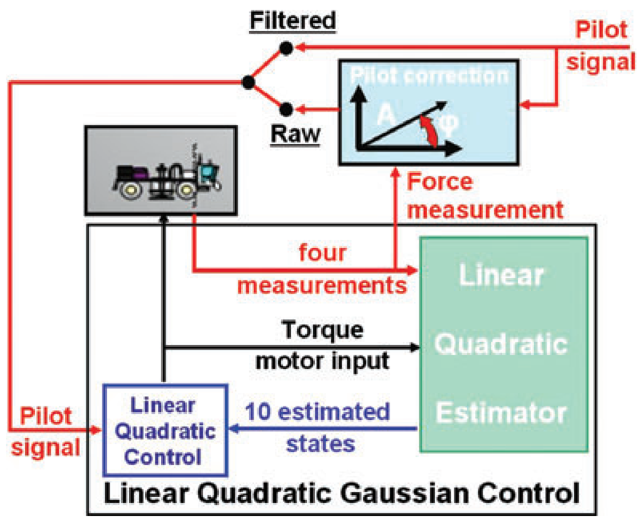

Figure 9 Two ways are made available to control the downgoing signal (S): the 'raw' mode uses the measured ground force (GF) as representative of S; the 'filtered' mode uses the estimated ground force as representative of S. Quality controls are always performed between the pilot and the measured ground force.

$u(k)$ = Torque motor command at time k

$e(k)$ = Pilot–estimated weighted sum GF at time k (simplified equation)

R = Energy ponderation parameter

Q = Error ponderation parameter

To minimize J the linear quadratic control continuously adjusts the estimated weighted sum GF to the reference pilot signal (the estimated weighted sum GF is computed with the estimated reaction mass and baseplate accelerations, output from the model). Linear quadratic control also limits the amplitude of the torque motor command. The R/Q ratio can be modified to improve the performance of the control until the limits of the vibrator/ground system are reached (Fig. 8).

This computation is able to take into account a trend to more easily predict and adapt to variable conditions, particularly those of the ground. Together, linear quadratic astimator and control provide a full digital and robust servo-control that correct for non-linearity and measurement noise. The digital model allows the system to adapt to rapid variations in relationships between the states. Easy to set-up, it makes possible all sweeps compatible with the performances of the vibrator.

TWO WAYS OF CONTROLLING THE VIBRATOR

The measured ground force, as calculated by the weighted sum formula, is used in the industry as the best estimate of the downgoing signal emitted by the vibrator to compute the quality control (QC) values for the sweeps. Phase, distortion and fundamental amplitude of the measured ground force are compared to the reference pilot signal.

Their continuous tracking provides a much better control than the original phase compensation method based on zero-crossing measurements, particularly at low frequencies. In practice, Sercel's vibrator electronics offer two ways of controlling the downgoing signal emitted by the vibrator (Fig. 9): in 'filtered' mode, the estimated ground force output from the model is considered as representative of the downgoing signal. This ground force is the weighted sum of the estimated reaction mass and baseplate accelerations states that were modified from the corresponding measures by the Kalman filter (from noise and inconsistencies with the model). As the QC algorithm compares the measured ground force to the pilot, their values may include discrepancies between the measured and the estimated ground force. However, if we look at the downhole measurement (far-field), this 'filtered' mode shows a greater consistency of the downgoing signal with the pilot.

In 'raw' mode, the measured ground force is considered as representative of the downgoing signal. This functionality is performed by an extra loop in the servo-control, used to modify the pilot signal input in the linear quadratic control according to the phase and amplitude of the measured ground force. Since quality controls are computed with the measured ground force, values are good but may not reflect the downgoing signal. This is the traditional way of controlling vibrators and the preferred option of most contractors.

