Hydraulic Test Systems Outperform with Waveform Replication control

Abstract

Hydraulic actuators are versatile vibration and shock test systems. However, their nonlinear response causes significant waveform distortion that precludes their use in many common testing situations. Waveform Replication controllers overcome the nonlinear response, turning the hydraulic actuator into the capable performer it should be. Two properties of a hydraulic actuator cause the non-linear response: the oil column resonance and the oil flow through the servo valve. For both single axis and multi axis hydraulic vibration systems a waveform replication controller compensates for these effects by learning of their existence in the error between the desired and achieved waveforms. Contrast this to a linear control algorithm that has no mechanism to compensate for the nonlinear distortions. Examples of improvements using waveform replication techniques for single axis and multi axis systems are given. Manufacturers of linear controllers are urged to consider this technique in their future product plans. Owners of hydraulic vibration and shock test systems are urged to expand their testing capability with a waveform replication controller.

Introduction

Hydraulic Actuators have unique features that make them the actuator of choice for many shock and vibration tests.

For many systems, like The Cube 6 degree of freedom shaker, automotive engine valve actuators, or multi-axis vibration systems, the feature that makes these systems possible is the large force to size ratio of a hydraulic actuator. For example, engine valves can be opened 10 mm in 3 milliseconds with hydraulic actuators slightly more than an inch square. In the Cube, 6 actuators with 10,000 static pounds force each fit inside a box about 2 feet on a side. Multi-axis high frequency shake tables for geotechnical earthquake simulations on centrifuges are possible because the hydraulic actuator produces the needed 30,000 lbf in a volume less than 2 cubic ft.

Other applications need long strokes, and hydraulic actuators meet that need easily. Road motion simulators, transient shock simulators and earthquake simulators all need strokes from 4 to 20 inches. 4 poster systems that the automotive industry uses to test suspensions need 2 to 10 inches of stroke. The Navy’s Mil-S-901 shock test requirements need 10 to 20 inches of stroke. Low frequency earthquake systems need 10 to 20 inches
of stroke. These applications typically need velocities from 40 to 200 inches per second, which can be delivered with modern valves.

The large side load capacity of a hydraulic actuator is an important feature. Single axis vertical systems can carry large head expanders with large overhanging loads. When using them in multi-axis systems, the actuators themselves get shaken sideways, so they need to have plenty of side load capacity to survive.

With long strokes and high side load capacity, these shakers can do long duration classical shocks with big loads. They can do high acceleration, high velocity transient waveforms for shock testing, while other actuators are simply unable.

In practice, users of hydraulic actuators have been less than thrilled with results. The acceleration waveform often does not match the desired waveform as well as hoped or expected. Distortion of the waveform is pronounced. There may be large peak accelerations that overshoot the specification. There may be a lot of energy in frequency bands where it is not desired or expected.

Waveform replication is the answer.

**Benefits of Waveform Replication on Hydraulic Actuators**

Waveform replication control techniques improve the hydraulic actuator response remarkably, and enable the hydraulic actuator to live up to its promise as a powerful, capable test system. Waveform replication control corrects for distortion to produce waveforms that match the desired waveform very closely.

Hydraulic actuators produce harmonic distortion in sine waves when the frequency is below the oil column resonance frequency. The actuator wants to bounce at the oil column resonant frequency, and the resonance shows up as harmonic distortion. Waveform replication control dramatically reduces distortion and allows the hydraulic actuator to produce low distortion sine waves.

Long duration classical shocks that excite the oil column resonance generally don’t meet their tolerance specifications. Linear controllers have proven incapable of correcting for the distortion. With waveform replication techniques, classical shocks can be generated that meet Mil Specs.

When doing high G transient waveforms, the hydraulic actuator may generate spikes at the acceleration peaks, generating excess high frequency noise and overtesting the product. Again, linear controllers are unable to correct for that distortion, while waveform replication controllers have been quite successful. The Transient Waveforms match originals very closely when waveform replication techniques are used.

