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Giving the CUBE™ a Health Checkup

Introduction

CUBE™ Systems are high performance, multi axis vibration testing machines. They have 6 actuators and valve sets and 12 hydrostatic pad bearings inside. Disassembly for the purpose of simple inspection is impractical. Hence, a procedure for determining the health of these components without disassembly is required.

Note that the best CUBE™ performance is achieved with the proper, clean, cool oil. That means oil that is Mobil DTE 26 or equivalent viscosity, 115 degrees or less, and meets ISO cleanliness rating of 15/13/10 for the 2-micron, 5-micron and 15-micron particle sizes. A very first test that should be done whenever the CUBE™ performance seems to deteriorate is to have a competent lab do a complete oil analysis.[1]

This document defines several tests used at Team Corporation to verify that all components are working correctly and within specification. These tests can be run with a spectrum analyzer and will give an accurate assessment of the CUBE™'s health.

Five tests taken together give an excellent picture of the health of the internal components of the CUBE™. These tests check for serious problems as well as less serious but potentially damaging or performance limiting problems, specifically dirty or silted valves.

The first test to do is a "threshold test". We define the threshold as the voice coil voltage required to produce a discernable step in actuator position. Recall that Team uses a voice coil driven pilot valve to move a slave valve, which in turn supplies oil to the actuator. A low threshold verifies, among other things, that the voice coil works electrically, that the pilot and slave valves move freely, and that the actuator and pad bearings move freely.

The second test is to stroke the actuator very slowly from end to end, while simultaneously monitoring the position and voice coil drive signals. This test will show us that the actuator is free over its entire stroke. An actuator in good condition will move from end to end with almost no pilot or slave valve displacement (since very low flow is required). If there is damage to a piston or pad bearing, the servo loop will increase the voice coil drive voltage to keep the actuator following the command. Sudden jumps in the voice coil voltage that correspond to a given piston position indicate friction or possibly other internal damage.

The third test is to measure three transfer functions and their associated coherences. These transfer functions are easy to measure, and the three together are very informative. Specifically, the transfer functions are: the (slave valve displacement)/(command), the (actuator displacement)/(command), and the associated (acceleration)/(command). These transfer functions show the gain and phase of the servo loop, and could show larger problems with the CUBE™ structure. For example, if some internal screws were coming loose, the transfer function would change significantly. If a valve were contaminated and sticking, the transfer function would change.

Coherence is a measure of the percent of output energy that is caused by energy in the input. If all the energy in the output is caused by the input, then the coherence is 1. High coherence means there is little extraneous noise in the system, as all the output is commanded by the input. Low coherence means that

[1] For more information on hydraulic fluid requirements for the CUBE and other Team systems, please refer to Team Application Note GEN-0001, *Hydraulic Fluid Requirements for Team Systems*.

there is extra energy in the output that was not in the input, and is a good indicator that extraneous noise is getting into the system. Often the noise is in the form of nonlinear response to the command, and indicates that stiction, friction, and hysteresis are problems. This is usually caused by dirty oil.

The fourth measurement is the quiescent acceleration. This is defined as the residual acceleration measured on the CUBE™ when the input is zero. A measurement is made when the CUBE™ is delivered and can be repeated periodically. Increasing levels of quiescent noise mean that the hydraulic supply pressure is too high, the oil is too hot, the viscosity is too low, or the flow edges of the pilot valve are worn.

Finally, a measurement of the voice coil bias is made. The voice coil bias is the DC voice coil voltage needed to hold the actuator on center. Because the voice coil driven pilot valve is spring centered, the voice coil bias is a measure of the mechanical bias of the centering springs. It is a measure of how much force is needed to pull the pilot valve back to center against the centering springs. It is a measure of how far off of the flow center the bias springs hold the pilot spool. It must be pointed out that Team sets the initial voice coil bias at between 2.5 and 3.5 volts. This allows the Team Corporation proprietary "safety valve" to work. So, 2.5 to 3.5 volts is the expected level of voice coil bias. If it is radically different, and the oil temperature is around 115 F, then there may be a problem. The effect of too little voice coil bias is that the safety valve won't work and the CUBE™ could slam into the mechanical stops in the event of loss of servo control. Too much bias will reduce the overall level of CUBE™ performance, since it uses up dynamic range of the power amplifier (as well as indicating that something may have come out adjustment).

Making the Measurements

Actuator Position Threshold Test

This test checks for the smallest voice coil voltage that will cause the actuator to move. The test verifies that there is no mechanical friction in the system; that the pistons are floating free in their bores; that the valves are not sticking, and that there are no other conditions that would prevent the actuator from moving freely. The fact is that if a very small amount of voltage across the servo valve voice coil will cause the actuator to move, then the mechanical parts must not be rubbing or sticking.

To do the test, a very low-level square wave position command (100 mV) is input to the servo controller. The actuator position signal and the voice coil drive voltage are monitored on an oscilloscope or (preferably) a data acquisition system. The signals should be filtered at 100 Hz or so to allow the signal to show through the background noise. Both signals should be on the screen. Turn the amplitude potentiometer on the 2200 up until a good, clean displacement square wave is seen on the screen. Once you have a clean displacement square wave, then it's time to find the Threshold Voltage. Begin by slowly turning down the amplitude of the drive signal. Watch the position signal, and notice the amplitude of the Voice Coil Voltage impulse going down too. A .01 mV step in position is the standard displacement target. The voice coil voltage achieving that step must be less than .050 volts. Your scope or analyzer screen may look something like figure 1.

In figure 1, notice that a 3 or 4 mV impulse to the voice coil is all that's needed to drive the actuator to a 0.01 volt square wave response. This is the desired result. The allowable voice coil impulse is up to 50 mV. Depending on the oil condition, dither level, load, and even the signal filter frequency, the results will vary. The valve shown is a particularly good example, and the signal was filtered at 36 Hz to remove most of the 60-cycle noise.

Header1: Ch1 position threshold .5v rms dither 1000-lb load
Header2: 118f temp

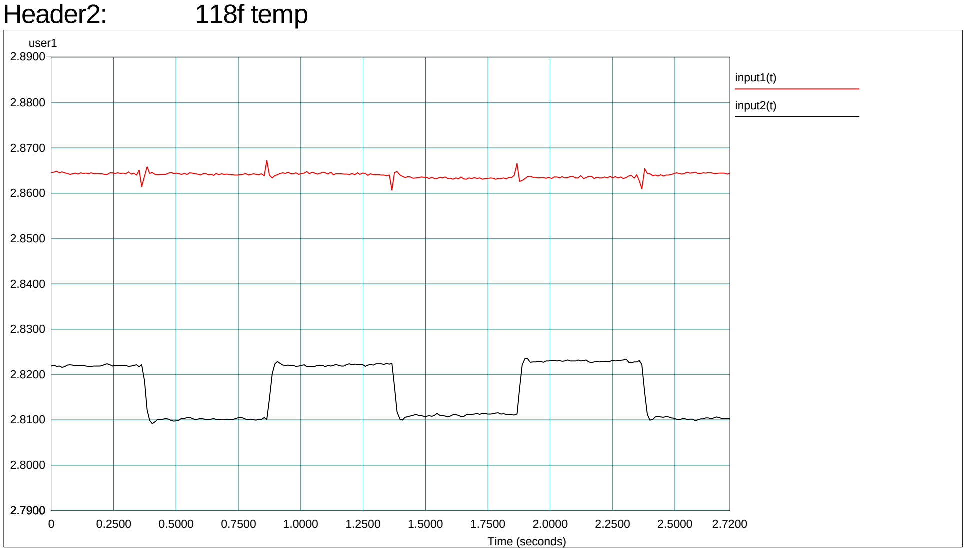


Figure 1. Voice Coil Threshold Voltage.

A good valve with clean oil will produce a square wave response very similar to that shown. The position signal will be a clean square wave of about 10 mV peak to peak, and the voice coil voltage (in red) will be a train of impulses. If the square wave does not repeat from cycle to cycle, is hunting around, or requires more than a 50 mV impulse, then the system is NOT healthy. The oil is probably dirty and not up to Team's oil cleanliness requirement.

