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## Optimizing the Performance of Pilot Control Loaders at NASA Vertical Motion Simulator

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The Vertical Motion Simulator at NASA Ames Research Center uses a large array of pilot control loaders to simulate the cockpit control interfaces for a range of current and proposed future aircraft, from fixed-wing transports and fighters to rotorcraft. To meet the evolving pilot control force cueing requirements of researchers, we have provided a wider dynamic range, improved frequency response, and created smoother motion results. These improvements have focused on fine-tuning the pilot control loader's analog controller and transducers as well as defining better procedures for optimizing frequency response characteristics. Using the pitch axis on a McFadden wheel and column-type controller as an example, this paper details the optimization procedures.

### Nomenclature

$F_A$	= acceleration force, lb
$F_{FB}$	= force balance, lb
$F_G$	= gravity force, lb
$F_P$	= pilot force, lb
$F_T$	= differential pressure transducer output force, lb
$F_{TB}$	= differential pressure transducer output force drift and bias, lb
$K_A$	= notch filter depth coefficient
$K_{CT}$	= center tap coefficient
$m$	= actuator mass, $(\text{lb} \cdot \text{s}^2)/\text{in.}$
$R_P$	= potentiometer resistance, $\Omega$
$R_1$	= center tap resistor, $\Omega$
$R_2$	= center tap resistor, $\Omega$
$s$	= Laplace operator, $1/\text{s}$
$\omega_n$	= variable depth notch filter notch frequency, $\text{rad}/\text{s}$
$\zeta$	= variable depth notch filter damping ratio
$\tau$	= time constant for integrator with phase lead, s
$\tau_n$	= time constant variable depth notch filter, s
$\tau_1$	= time constant for first zero, s
$\tau_2$	= time constant for first pole, s
$\tau_3$	= time constant for second zero, s
$\tau_4$	= time constant for second pole, s
$\tau_5$	= time constant for third zero, s
$\tau_6$	= time constant for third pole, s

### I. Introduction

Pilot control loaders (PCLs) are commonly used in flight simulators to simulate the control forces a pilot would feel when moving the inceptors in the actual vehicle due to air loads, force-feel devices, and control surface actuators. Pilot control force-feel cueing is an essential pilot cue that must be simulated accurately for handling qualities evaluations. It is also critical to pilot perception of simulation fidelity. The first pilot control loader system used at the NASA Ames Research Center in the 1960s was a Link electric loader that was later replaced by a McFadden hydraulic actuator pilot control loader. McFadden pilot control loaders were acquired for the various flight simulators at NASA Ames, including the Vertical Motion Simulator (VMS), which became operational in 1979. The VMS uses five interchangeable simulator cabs and employs a large selection of McFadden pilot control loaders to configure these cabs to represent a range of fixed- and rotary-wing aircraft. The requirements for PCL performance are primarily driven by the needs of aircraft handling quality research studies [1]. Usually the controllers are configured to represent the dynamic response and force-feel characteristics prescribed by the researchers. The force-feel characteristics include feel gradient, breakout, dead zone, friction, etc. Sometimes the force-feel characteristics must be adjusted during the real-time simulation without compromising the integrity of the system [2]. This means that the PCL must be capable of being programmed to match the natural frequencies of all and any anticipated pilot controls to provide a rapid response to customer needs. The challenge is to maximize performance and to know when optimal performance has been achieved.

In general, maximizing PCL performance requires that all the transducers in the PCL be optimally designed for their specific tasks. The transducers include the position potentiometer, velocity tachometer, differential pressure transducer, and the servo valve. Maximizing performance also requires that all feedback loops be frequency shaped, known as tuning, to achieve maximum loop gain. The combination of transducer improvements and frequency tuning increases the maximum values for parameter settings, reduces the apparent mass, and ensures the closed-loop-system low-frequency

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characteristics (pilot frequency response) approach that of an ideal second-order system.

This paper begins with a brief description of the VMS and a McFadden pilot control loader force feedback system including the McFadden analog controller. Improvements to the position potentiometer, tachometer, differential pressure transducer, and actuator servo valve are described next. Processes for optimizing PCL performance by tuning and the measurable results of the optimization effort are then described.

## II. Vertical Motion Simulator

The VMS combines a high-fidelity simulation capability with an adaptable simulation environment that allows the simulator to be customized to a wide variety of human-in-the-loop research applications. The distinctive feature of the VMS is its unparalleled large amplitude, high-fidelity motion capability. The high level of simulation fidelity is achieved by combining this motion fidelity with excellent visual and cockpit interfaces. An interchangeable cab (ICAB) arrangement allows different crew vehicle interfaces and vehicle types to be evaluated allowing fast turnaround times between simulation projects. The VMS motion system is a 6-degree-of-freedom combined electromechanical/hydraulic servo system, shown in Fig. 1. It is located in and partially supported by a specially constructed 120 ft tower. The motion platform consists of a 40-ft-long beam that travels  $\pm 30$  ft vertically. On top of the beam is a carriage that traverses the 40 ft length of the beam. A sled sits atop the carriage providing the  $\pm 4$  ft of travel in a third translational degree of freedom. A conically shaped structure is mounted on the sled and rotates about the vertical axis providing yaw motion. A two-axis gimbal allows pitch and roll motion. The ICAB is attached to the top gimbal ring. The motion capability of the VMS is summarized in Table 1.

The ICAB capability in the VMS allows the cockpit to be tailored to the research application. The VMS has five portable ICABs; an example is shown in Fig. 2, with different out-the-window visual fields of view. For each simulation study, the cab is equipped based on the simulation requirements and with the complete simulation environment except for motion. Equipping the cab includes installation of flight controls, fight instruments and displays, and

**Table 1 VMS motion capability**

VMS nominal operational motion limits			
Axis	Displacement, ft	Velocity,	Acceleration
Vertical	$\pm 30$ ft	16 ft/s	24 ft/s <sup>2</sup>
Lateral	$\pm 20$ ft	8 ft/s	16 ft/s <sup>2</sup>
Longitudinal	$\pm 4$ ft	4 ft/s	10 ft/s <sup>2</sup>
Roll	$\pm 18$ deg	40 deg/s	115 deg/s <sup>2</sup>
Pitch	$\pm 18$ deg	40 deg/s	115 deg/s <sup>2</sup>
Yaw	$\pm 24$ deg	46 deg/s	115 deg/s <sup>2</sup>

seats. Following equipage and checkout, the ICAB is transported and installed on the motion system. The ICAB capability allows the VMS facility to conduct fixed-base and moving-base simulation studies simultaneously. The VMS facility has sufficient pilot control loaders to equip all five interchangeable cabs for fixed-wing, rotorcraft, or piloted space vehicle simulation.