A given hydraulic shaker can do a wider range of tests using waveform replication control than using linear control. In order to use linear controllers, users find they must keep accelerations and velocities down, well below the shaker rating. That keeps the hydraulic shaker in a more linear range, and allows some testing to be done. For example, classical shocks are usually limited to short duration, say 11 msec pulses, even with long stroke actuators. By using waveform replication the shock durations can be lengthened until other limits, like the velocity or stroke limit of the shaker are reached.
The problem of excessive peaks on transient waveforms can be reduced with waveform replication. High fidelity earthquake motion can be achieved, with less spurious high frequency energy in the SRS. Both the time waveform and the spectral content of transient waveforms can be maintained, providing precise control of the SRS or Pseudo Velocity spectrum.

Another field that is enabled by waveform replication is multi-axis testing. With waveform replication the measured 6 degree of freedom (dof) motion can be reproduced in all axes simultaneously. The automotive industry has realized significant improvements in quality, noise reduction, comfort, ride and handling using multi axis waveform replication techniques. They have been able to record multi axis motions on the track and bring the recordings into the lab and recreate the motions on 6 dof shakers, like the CUBE.

In multi-axis systems, besides reducing the harmonic distortion, waveform replication corrects for distortions from outside influences, specifically the other actuators and load dynamics. In multi-axis systems, the dynamic behavior is very difficult to predict, and there is substantial cross talk between the actuators. Driving one actuator influences all the accelerometers, and even the other actuators. Waveform replication is able to gain knowledge of such interaction and correct for it.

**Waveform Distortion by a Hydraulic Actuator**

Tests that need a specific waveform are hard to do on hydraulic actuator. That is because a hydraulic actuator’s output acceleration is not linear with input command. It is not a linear system, and most control systems are designed to control a linear system.

**What is a linear system? What a Hydraulic Actuator is not.**

A linear system has three properties: homogeneity, additivity and time invariance. Homogeneity means that a change in input amplitude results in an equal change in the output amplitude. So if a 1 volt, 20 Hz drive gives a 5 G, 20 Hz output on the shake table, a 2 volt, 20 Hz drive would produce a 10 G 20 Hz output. Additivity means that if two signals are added at the input, the output has the same two signals in it, and they do not interact to produce a new signal. So, one could drive both a 20 and 30 Hz sine into the system and the output would have both 20 and 30 Hz in the output. For example, a linear system (output = input 1 + input 2) and nonlinear system (output = input 1 * input 2) are illustrated here.

![Graph (1) 20 and 30 Hz sine waves simultaneously presented to input of system](image)
However, the output of a linear system may be different in amplitude and phase from the input. For a linear system, the amplitude and phase response with frequency are described by the frequency response function or transfer function of the system.

Time Invariance means that the response does not change with time, so that the transfer function is not dependant on when the input signal is applied.
Hydraulic Actuator Nonlinear Response

Hydraulic actuators are fairly time invariant, but they are not homogeneous or additive. For example, the acceleration output of one hydraulic actuator for a sine input at 20 Hz looks like Figure (1). The THD in this case is about 27%.

Figure (1) Distortion of sine wave due to non linear behavior of hydraulic actuator.

Figure (2) Harmonic content illustrating that new frequencies are created by hydraulic actuator.
A heavily loaded, high velocity earthquake system produces this distortion of the waveform. A linear controller was only partially successful in reproducing the desired waveform. The black trace was the commanded waveform, the red is the measured response.

Figure (3) Overshooting at the peaks is another form of distortion

**Sources of Distortion**

A hydraulic actuator used for vibration and shock testing consists of a stiff double ended actuator and a high frequency response servo valve. The servo valve accepts an electrical command signal, and directs a supply of high pressure oil to the actuator to make it move. A servo controller is required to keep the actuator in the center of its stroke.