This is an example of a sticky pilot caused by DIRTY OIL. The oil had an ISO contamination level of 18/15/10, which is high, compared to the CUBE™ 's requirement 15/13/10 for the 2u/5u/15u measurement system.

Header1: Sticky Pilot Threshold test Not enough dither
Header2: 0.5v dither oil temp 130f

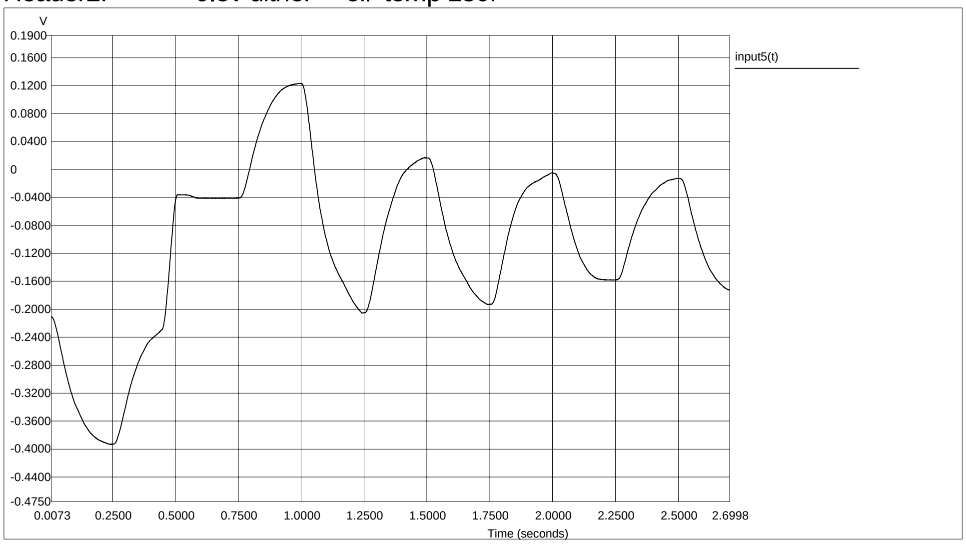


Figure 2. Position signal of dirty valve is NOT a nice square wave.

Header1: Sticky Pilot Threshold test Not enough dither
Header2: 0.5v dither oil temp 130f

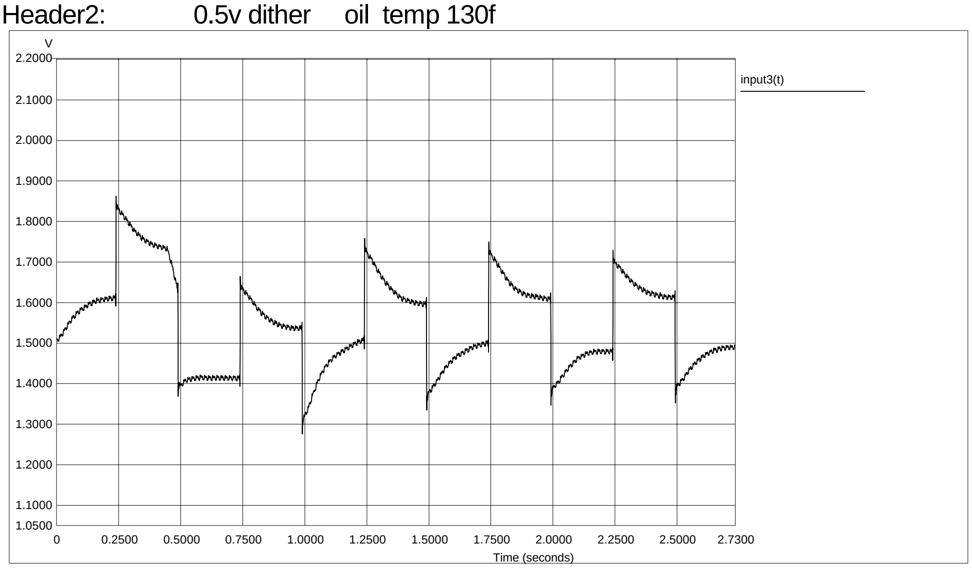


Figure 3. Voice Coil Voltage. Should be a train of Impulses, NOT This.

Increasing Dither to a Sticky Pilot can help.

Header1: Sticky Pilot Threshold test. Same Valve, *2 volt dither* Threshold Found
Header2: 2.0-v dither. Oil temp 130f Dirty oil 18/15/10 ISO 4u/6u/15

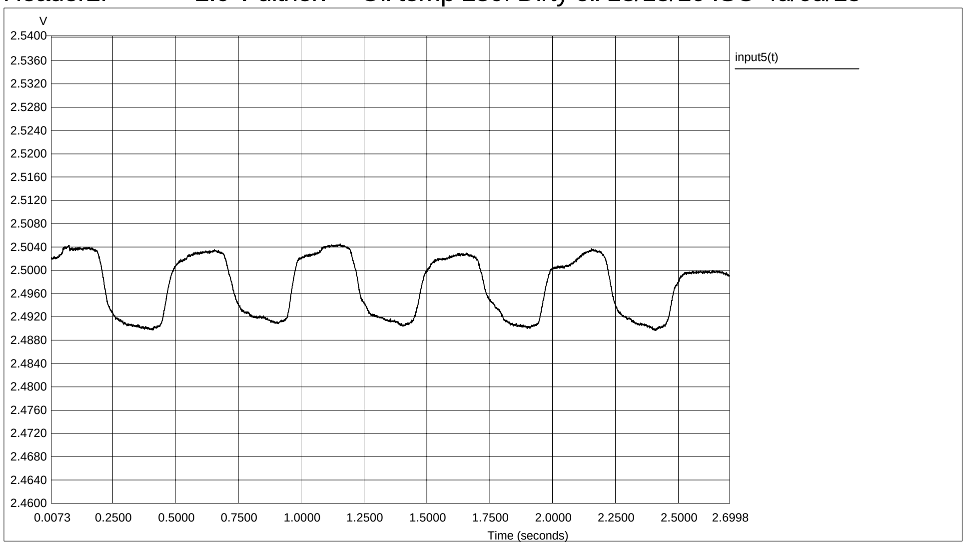


Figure 4. 10 mV square wave is achieved by adding dither

Header1: Sticky Pilot Threshold test Same Valve, 2 volt dither Threshold Found
Header2: 2.0 v dither oil temp 130f Dirty oil 18/15/10 ISO 4u/6u/15

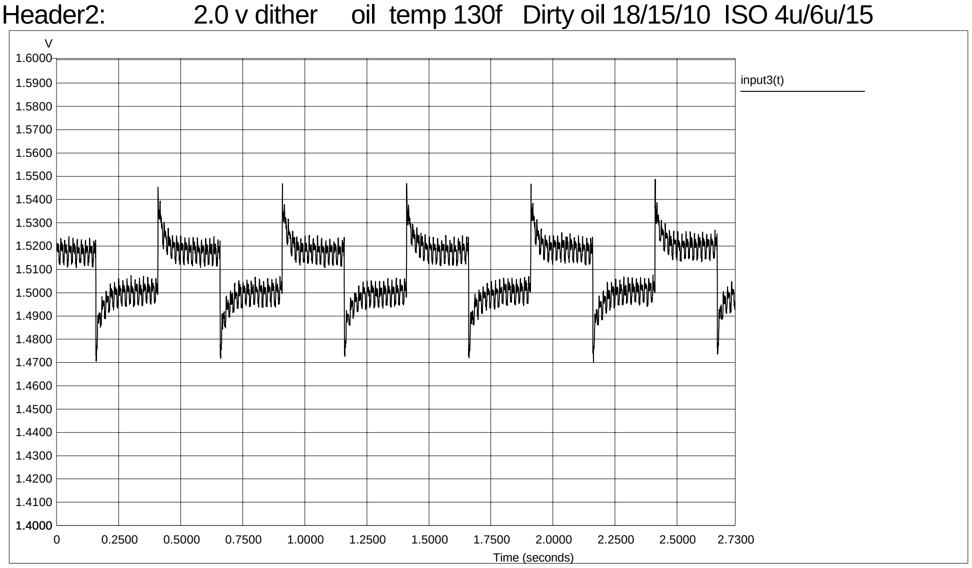


Figure 5. Voice coil threshold is 40 – 50 mv. Notice hysteresis.