## III. Ideal Force Feedback McFadden Pilot Control Loader

An ideal second-order model for a force feedback McFadden PCL single axis, shown in Fig. 3, can be the axis of any of the McFadden PCLs. If the frequency tuning has been carefully done, this model holds well for frequencies up to about 30 Hz depending on the particular actuator.

There are three transducers mounted on the PCL actuator that provide feedback signals to the McFadden analog controller. These are the differential pressure transducer (DPT), position potentiometer, and tachometer. The DPT converts hydraulic pressure difference on the actuator piston to an electrical signal scaled to force. The other two transducers, the position potentiometer and tachometer, convert pilot control position and velocity, respectively, into scaled electrical signals. A fourth transducer, the PCL actuator servo valve, converts an electrical input signal into hydraulic fluid flow.

Those controls on the front panel of the McFadden analog controller that set the pilot control characteristics include force balance, position trim, gain, spring gradient, and damping factor. The force balance potentiometer removes force bias in the differential pressure transducer output. The position trim sets the initial position of the pilot control. Gain sets the natural frequency. The spring gradient and damping factor potentiometers are normally set to zero when the external Pilot Force Program is engaged because the program will now supply these settings. The Pilot Force Program is an external program that receives feedbacks from the pilot control loader and generates all the physical characteristics required for simulating pilot controls. This would include such characteristics as force breakout, friction, stiction, position stops, dead zone, and so forth.

Control in the PCL comes from the feed-forward path and three feedback loops. The feed-forward path consists of gain and two integrator blocks. The feedback loops are force, velocity, and position. When force is applied to the pilot control, a force feedback signal is generated that includes pilot force, gravity, and inertial force. The force feedback signal is compared with all other force signal inputs. The difference creates a force signal error that drives the pilot control in the direction of the applied force. The damping force feedback, spring force feedback, and Pilot Force Program input create the pilot control force feel. If the damping factor, spring gradient, and Pilot Force Program input are all set to zero, then the pilot will feel only gravity and inertial force effects.

Each loop was examined to identify the key factors that limited performance. The differential pressure transducer force drift and bias comprise the force term  $F_{TB}$  and cause an asymmetrical force breakout at position trim. Any problems that limit the feedback gains associated with the position potentiometer and tachometer result in limited-force gradients. High-force gradients are required for the proper simulation of the nonlinear functions such as force breakout, friction, stiction, stops, etc. Smooth operation of the PCL actuator servo valve is required for zero turnaround bump. PCL actuator

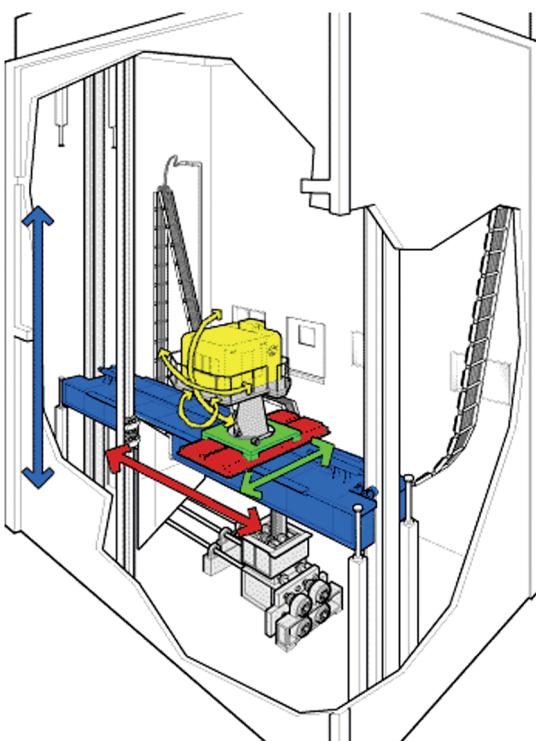


Fig. 1 Cutaway diagram of the VMS facility.

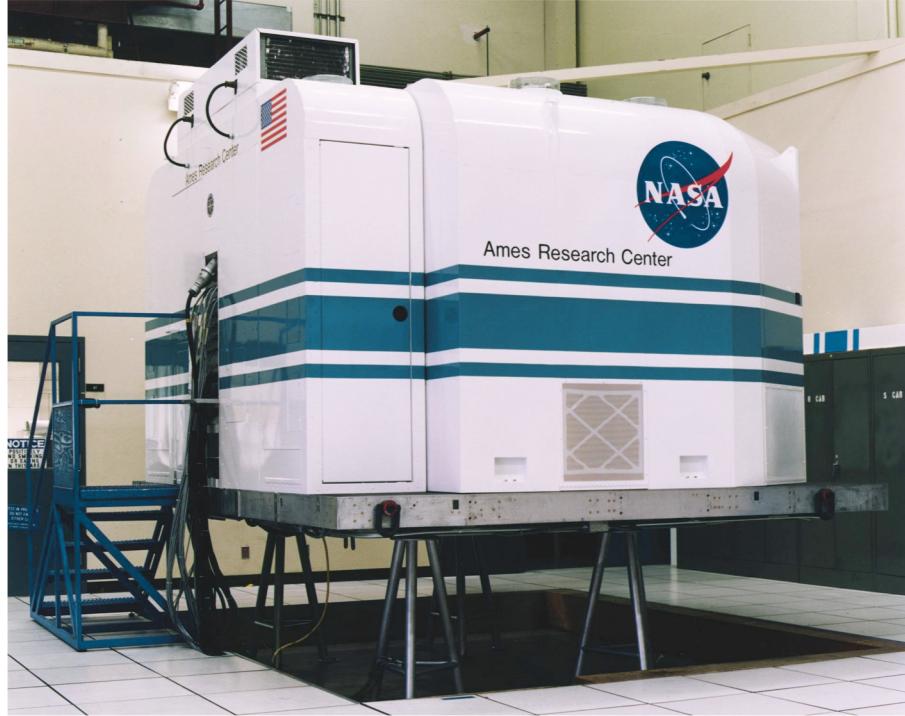


Fig. 2 Interchangeable cab mounted on test stands.

frequency roll off limits performance in the pilot frequency range. The following sections will explain the improvements made to these hardware devices to improve the performance of the McFadden pilot control loaders.