When the servo valve is given a positive command voltage, the actuator moves in one direction while a negative command moves the actuator in the other direction. The servo controller takes the signal from the test controller, be it sine, random or shock, and generates the drive signal to drive the servo valve.

The hydraulic actuator with load mass is essentially a 2nd order spring-mass system. The oil trapped in the cylinder between the piston and the valve is compressible and has an effective spring rate of \( \frac{4\beta \times A^2}{Volume} \) [force/distance]. The natural frequency of the actuator spring–mass system is approximately

\[
\frac{1}{2\pi} \sqrt{\frac{K}{M}} = \frac{1}{2\pi} \sqrt{\frac{4\beta \times A^2}{Volume \times LoadMass}} \text{ [Hz]}
\]

This resonance is damped by leakage flow across the piston and valve, and often a dedicated damping orifice. For typical hydraulic shaker applications the resonant frequency is between 50 and 200 Hz. The hydraulic actuator is a relatively linear system, but the resonant behavior does exacerbate the distortion problem.
A convenient picture is to imagine driving a spring-mass system from the bottom of the spring. In order to move the mass, the spring must be compressed to transmit the force to the mass. For a vertical hydraulic actuator, that means delivering some oil to the volume under the piston to generate the pressure to move the piston.

The source of the distortion is the fact that the servo valve is not a linear flow controller and it has a non-linear flow response with pressure across the valve. A servo valve comprises a spool with lands sliding in a sleeve, which has porting grooves matched to the lands. The openings between the lands and grooves form four flow control orifices that simultaneously direct oil from the hydraulic power source to one side of the actuator and direct the exhausted oil from the other side back to the reservoir.

*The oil flow through the control orifices is a function of both the area of the orifice and the square root of the pressure drop across the orifice. It is this relation of flow to the square root of the pressure drop that is a major source of the non-linear behavior of the hydraulic actuator system.*

To understand the situation, consider that for pure sine acceleration, the pressure in the actuator and the actuator velocity must both vary sinusoidally. But if the pressure varies sinusoidally, the flow to the actuator, which is a function of the square root of the pressure, won’t be sinusoidal. Velocity is proportional to flow and, if the velocity isn’t sinusoidal, the acceleration waveform won’t be either.

The nonlinear pressure-flow relation of the servo valve introduces distortions in the waveform, which in turn excite the oil column resonance, (predominantly when the test frequency is well below the oil column resonance) and leads to significant harmonic distortion of sinusoidal motion.

Graph (6) Distortion of square root function on sine wave.

Hence, in order to produce low distortion sine acceleration, the valve spool position must be driven in something other than sine motion. This can be accomplished with a waveform replication control system.

Other effects also cause significant distortion. When doing random vibration or transient shock waveforms, the sudden closing of the flow control orifices in the servo valve causes large pressure spikes and subsequent bouncing of the load mass on the oil spring. This is
the same phenomenon as the “water hammer” one sometimes experiences when closing the faucet too fast. High velocities and large loads contribute to the effect.

**Single Axis Waveform Replication Application Examples**

**Low Distortion Sine waves are achieved using waveform replication**

This 25 Hz, 12 G sine wave done on a long stroke, high velocity shaker has 2.5% THD. Open loop, without a waveform replication controller, this waveform has about 30% THD.

![Figure (4) Low Total Harmonic Distortion Sine Wave using Waveform Replication](image1)

![Figure (5) Spectral content of the acceleration waveform](image2)

**Half sine Classical Shocks**

These are 15G 30 msec half sine shocks done on a 20,000 lbf, 6 inch stroke actuator with a 500 lb load. The total moving mass including the table and piston is about 1000 lb. The point by point RMS error for the waveform replication pulse is less than 15%.