By increasing the dither to 2 volts, the square wave response cleans up significantly. However, this system needs clean oil! A CUBE™ should require less than 50 mV threshold with 1 volt RMS of dither. If your CUBE™ does not produce a clean square wave, and requires more than 1 volt RMS dither the oil must be checked and cleaned. Continued operation of the CUBE™ with this level of contamination is asking for trouble.

Static End to End Displacement Test

The actuator is given a sinusoidal command to stroke from one end to the other, very slowly. The test checks that the pistons are free to travel full stroke without any friction. The displacement signal is plotted against the command signal on an X-Y plot. The trace should be a straight line, with no hysteresis.

Plot Header1: Cube Actuator End to End Stroke.prj
Plot Header2:

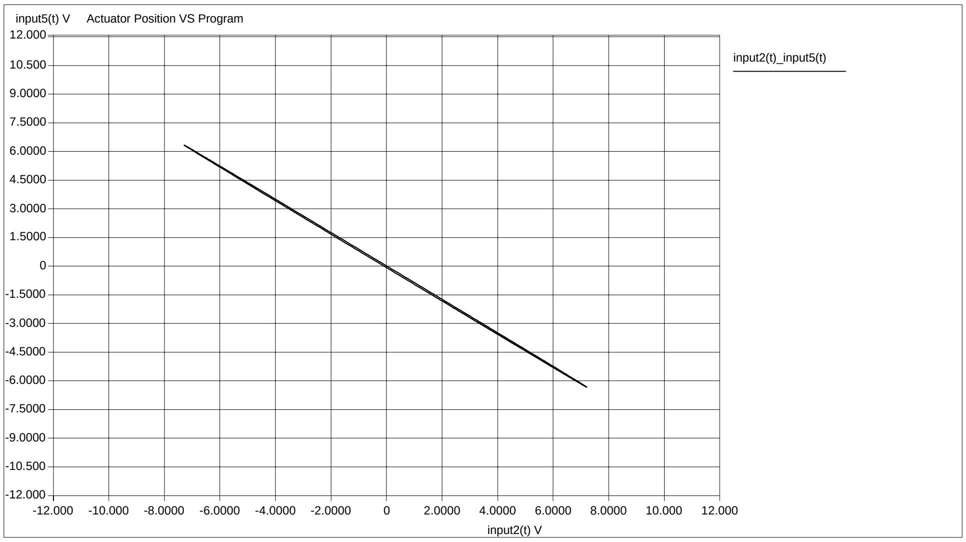


Figure 6. The actuator tracks the program signal perfectly

Plotting the Voice Coil voltage against the position signal shows how much drive (which also is a measure of pressure) is needed to move the actuator. It should be smooth, with little hysteresis, and NO jumps or discontinuities.

Plot Header1: Cube Actuator End to End Stroke.prj
Plot Header2:

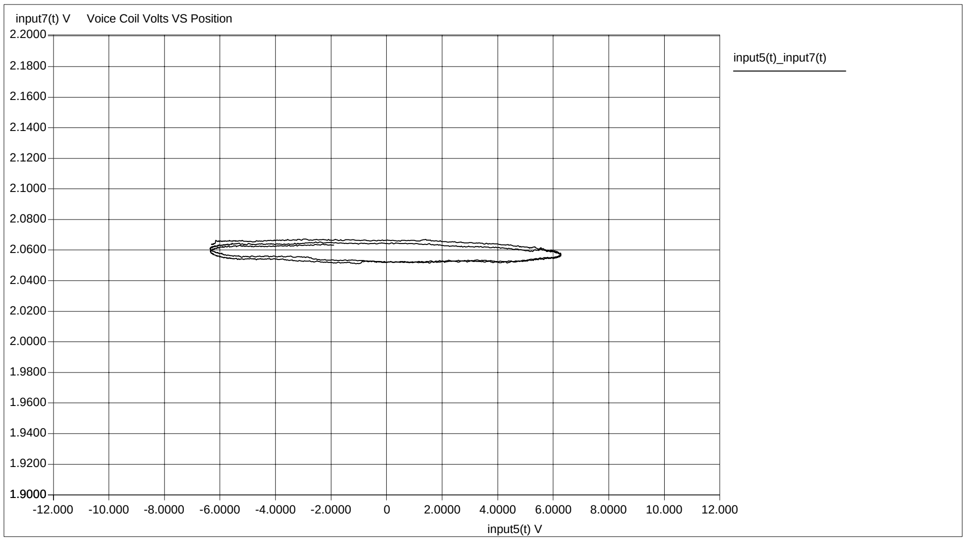


Figure 7. The Voice Coil voltage smooth and less than +/- 10 mv

A lisajous of the actuator position on the X-axis and the Voice Coil voltage on the Y-axis should be a smooth curve with little hysteresis.

Acceleration, Actuator Displacement and Slave Displacement Transfer Functions & Coherence Tests

These tests are performed to verify that the actuator has sufficient coherence over the specified bandwidth to allow waveform replication software to achieve satisfactory results. Team requires that the position response have good coherence (0.9 to 0.95) to at least 100 Hz, and that the acceleration coherence be better than 0.9 to at least 200 Hz. The slave valve displacement coherence should be above 0.94 to 250 Hz. The slave and acceleration coherence may be low at low frequencies due to the small signal level. The displacement coherence should be good down to the lowest excitation frequency.

The tests are run on PAIRS of actuators. We drive both actuators at 100 % amplitude on the 2200 and adjust the level with the input signal. The responses you get should be close to the "as delivered" responses. Big differences should be examined. Are they explained by differences in the measurement conditions, location of the center of gravity for example, or is the base coming loose from the reaction mass?

At Team Corporation, during the initial set up, the shaker responses are matched using the slave and position loop gains in the 2200 to achieve the best result possible. We find that the best result is always achieved when the slave loops are closely matched first. (See the 2200 Operation and Maintenance Manual for information on setting the slave loop.) A scope set to the X-Y mode with one slave on the X-axis, the other on the Y-axis is a very easy way to match the slave loops after the initial adjustment. ***Note that to adjust the slave loops you must remove the position loop gain.***

NOTE: In all the examples that follow, the plots are not valid below 3 Hz.