Tuning techniques were developed to optimize the force feedback open-loop gain as low-loop gain decreases the natural frequency of the pilot control. This required additional use of lead-lag functions, notch filters, integrator with phase lead, nonlinear damping compensation (NDC), and dither in the McFadden controller. Optimal performance of this loop results in the maximum possible natural frequency for the pilot control. The goal of the tuning process is to improve the dynamics to approximate the idealized model in Fig. 3 as closely as possible. The tuning functions are discussed in detail in Sec. V.

#### IV. Optimizing Pilot Control Loader Transducers

This section describes improvements to the PCL actuator transducers. These are the position feedback potentiometer, velocity feedback tachometer, differential pressure transducer (force feedback), and PCL actuator servo valve. These transducers are illustrated in Fig. 4 for a cyclic PCL.

##### A. Position Potentiometer

Position feedback is measured in the McFadden PCL with a precision potentiometer as shown in Fig. 3. Position feedback provides a force feedback term when scaled by spring gradient. The larger the spring gradient, the stiffer the feel-system gradient. But this also means that larger position feedback loop gains are required for

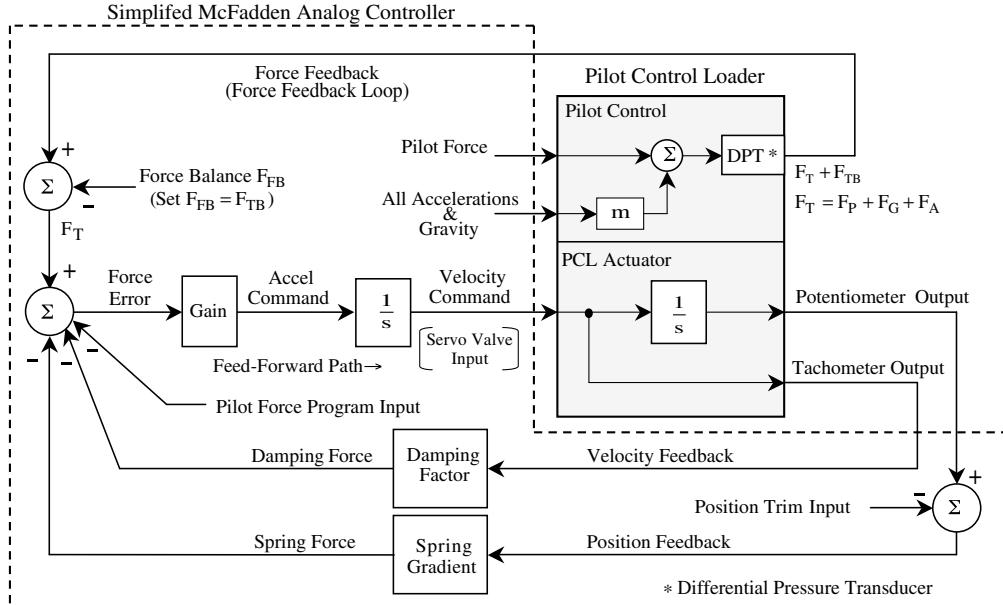


Fig. 3 Idealized PCL force feedback translational model for an idealized single axis.

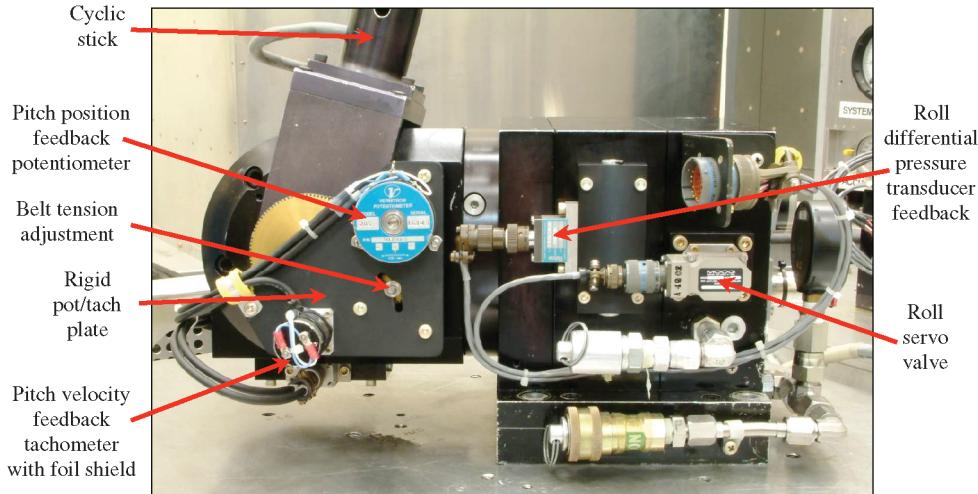


Fig. 4 McFadden cyclic side view.

simulating larger spring gradients and this is where the specifications and quality of the potentiometer become important, as are the mounting and connection of the potentiometer to the pilot control.

Larger position feedback gain capability is required to improve the maximum force gradient of 200 lb/in., as supplied from the manufacturer. Attempts to increase the feedback loop gain to achieve this uncovered instabilities. There were several sources for the instabilities. At specific settings of the position feedback loop gain, the pilot controller would be unstable at certain positions of the pilot control. The pilot controller was not only unstable at the zero position, but it was also unstable at other random locations. The instability at the zero position is the result of distortion in the resistance of the potentiometer's mandrel caused by the center tap supplied with the original potentiometers.