![Figure (6) Linear Controller response](image3)

![Figure (7) Waveform Replication controller](image4)
**Transient Shock**

A Team 10\" stroke hydraulic shaker with 10,000 lbf and 600 lb total moving mass is used to produce this shock. The peaks are over 16 G, and Velocities over 120 inches per second. The waveform is specified to meet SRS criteria to 250 Hz. Total stroke required is about 8 inches. This shock pulse is one of many that may be used for Mil-S-901 Subsidiary Component Shock testing of commercial off the shelf (COTS) equipment.

![Waveform Image](image)

Figure (8) Subsidiary Component Shock Tests can be run using waveform replication

![Pseudo Velocity Comparison Chart](chart)

**Pseudo Velocity Comparison**

5% and 25% Damping

Navy requires 3.5 Hz and above

![Chart Image](chart2)

Figure (9) This transient shock meets this Navy criteria for COTS equipment
Multi-axis examples of Waveform Replication

The Team Tensor High Frequency 6 dof Multi Axis Vibration test system does accurate waveform replication to 500 Hz.

Figure (10) Team Tensor, 6 dof multi axis high frequency shaker

Team CUBE is currently rated to 250 Hz, soon to be upgraded to 500 Hz.

Figure (11) Team CUBE cutaway to show the 6, 10,000 lbf shakers inside.
Swept sine on the Tensor to 500 Hz

Figure (12) Point by Point RMS error decreases with each iteration

Figure (13) Sine response in all 6 channels matches desired in amplitude and phase.
Multi Axis automotive engine vibration replication on the Tensor

Figure (14) Measured 3 dof engine vibration with frequency content to 500 Hz.

Figure (15) Spectral match of 3 dof engine vibration data to 500 Hz.
Multi axis engine vibration replication.

This data measured on the motor mounts during a run up in speed.

Figure (16) Spectral match of engine vibration to 500 Hz.
Automotive Road Load Data on Team 6 inch stroke Multi Axis Shake Table

Figure (17) Road motion replication with 200 Hz frequency band

Figure (18) PSD match of road motion replication
Considerations

Waveform replication does have its limitations. No matter how good the controller, one cannot exceed the mechanical limitations of the system. The force, velocity and stroke limits must be respected. In fact, waveform replication in some instances requires more dynamic range in order to make the needed corrections. In other words, the system specifications may need to be derated. The reflected impedance can be larger than the static mass, requiring more force and velocity capability of the system. In that case the test may not converge completely, so the test mass may need to be reduced, the test level reduced, or some level of non-convergence accepted.

In Multi-axis systems, the multi axis test system will not replicate “non rigid body” motion of the shake table. The table is designed to behave as a rigid body over the rated frequency band, so, trying to make it move as a set of unrelated points will not work. The data should be checked to ensure it can be replicated.

One technique to check the data is to display it visually with modal analysis software. Create a simple model of the accelerometer locations, and assign the measured data to those points. Then use the visualization capability of the software to show the motion. If there is relative motion between the points, the data is not from a rigid body, and consideration must be given to that fact.

Non rigid body motion can be handled by many multi axis controllers by using more than six feedback accelerometers and using a “least squares fit” techniques to get a “best match” to the complete data set.

Another consideration is that the iterative waveform replication algorithm can be time consuming for long time histories. It can be a slow procedure, and it may require some user judgment. One will wait while each successive iteration is played out, then the test results must be inspected to see if they are good enough, and, if another iteration is needed, there is a delay while the new drive waves are computed. One cannot typically click the go button and walk away.

Future Work

Waveform replication controllers for single axis need to be brought to market. It is a simple algorithm that could be added to most commercial controllers that would enhance their user’s satisfaction. Controller manufacturers are encouraged to add it to their offerings. For now, Team offers a limited scope single axis waveform replication capability in our HDRS software.

Conclusion

Waveform replication will transform your single axis hydraulic shaker into the versatile workhorse it should be.

Waveform replication is required for many types of tests on multi-axis test systems, and may still be the only option if waveform fidelity is required.

Use waveform replication on hydraulic actuators to produce high fidelity waveforms not attainable with linear controllers.