Example Responses: Acceleration Transfer Functions and Coherence

Amplitude Match

Header1: Ch 1, Ch 2 shaped random to 500Hz .35 volts rms

Header2: 118f temp, 12 gpm sprinkler on 1000 lb load on top to simulate HE

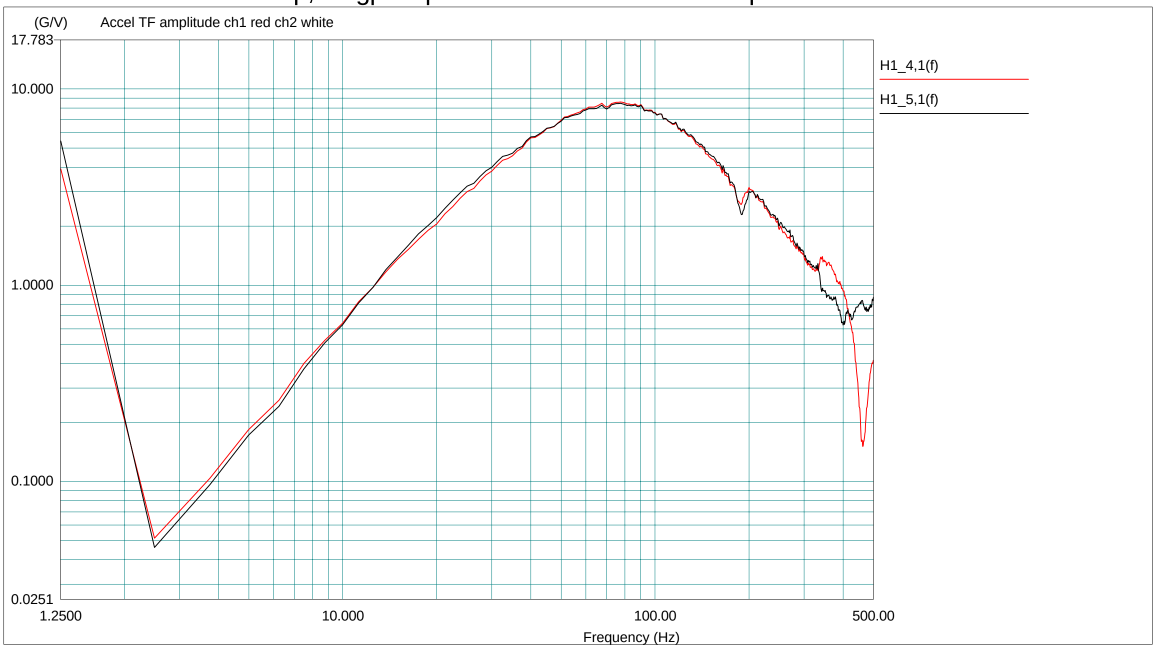
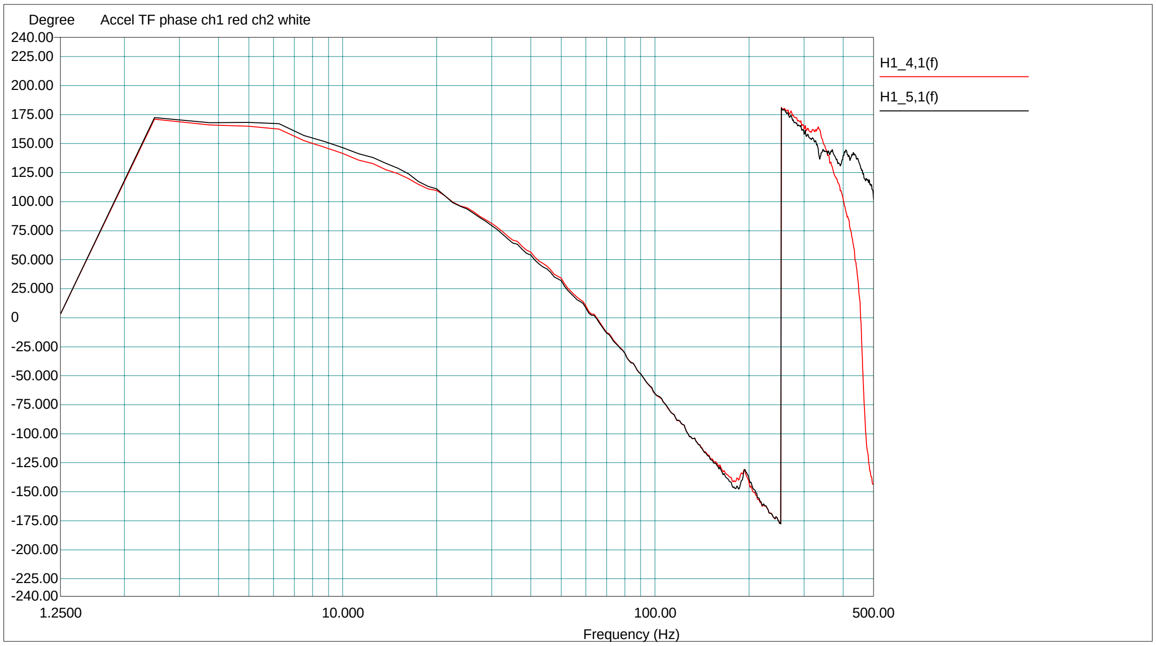


Figure 8. Acceleration Transfer Function amplitude ratio (Accel/input) of Actuators 1and 2 after matching.

This shows that the accelerations (measured with accelerometers located on the CUBE™ directly in line with the actuators) are very closely matched. This is good, but not necessary. The information to be gleaned from this plot is general frequency response information. It shows where the oil column resonance is, and where other system resonances are present. This example has an oil column resonance (as shown by the peak of the “haystack”) at 75 to 80 Hz. At 190 to 200 Hz, a second resonance appears. Is this a frequency that shows up in the spectral error analysis of your waveform replication software? The two traces diverge above 300 Hz. Watch to see if this behavior changes over time.

Phase Match

Header1: Ch 1, Ch 2 shaped random to 500Hz .35 Vrms
Header2: 118f temp, 12 gpm sprinkler on 1000 lb load on top to simulate HE



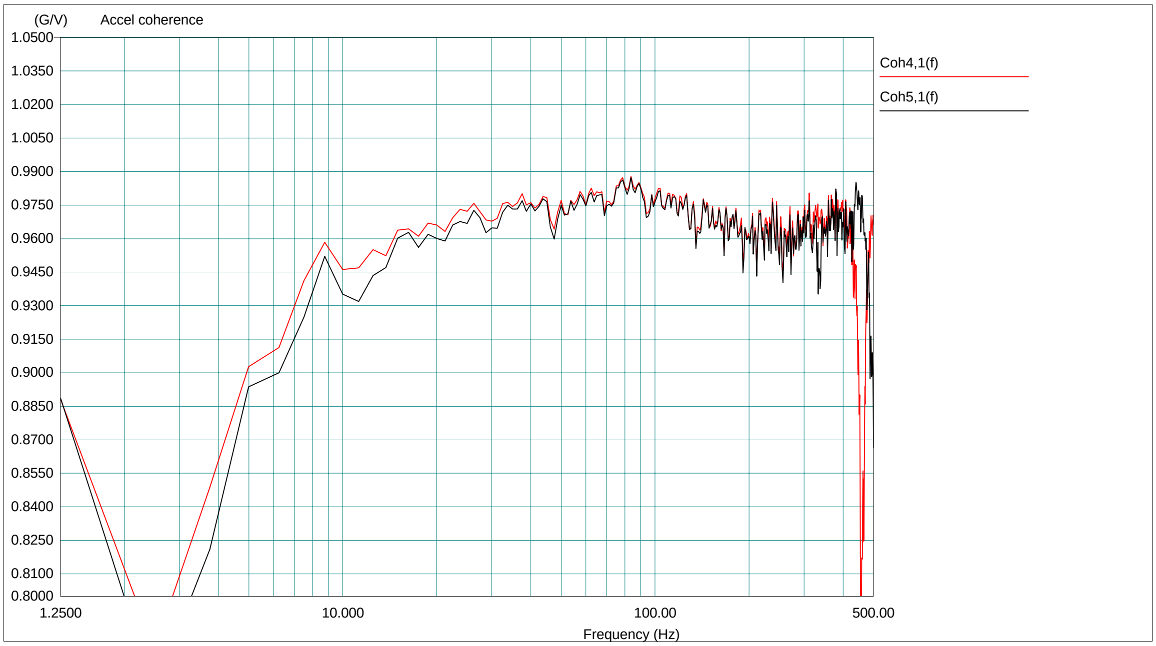
Spectral Lines: 800 Time Capture Points: 2048 Frequency Span: 1000
Average Type: Exponential Average Domain: Frequency Average Number: 32
Frame Number: 0 Window Type: Hanning

Figure 9. Acceleration Transfer Function Phase (Accel /input) of Actuators 1and 2 after matching.

In our experience, a good phase match can often be achieved even though the amplitudes don't match. The phase match is an excellent window on the servo loop settings. When setting loops, remember that you should aim for amplitude response that is -3dB at the 90-degree phase lag frequency. Since the 0 dB amplitude is arbitrary, you should aim for a good phase match first. Once you have a good phase match then the amplitude can be adjusted with the Amplitude Pot or the control software.