All precision potentiometers used in PCL applications at the VMS use a carbon mandrel. The linearity specification for this type of potentiometer is achieved by trimming the mandrel through various techniques that range from notching, nibbling, laser cutting, etc. What can suffer in the process is electrical smoothness [3], which is defined as the maximum instantaneous variation in output voltage from the ideal voltage. To check for electrical smoothness, a potentiometer/tachometer precision motion tester was designed and fabricated. This tester uses a Galil motion control system, which consists of a Galil stepper motor, power supply, amplifier, and Galil PC software. The software allows for programming test conditions.

Testing the original potentiometers showed distortions at the center tap and other random locations. Then, we purchased several different precision potentiometers without center taps from different vendors. All had the same linearity and electrical smoothness

specifications; however, some varied significantly in actual electrical smoothness. In collaboration with a manufacturer, a potentiometer without a center tap allowing for the best electrical smoothness and best linearity possible was developed for this application. After we made this change, no appreciable errors in linearity were detectable, and there was a considerable improvement in electrical smoothness. Oscilloscopes of the electrical smoothness test for an original and replacement potentiometer are shown in Fig. 5.

Using a potentiometer without a center tap and incorporating a pseudocenter tap circuit as shown in Fig. 6 eliminated the instabilities caused by the potentiometer center tap. The two resistors in series between each of the potentiometer's reference connections provide the zero position's reference in place of a center tap ground. If the resistors are equal, the reference position is the same as the position of the original center tap. The actual value of the resistors is not critical, but it is best if the values selected have the same series resistance as the potentiometer. This helps to improve common mode noise rejection in this circuit, and, in particular, when the wiper is in the pseudocenter tap location.  $K_{CT}$  (Fig. 6) is a coefficient from 0 to 1 that is the location of the pseudocenter tap. If the pseudocenter tap is to be at the center of the potentiometer's mandrel, then  $K_{CT} = 0.5$  and both resistors will be one-half of the potentiometer's resistance.

Shielded twisted-pair cables are used between the McFadden controller and the simulator cab, and this cable length can be a few hundred feet. Because all signals and power are carried to the VMS through a cable carriage, the electromagnetic noise environment is severe. For this reason, a noise rejection circuit must be used. This is one of the reasons for the instrumentation amplifier and shielded twisted-pair cables. The other reason for using an instrumentation

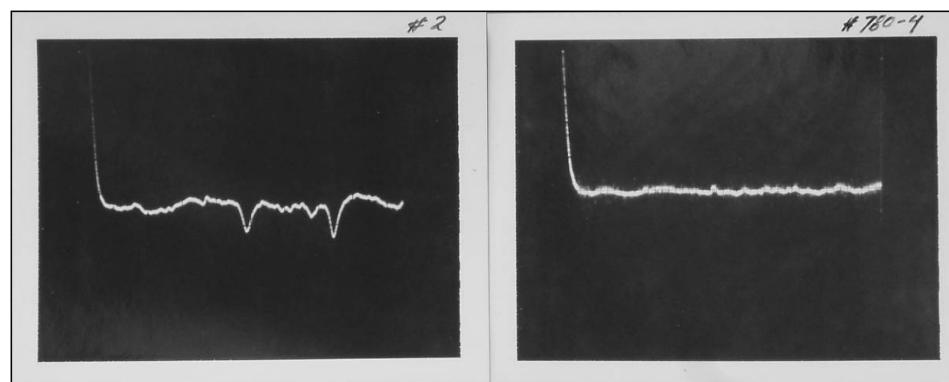


Fig. 5 Potentiometer noise test oscilloscopes.

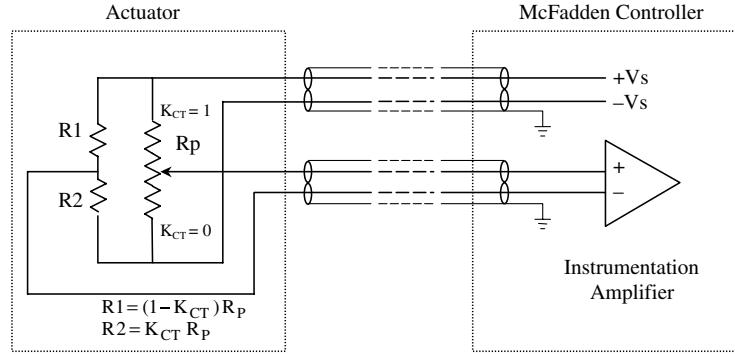


Fig. 6 Potentiometer with pseudocenter tap circuit.

amplifier is to prevent potentiometer loading or distortion of the potentiometer's linearity.

Another possible source of position feedback instability is the mounting hardware for the position feedback potentiometer. The mounting hardware was strengthened to minimize compliance that could contribute to an instability. The potentiometer was attached directly to a rigid plate, as shown in Fig. 4, and a slot was cut into the plate so that a sprocket could be used for belt tensioning. The potentiometer was also made with a slotted shaft that allows adjustment of the potentiometer position from the outside.

Another possible source of position feedback instability is the compliance in the belt drive used for the position feedback potentiometer. This is minimized using belts made of polyurethane with a stainless steel cable center. This particular belt design allows for some offset between sprockets, and the stainless steel cable center minimizes cable stretch. As much as possible, cable distance between sprockets should be kept short and where there is an open stretch of cable, sprocket idlers should be used. Otherwise, sustained oscillations are possible when high position feedback gains are used.

The new potentiometer, without the center tap and incorporating a pseudocenter tap circuit, eliminated the instability at the center tap location for high force gradient settings, as shown in Fig. 5. The use of a rigid mounting plate and a better belt drive allowed force gradients to typically exceed 300 lb/in. compared with the factory supplied rating of 200 lb/in.

## B. Velocity Tachometer

Velocity feedback provides a damping force term when scaled by damping factor (Fig. 3). The damping factor is usually adjusted to give the PCL a specific response. For example, the damping factor may be adjusted to give the PCL a slight overshoot response to a step input that is equivalent to a damping ratio of 0.707 for a second-order linear system. Damping is essential for simulation of the nonlinear functions and is referred to as NDC. This is explained in more detail in Sec. VI. Nonlinear function examples are force breakout, friction, stiction, and electrical stops. Damping is necessary to keep the position loop stable when high position feedback gains used in the nonlinear functions are active. The limit to the amount of velocity feedback gain that can be used also limits the amount of position feedback gain used. In fact, velocity feedback gain limits proved to be the limiting factor associated with achieving high position feedback gains. And so an effort was made to improve the maximum velocity feedback gain.