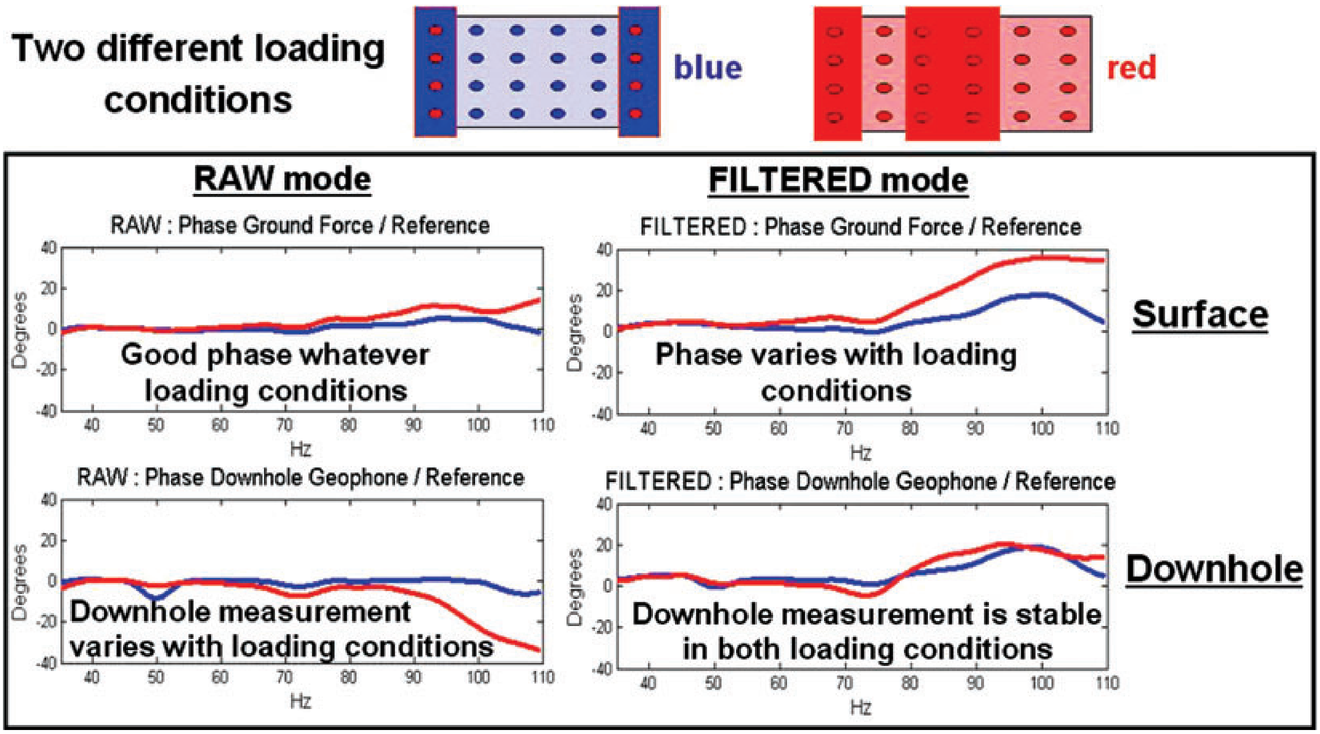

Figure 10 Phase response of measured ground force and downhole measurement for two different loading conditions with 'raw' and 'filtered' modes.

The difference between these two modes was evidenced by comparing measurements between the measured ground force and downhole geophones buried at 150 m depth below the surface to measure the far-field (Fig. 10). A sweep was emitted with different loading conditions of the baseplate (symmetrical or not). In 'raw' mode, phase does not vary with loading condition but the far-field does. In filtered mode the reverse occurs. If we look at the downhole measurement, 'filtered' mode offers a better and more repeatable control. It should be preferred even if QC values are worse.

REAL TIME QUALITY CONTROL AND GUIDANCE

With Sercel's vibrator electronics, QC values (phase, distortion and fundamental amplitude) are output in real time (every 0.5 s) from the digital servo drive installed in each vibrator. They are always calculated from the comparison of the pilot signal with the measured ground force whatever the mode selected. The average and maximum values of these QC's over the sweep length are transmitted by radio (VHF analogue or digital) to the digital pilot generator, another part of the vibrator electronics that is interfaced with the central unit. Then for every vibrator at every sweep, the operator is able to display the current average or maximum values of the distortion, phase and amplitude, along with the averages of these values for the last 50 sweeps. These synthetic bar graphs help in detecting trends and anticipating vibrator maintenance. Geographical displays of QC values are available to evidence possible relationship with terrain and obstacles. All QC values are saved together with the line and shot numbers, the GPS time and location, the ground parameters (ground viscosity and stiffness), etc.

Comprised of two distinct parts, a digital servo drive installed in each vibrator radio-linked with a digital pilot generator in the recorder, an efficient integration of the sources with the recorder is achieved. This system is able not only to trigger the recorder as soon as the vibrators are ready to sweep (navigation mode) but also to provide vibrator guidance and vibrator fleet management when more sophisticated vibroseis methodologies are used.

CONCLUSIONS

The control of the vibrator has changed over the years from a phase control to a more complete ground force control. For practical reasons (independent evaluation of the vibrator performance) the industry still considers the weighted sum of the analogue output of the reaction mass and baseplate accelerometers as representative of the emitted downgoing signal. However, we think new approaches can provide a better estimate. One is the possible use of several accelerometers to obtain a more representative measurement of the overall motion of the reaction mass and of the baseplate. The other is to use the estimated ground force as made available by the linear quadratic estimator instead of the measured ground force.

Today, vibrator electronics not only control the vibrator. They provide real time quality control, vibrator guidance and fleet management that enable the increase of land vibroseis acquisition productivity.

ACKNOWLEDGEMENT

The authors are very grateful to Denis Mougenot for his contribution in finalizing this article.

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