Coherence Match

Header1: Ch 1, Ch 2 shaped random to 500Hz .35 Vrms
Header2: 118f temp, 12 gpm sprinkler on 1000 lb load on top to simulate HE



Spectral Lines: 800 Time Capture Points: 2048 Frequency Span: 1000
Average Type: Exponential Average Domain: Frequency Average Number: 32
Frame Number: 0 Window Type: Hanning

Figure 10. Acceleration Coherence of matched actuators 1 and 2 running together.

For the coherence assessment, it is important that only one pair of actuators is running at a time. Since the coherence is a measure of how much output energy is caused by energy in the input, any additional acceleration from cross axis terms will reduce the coherence.

Example Responses: Actuator Position Transfer Functions and Coherence

Amplitude Match

Header1: Ch 1, Ch 2 shaped random to 500Hz .35 Vrms
Header2: 118f temp, 12 gpm sprinkler on 1000 lb load on top to simulate HE

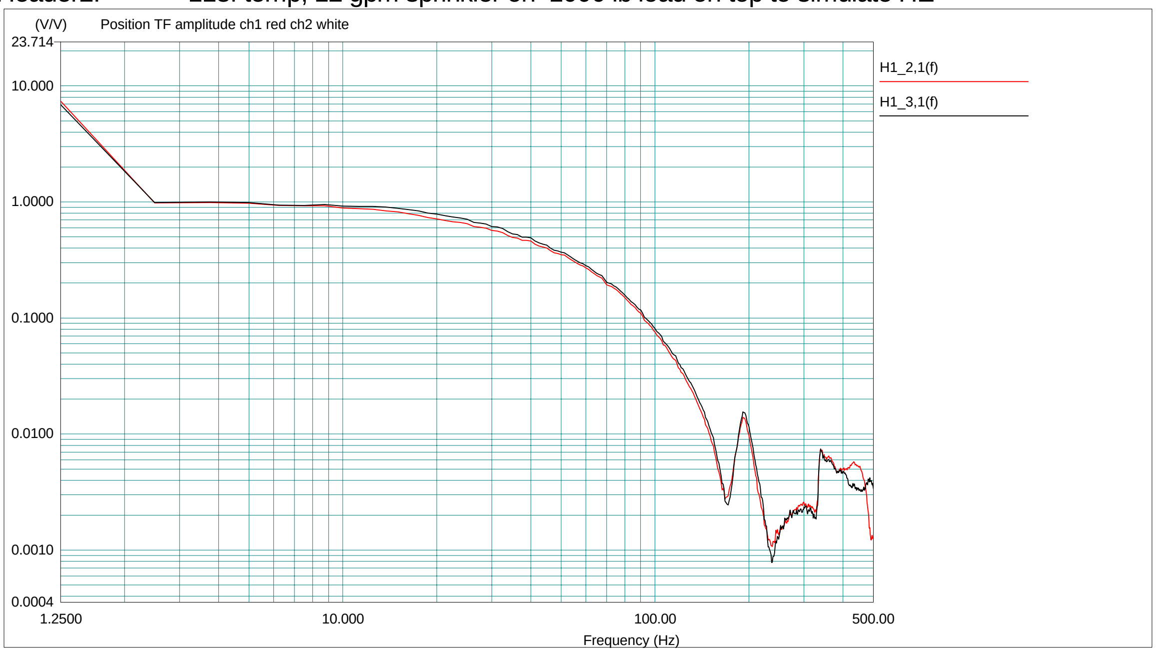


Figure 11. Position Transfer Function, Amplitude Position/Input

Notice the peak in the response at 200 Hz, and recall that there was a similar feature in the acceleration trace. This is some dynamic response of the CUBE™ structure, and may change with load. It should be watched to see if it moves around on the frequency axis over time. If it moves down in frequency, it could indicate something is coming loose.

Example Responses: Horizontal Actuators (5,6) Position Transfer Functions for a CUBE™ with a Head Expander

Header1: Ch 5, Ch 6 shaped random to 500Hz .25 rms
Header2: 117f temp, 1000 lb load on top to simulate HE

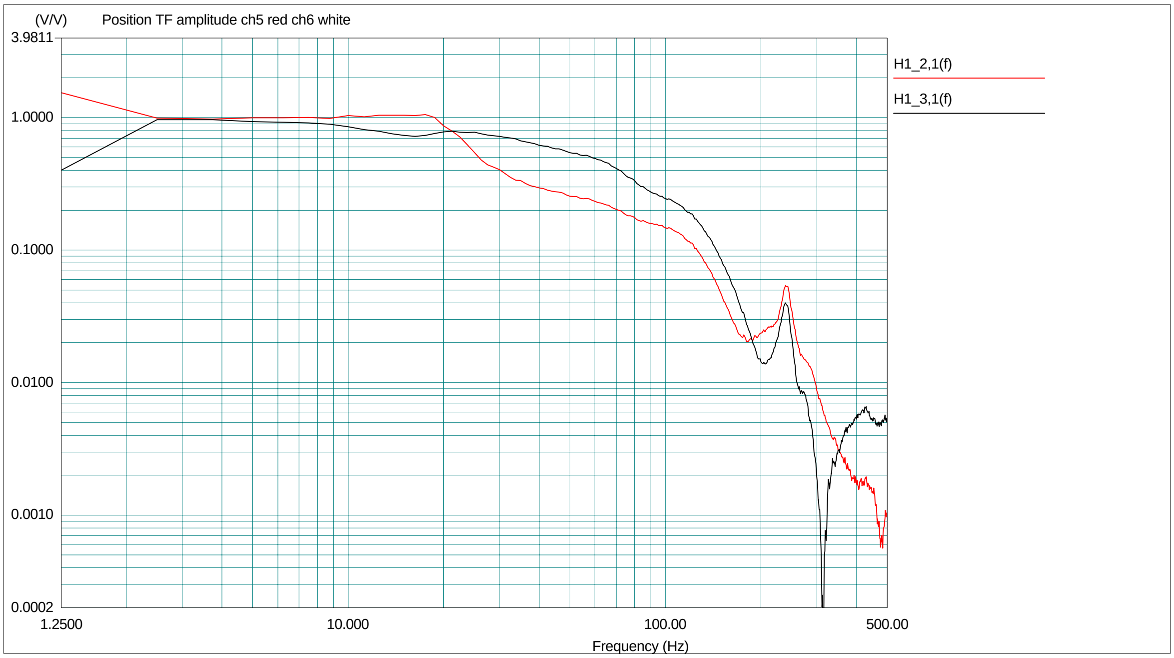
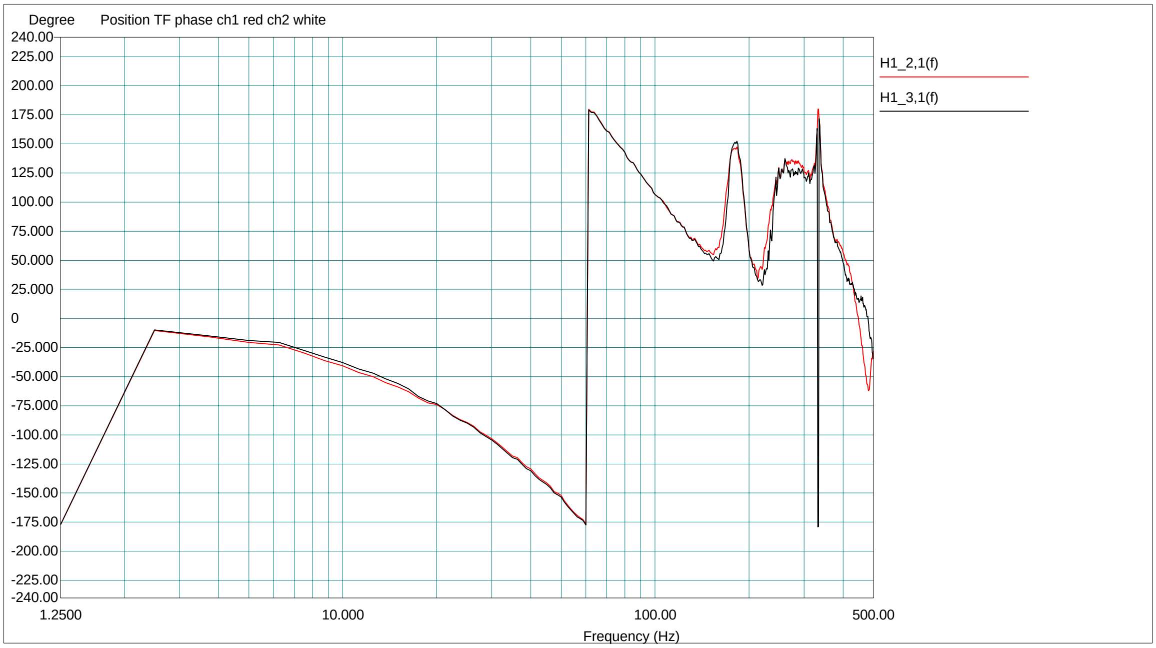


Figure 11b. Amplitude and phase are almost impossible to match with an off center load.