The original tachometer's 1/8-in.-diam shaft, relatively high armature inertia, and low torsional stiffness, coupled with the high-frequency response of the McFadden PCL, caused high-frequency oscillations at feedback gains required for dampening the high position feedback gain nonlinear circuits. Such oscillations can result in shaft failure. A tachometer with a 1/4-in.-diam shaft and 14-segment commutator minimized this problem. The higher inertia from the larger shaft did not prove to be a problem and it was possible to obtain much higher velocity feedback loop gains that were more than sufficient for the damping requirements of the nonlinear circuits.

In addition, the 14-segment commutator provides smoother signals than the original seven-segment tachometers.

Another problem was noise pickup by the tachometer. The tachometer contains coils, which make good magnetic field detectors. Although common mode rejection circuits can eliminate noise pickup on cables, noise pickup on the tachometer is treated as signal and the only effective protection is shielding. Foil shields (Fig. 4) proved to be an effective solution for low magnetic field noise environments. More elaborate shielding techniques are necessary in noisier environments.

The new tachometer design, with the 1/4-in.-diam shaft, allowed for much larger damping factors. This is critical for the operation of the NDC circuit. In addition, these improvements also increased the maximum force gradients.

## C. Differential Pressure Transducer

Force feedback is accomplished in the McFadden PCL by a differential pressure transducer (Fig. 3) that detects any pressure difference between both ends of the PCL actuator piston. Any pressure difference means that the pilot, gravity, and/or inertial effects have applied a force to the PCL. The differential pressure transducer used in the McFadden PCL must have low temperature drift to minimize troublesome checking of force balance.

Temperature drift generates a force offset in the differential pressure transducer output. The pilot can feel this force offset, and it becomes most noticeable in the nonlinear circuit for force breakout. A force offset gives the force breakout an asymmetrical feel. The temperature drift can be reduced by using a hydraulic oil cooler, but it is almost impossible to keep the hydraulic oil at a precise temperature because both the hydraulic oil flow rate and ambient temperature are not constant. Using an oil cooler set to keep the oil at an average ambient temperature, however, can minimize the temperature drift. In the VMS, the oil temperature is set at 70°F.

As with the position feedback potentiometer, a key requirement for the differential pressure transducers is linearity. A new differential pressure transducer was designed with emphasis on minimum temperature drift and is shown in Fig. 7. The new transducer also has improved linearity and less phase lag.

The new differential pressure transducer significantly reduced the force drift problem associated with the original differential pressure transducer. In addition, the more consistent performance of the new actuator servo valve makes the valves interchangeable with little or no effects.

## D. Pilot Control Loaders Actuator Servo Valve

The actuator servo valve is the device that controls fluid flow to and from the rotary PCL actuator causing the pilot control to move. This fluid flow is proportional to the current input. The original servo valves supplied with the McFadden PCLs were custom designed for this application.

When the original servo valves were no longer available, Moog, Inc. replaced the original valve with a custom-manufactured servo valve. The series 30 servo valve was chosen as the replacement as it roughly matched the flow rate of the original servo valve. This valve

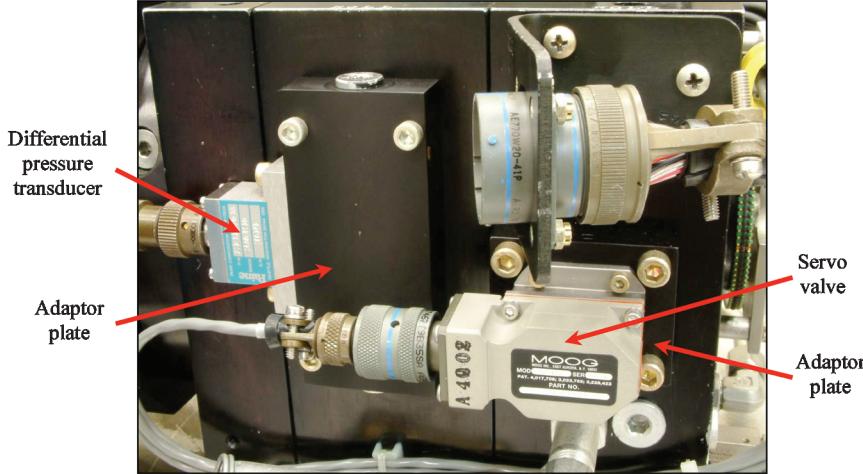


Fig. 7 Differential pressure transducer and servo valve.

had to be custom manufactured for our application. The performance of the new servo valve exceeded the original servo valve's performance in bandwidth and phase lag.

Subtle effects of the servo valve dynamics become obvious when developing force feedback open-loop Bode plots. One of these subtle but important effects is stiction. This shows up as a sudden drop in force (differential pressure) and change in phase lag, usually at higher frequencies such as 300–600 Hz. This can result in a pilot control turnaround bump. Based on this observation, an in-house servo valve tester, as illustrated in Fig. 8, was developed by fabricating a block to mount a servo valve and a differential pressure transducer. Fluid flow was dead headed to simulate a locked PCL. This eliminated the need for the position and tachometer feedback loops. The same force feedback control loop or electronics, as used in the McFadden PCL, was used for this servo valve tester. In this manner, servo valve performance can be compared under identical testing conditions and under force feedback open-loop conditions similar to the way the servo valve is actually implemented. For testing both servo valves and differential pressure transducers, one differential pressure transducer and servo valve were used as standards.

Figure 9 illustrates the frequency response or Bode plots of force (differential pressure) output versus servo valve input for the new Moog model 30-407 servo valve. The Bode plot in Fig. 9a shows the typical response of a valve without the use of dither. Servo valve stiction has caused a dramatic loss in response at 400 Hz, which can result in pilot control turnaround bump. The Bode plot in Fig. 9b shows the frequency response with dither added to the circuit. This clears the stiction problem and slightly improves the phase at lower frequencies.