An offset load, such as that created with a head expander, mean the actuators are loaded differently. The result is that the transfer functions will NOT match. That's okay and is the reason waveform replication controllers exist.

Header1: Ch 1, Ch 2 shaped random to 500Hz .35 Vrms
Header2: 118f temp, 12 gpm sprinkler on 1000 lb load on top to simulate HE



Spectral Lines: 800 Time Capture Points: 2048 Frequency Span: 1000
Average Type: Exponential Average Domain: Frequency Average Number: 32
Frame Number: 0 Window Type: Hanning

Figure 12. Position Transfer Function, phase response, Position/Input, associated with figure 11.

Header1: Defiance Ch 5, Ch 6 shaped random to 500Hz .25 rms
Header2: 117f temp, 1000 lb load on top to simulate HE

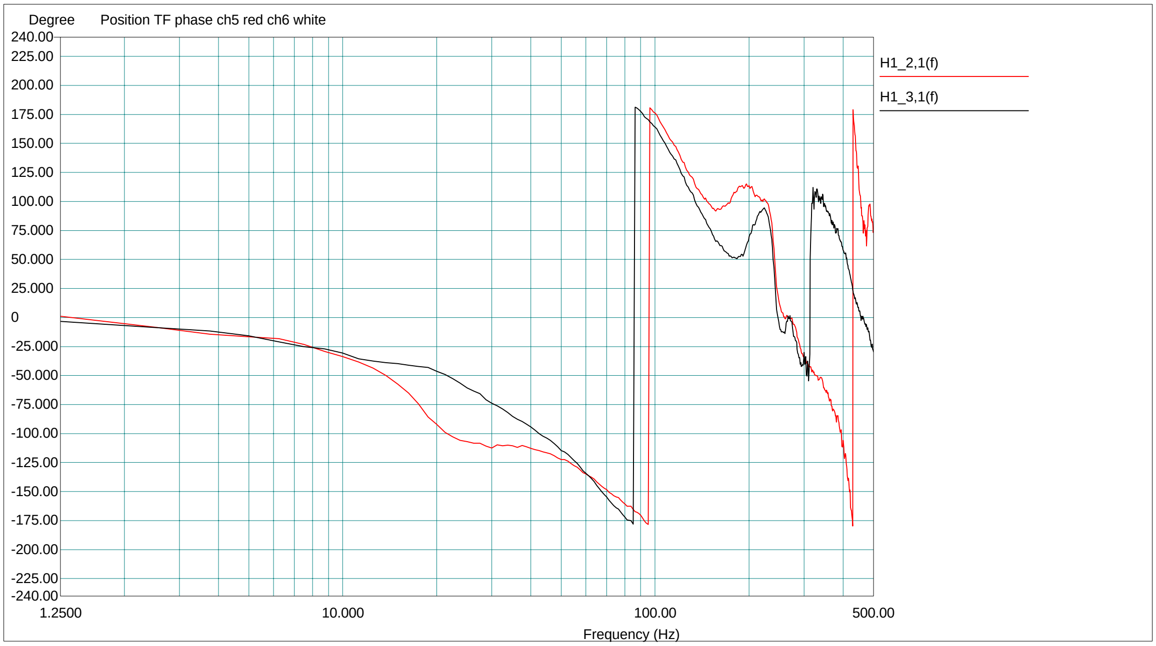


Figure 12b. Position Transfer Function phase response, Position/Input, associated with figure 11b.

Header1: Ch 1, Ch 2 shaped random to 500Hz .35 Vrms
Header2: 118f temp, 12 gpm sprinkler on 1000 lb load on top to simulate HE

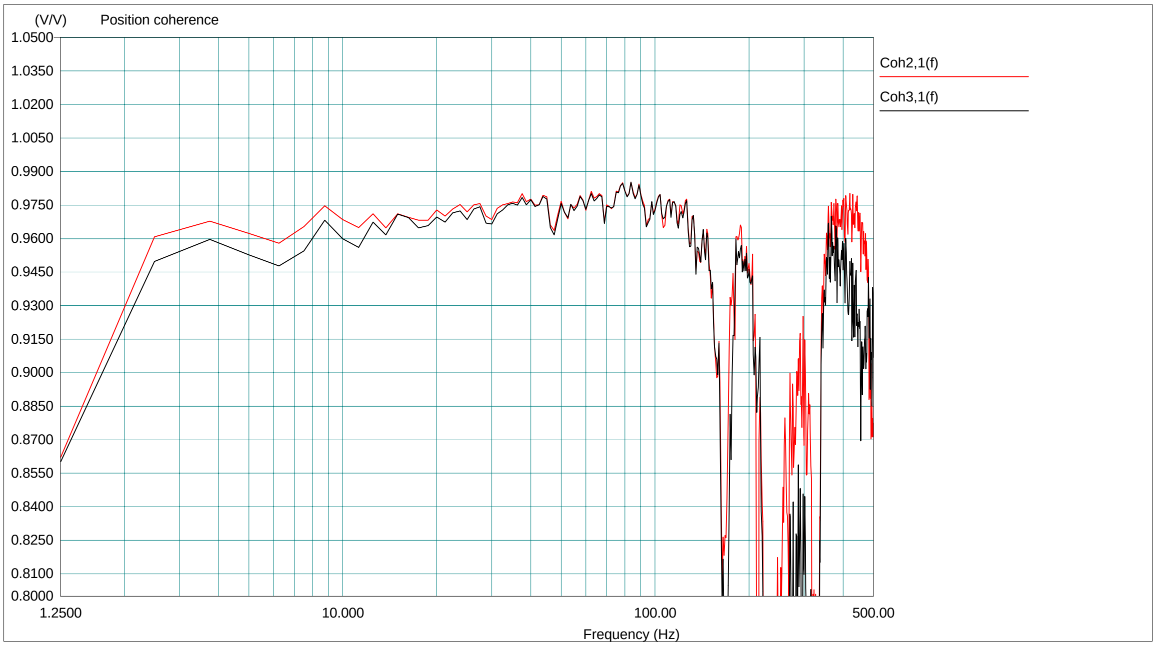


Figure 13. Position Coherence, Position/Input

Notice that the position coherence is well above 95%, even at frequencies down to 3 Hz. The low frequency extension depends on the drive signal frequency and amplitude and measurement system resolution, as well as the condition of the actuator. If the valves or piston bearings or pad bearings are not in good shape, the coherence will be low. Coherence that is more than a couple of percentage points different from the "as delivered" level warrants further inspection.