The original servo valves had a  $-45$  deg phase lag at approximately 9 Hz, whereas the new valve's  $-45$  deg phase lag point is at 30 Hz. At 100 Hz, the new valve has more than 45 deg less phase lag than the original valve, which means that less phase-lead compensation is required to frequency tune the force feedback open loop. Consequently, the new servo valve also improved the linear behavior of the PCL at low frequencies up to approximately 30 Hz. This is important, as one requirement for improving the performance of the McFadden PCL is to get the actuator assembly to appear as a simple integrator in that frequency range. The more it appears as a simple integrator, the more the PCL can be made to look as an ideal second-order mechanical system.

The new servo valve provided a dramatic improvement over the original PCL actuator servo valve. It increased the pilot frequency range bandwidth. There was also an improvement in less phase lag in the upper frequency range where tuning is required. This makes tuning easier to accomplish. The end result is a larger pilot frequency range and a larger feed-forward path gain for smoother pilot control response.

## V. Tuning Circuits

An expanded functional diagram for the McFadden analog controller (Fig. 3) is shown in Fig. 10, which now includes the elements associated with tuning. These include the lead lag, notch filters, integrator with phase lead, NDC, and dither. The NDC and dither are set by trim potentiometers located on the printed wiring boards. All circuits for which the components can vary among PCLs have components mounted on standoffs so that they can be easily exchanged.

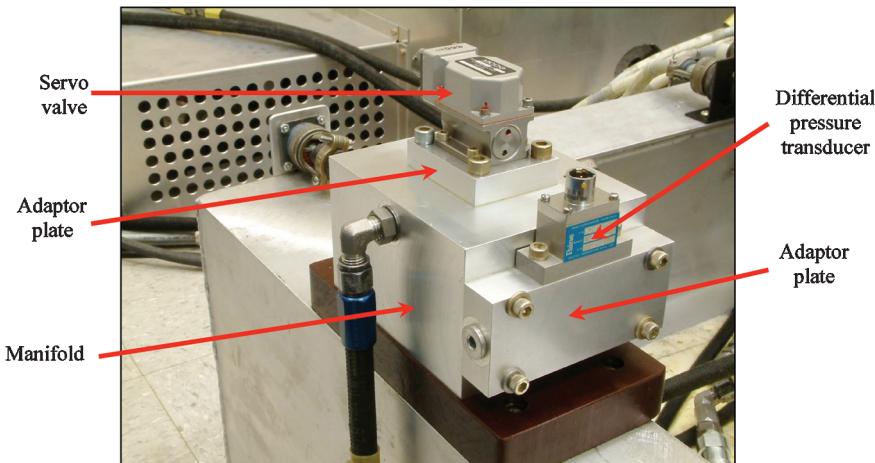


Fig. 8 Differential pressure transducer and servo valve tester.

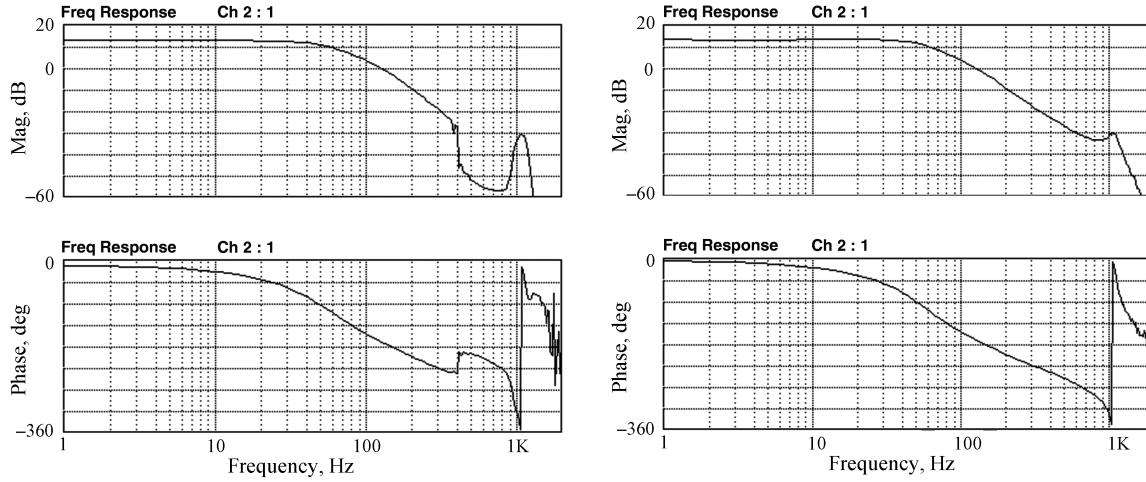


Fig. 9 Servo valve response without and with dither.

These would include the notch filters, phase lead, and integrator with phase-lead circuits.

#### A. Force Feedback Loop

Although the mass  $m$  of the actuator cannot be varied to change the PCL's natural frequency (other than to build a lighter actuator), the feed-forward path gain can be varied to provide some control over the PCL's natural frequency. In frequency tuning the McFadden PCLs, one goal is to get the feed-forward path gain large enough so that further increases in the feed-forward gain do not cause significant increases in the natural frequency. Then, by providing a potentiometer adjustment for decreasing the feed-forward gain, the ability to decrease the natural frequency is achieved. The relationship between the feed-forward gain and natural frequency is used to determine when the optimal feed-forward gain is achieved. Large feed-forward gains are achieved through the use of lead-lag functions in the force feedback loop.

Up to three first-order lead-lag functions are used to shape the response of the force feedback open loop where phase compensation is practical. A caution in using a phase-lead function is the high frequency gain that results in troublesome high resonance frequencies that would ordinarily be suppressed. Limiting the amount of phase

lead per first-order lead-lag function or circuit can at least reduce this effect. For example, cascading two first-order 30 deg functions to obtain a second-order 60 deg phase-lead function reduces the high-frequency gain by 3.8 dB, as opposed to using a single first-order 60 deg phase-lead function. The saving is more dramatic when trying to implement higher phase leads with a single first-order function. The reduction in high-frequency gain, however, comes at the cost of more circuitry. A maximum of 45 deg per first-order phase-lead function was chosen as a practical compromise between the number of circuits required versus the resulting reduction in high-frequency gain.

The third order lead-lag function shown in Fig. 10 is of the form

$$\frac{(\tau_1 s + 1)(\tau_3 s + 1)(\tau_5 s + 1)}{(\tau_2 s + 1)(\tau_4 s + 1)(\tau_6 s + 1)} \quad (1)$$

The time constant requirements are

$$\tau_1 > \tau_2, \quad \tau_3 > \tau_4, \quad \tau_5 > \tau_6 \quad (2)$$

#### B. Feed-Forward Path

The nonideal response of the actual PCL actuator limits the performance of the pilot control loader at low frequencies. The

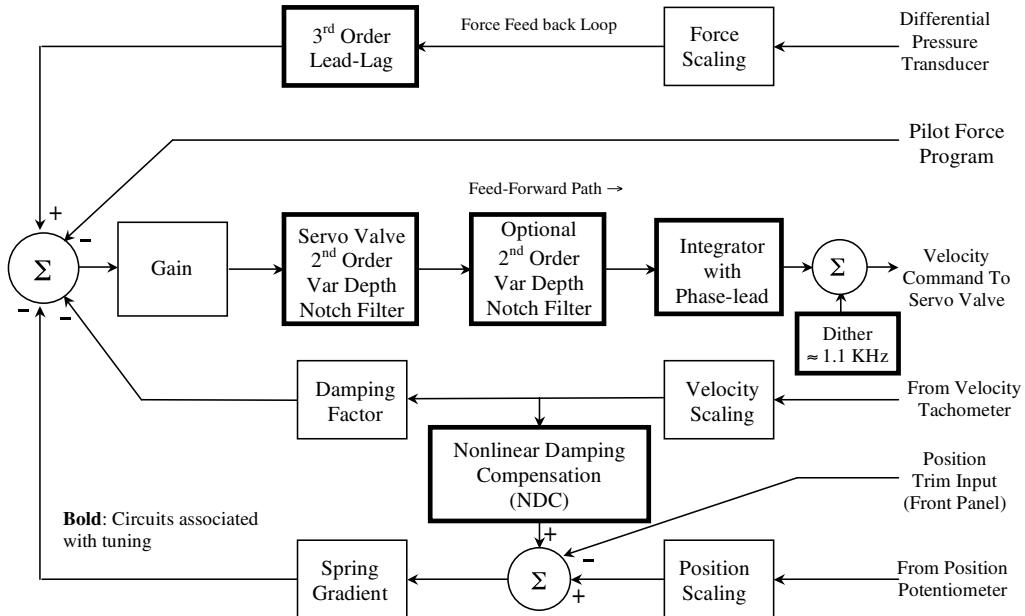


Fig. 10 McFadden analog controller functional diagram.

actuator dynamics have a nonlinear frequency roll-off that, however, can be compensated by improving the acceleration command to position output for the ideal model. This is accomplished by inserting a first-order phase-lead term into the acceleration command to velocity command integrator that is in the feed-forward path. The integrator with phase-lead function is used to convert the PCL actuator acceleration command to a velocity command and compensate for the high-frequency phase lag in the actuator dynamics.

The function shown in Eq. (3) replaces the simple integrator shown in Fig. 3 that generates velocity command. The lead term is used to provide phase compensation for the frequency roll-off of the PCL actuator. The application of this circuit will be described in more detail in Sec. VI.B:

$$(\tau s + 1)/\tau s \quad (3)$$

Notch filters suppress servo valve resonant frequencies and any other peak frequencies that occur where phase compensation is not practical. The second-order variable depth notch filter is used in place of a standard second-order notch filter to get the amplitude attenuation necessary while minimizing the phase lag at lower frequencies. The transfer function for the second-order variable depth notch filter is given by

$$\frac{\tau_n^2 s^2 + 2K_A \zeta \tau_n s + 1}{\tau_n^2 s^2 + 2\zeta \tau_n s + 1} \quad (4)$$

where  $K_A$  is the attenuation coefficient that is scaled from 0 to 1. A value, for example, of 0.5 would give a -6 dB attenuation at the

center frequency  $\omega_n$ , where  $\omega_n$  is equal to  $1/\tau_n$ . The damping ratio  $\zeta$  provides control over bandwidth. Figure 11 provides an example of various depth settings for a fixed value of  $\zeta$ .

The preceding sections explained hardware improvements to the PCL actuator. This was followed by an explanation of the tuning circuits that will be used for the final steps of optimizing PCL performance. With the frequency tuning circuits and improved transducers, we are ready to optimize PCL performance.

## VI. Optimizing Pilot Control Loader Performance

This section explains the tuning procedures for optimizing performance of the PCL. Each type of PCL is different in its requirements for tuning. What follows is a general guide that illustrates the principle behind the tuning procedure.

The pitch axis of a McFadden wheel and column assembly will be used to illustrate the optimization procedures. The procedures are the same for the roll axis or other types of McFadden PCLs. The phase-lead compensation required will vary for different PCL types due to slight differences in mechanical design.

### A. Setting Servo Valve Dither

Servo valve dither is used to eliminate servo valve stiction effects [4]. The first step is to check that hydraulic pressure and oil temperature are correct. Servo valve dither is set by looking at the differential pressure transducer output while adjusting both the frequency and amplitude of the dither signal that is fed directly to the servo valve input. The dither signal circuit generates a square wave