Example Responses: Slave Valve Position Transfer Functions and Coherence

Amplitude Match

Header1: Ch 1, Ch 2 shaped random to 500Hz .35 Vrms
Header2: 118f temp, 12 gpm sprinkler on 1000 lb load on top to simulate HE

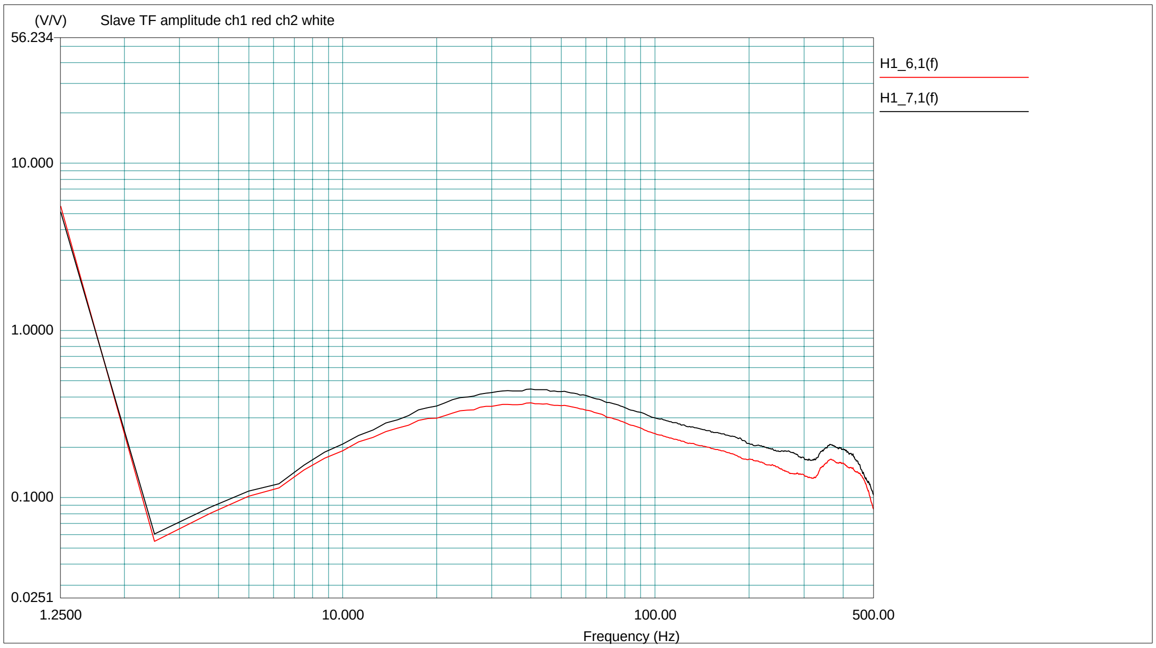
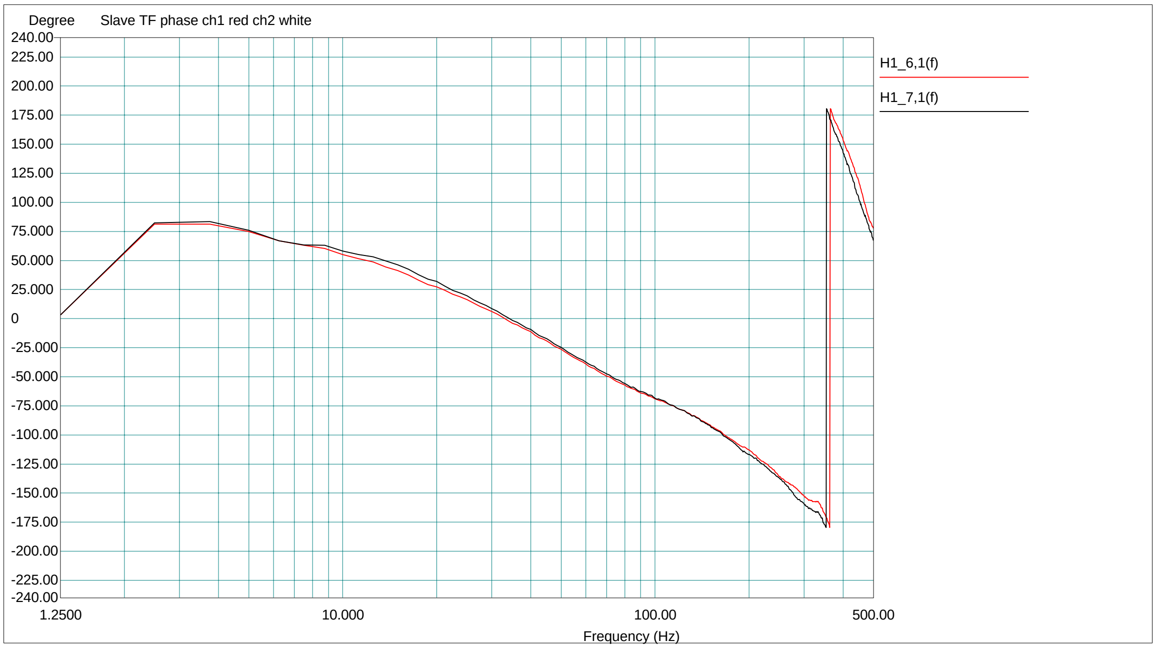


Figure 14 Slave Displacement Transfer Function Amplitude Displacement/Input

Having a good match in actuator position and acceleration may leave the slave valve amplitude with significant mismatch. This is due to slightly different flow gains in the servo valves, and is quite common. At 100 Hz for example the TF of one valve is about 30% higher than the other.

Slave Displacement Phase

Header1: Ch 1, Ch 2 shaped random to 500Hz .35 Vrms
Header2: 118f temp, 12 gpm sprinkler on 1000 lb load on top to simulate HE



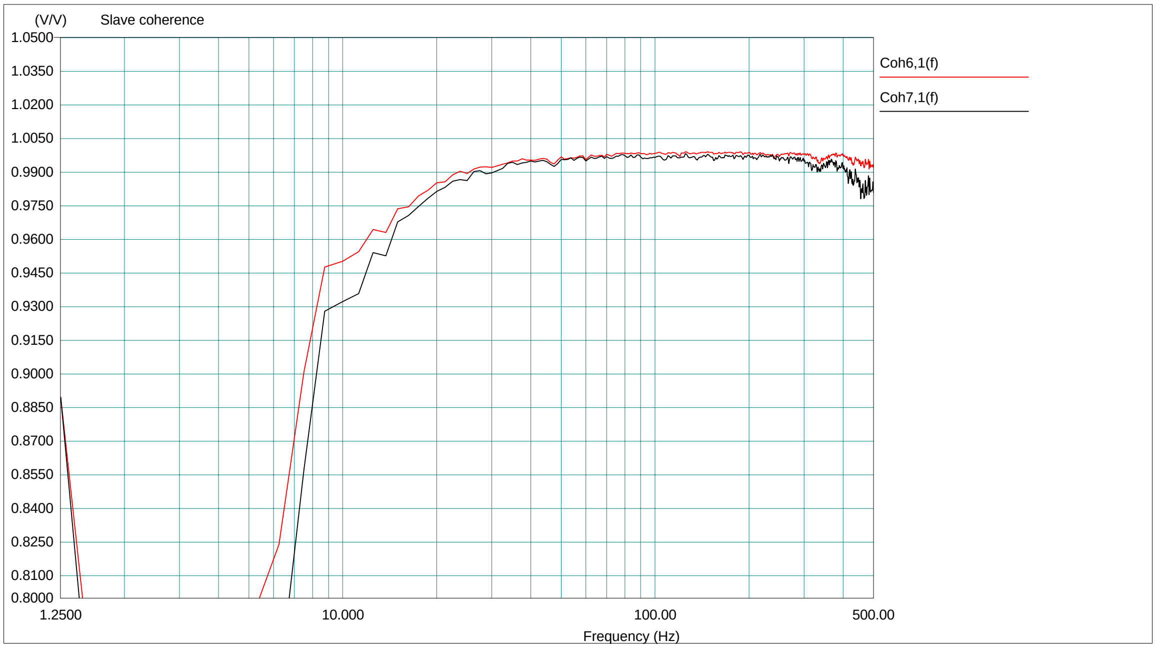
Spectral Lines: 800 Time Capture Points: 2048 Frequency Span: 1000
Average Type: Exponential Average Domain: Frequency Average Number: 32
Frame Number: 0 Window Type: Hanning

Figure 15 Slave Phase

But the slave phase is right on, showing that the phase match is more important than amplitude match when trying to match the position servo loops.

Slave Coherence

Header1: Ch 1, Ch 2 shaped random to 500Hz .35 Vrms
Header2: 118f temp, 12 gpm sprinkler on 1000 lb load on top to simulate HE



Spectral Lines: 800 Time Capture Points: 2048 Frequency Span: 1000
Average Type: Exponential Average Domain: Frequency Average Number: 32
Frame Number: 0 Window Type: Hanning

Figure 16 Slave Coherence

The slave coherence should be above 0.95 at frequencies out to 200 Hz or so at the very least. Different samples have individual characteristics, and it is important to compare each valve to itself over time rather than comparing valve to valve. Valves have differing values, even in the factory.

Quiescent Acceleration Noise

The quiescent acceleration on the CUBE™ is the result of pressure fluctuations in the control ports. These pressure fluctuations are due to turbulence. Turbulence increases with the oil temperature, the oil pressure and the condition of the flow edges of the servo valves, so these things will all influence the quiescent noise on your CUBE™. If you have thin, hot oil, expect high levels of acceleration noise. The pilot valve condition is the more important, since noise in it's output is amplified in the slave stage. The quiescent noise is a useful measure of the pilot condition, all other things being equal (particularly oil temperature and pressure).

A word of caution: The pilot is very sensitive and will respond to seemingly insignificant amounts of electrical noise. In the graph of acceleration spectral density below, notice that the 60 and 120 Hz components are orders of magnitude above the random (turbulent induced) noise. Hence, most of the quiescent vibration on this table is from power line electrical noise.

Header1: Qnoise Oil 119F 3000psi 0.5volt dither
Header2: 1000 lb on top

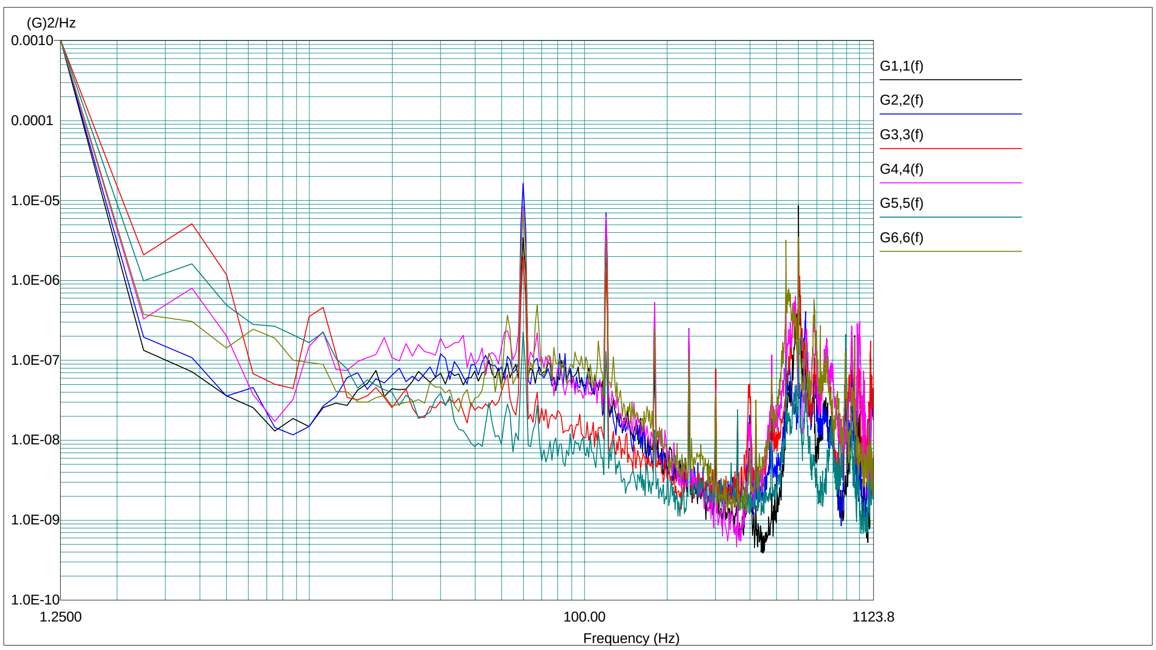


Figure 17 Power Spectral Density of the background acceleration on all 6 actuators in a CUBE™

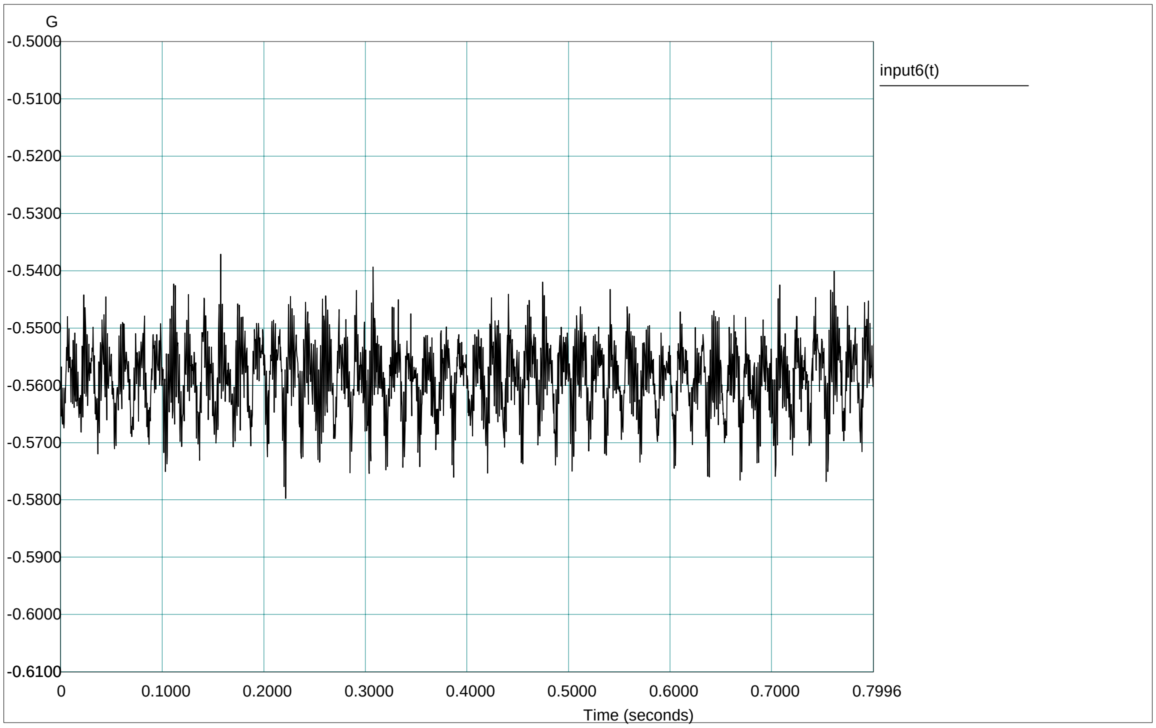


Figure 18. Time History of Background Acceleration on CUBE™. In this case it has peaks of 20 mg. Predominant frequency is 60 and 120 Hz.

The level of quiescent noise you can tolerate depends on the tests you are running. High-level random vibration tests probably don't require low levels of background noise. Low-level waveform replication may require very low levels of background noise. We have found that reducing the pressure and temperature of the hydraulic oil can be very effective in lowering the quiescent noise.

Voice Coil Bias Voltage

The final measurement to make is the Voice Coil Bias Voltage. With the CUBE™ under servo control, and all actuators somewhere near the center of their strokes, simply measure and record the voice coil voltage. The voice coil voltage is dependent on the system temperature, so it is best to measure it when the CUBE™ has reached normal operating temperature.

A value from 2.5 to 3.5 volts it typical. Values less than 2.5 volts may leave your CUBE™ unprotected, and may warrant further study. The main thing to watch for, however, is a significant (+/- 1 volt) change in the bias level over time (same temperature is vital, as it can change that much with temperature).

Team

Conclusion

Running this series of assessments periodically can quickly tell you if your CUBE™ is in good health and if your oil is in satisfactory condition. We usually find that dirty oil is the cause of degraded performance and improving the condition of the oil has solved many of the issues of seemingly deteriorating performance.