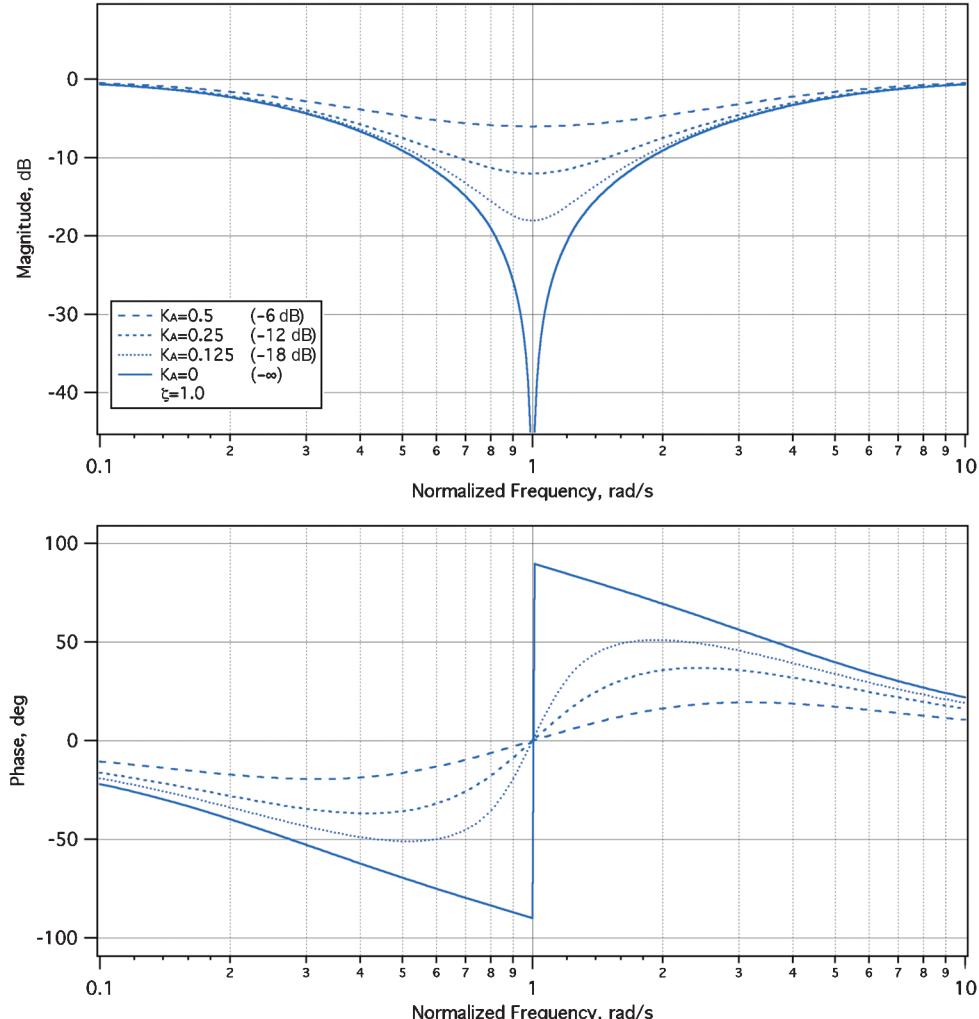


Fig. 11 Variable depth notch filter frequency response plots.

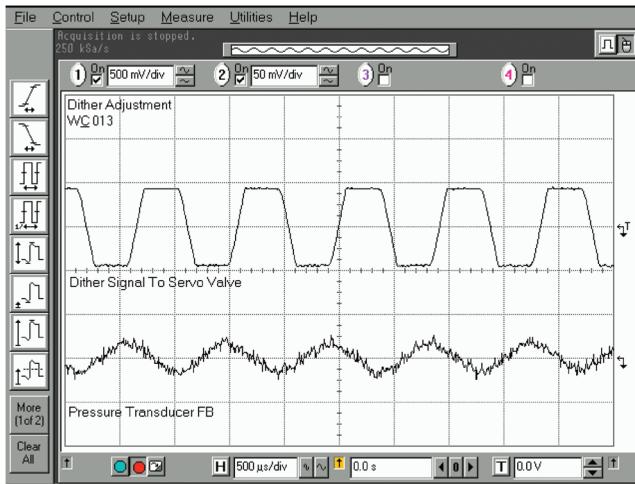


Fig. 12 Servo valve dither adjustment oscillosgraph.

for which the frequency range is from approximately 600 to 1.5 kHz and an amplitude adjustable to 1.5 V. First set the amplitude to 0.5 V, and then adjust the frequency until the differential pressure transducer shows a peak sinusoidal output. The peak will occur at the resonant frequency of the servo valve, which in the VMS system is approximately 1.1 kHz. Then adjust the dither square wave amplitude to obtain a 20 mV peak output on the differential pressure transducer output as illustrated in Fig. 12. If the input dither signal amplitude approaches 1 V peak, there is probably excessive stickiness within the servo valve and the performance of the valve is suspect. The ultimate test is to check the smoothness of the PCL with zero force conditions (limp stick mode). If the movement of the particular axis is smooth with no noticeable turnaround lag or stickiness, then the valve is operating correctly. In some situations, up to a 50 mV peak output on the differential pressure transducer may be necessary to obtain a smooth pilot control action. This should be the exception. If in doubt, a frequency response check of the servo valve should be performed.

#### B. Shaping Actuator Response

Shaping the overall actuator position to acceleration input response consists of setting the phase lead in the integrator with phase lead compensator in Fig. 10 so that the overall response of the integrator or acceleration command to the position potentiometer output is an approximation for a second-order integration. The ideal relationship between the position output and the acceleration command is a second-order integrator or  $1/s^2$  (Fig. 3). However, the

actuator dynamic position-to-velocity command has a frequency roll off typically in the 10–20 Hz range as illustrated in Fig. 13.

The amplitude slope and phase in Fig. 13 show a reasonable match with a pure integrator up to about 16.7 Hz where the amplitude is now 45 deg out of phase. To compensate, the integrator phase-lead corner frequency is set to 16.7 Hz, which gives +45° of phase lead at the same frequency. A frequency response of the position output to acceleration command input with the compensator is illustrated in Fig. 14.

The amplitude slope in Fig. 14 now shows a reasonable correlation with the ideal  $-40$  dB per decade of a  $1/s^2$  slope. The second-order 90° roll off is out to 26.0 Hz. The frequency response plot in Fig. 14 shows that the combination of the electronic integrator with phase lead and hydraulic actuator form a good approximation of a linear second-order system up to at least 10 Hz.

#### C. Shaping Force Feedback Open-Loop Response

Shaping the force feedback open-loop response is necessary so that the feed-forward path gain can be increased to maximize the natural frequency without causing instabilities. Optimal gain is achieved when further increases in the feed-forward gain do not cause any significant change in the natural frequency of the PCL.

The force feedback loop (Fig. 3) is the remaining loop when the damping factor and spring gradient are both set to zero in the McFadden analog controller. Shaping the force feedback open loop for optimum response consists of first plotting a baseline response (before any phase-lead compensation has been added) and then

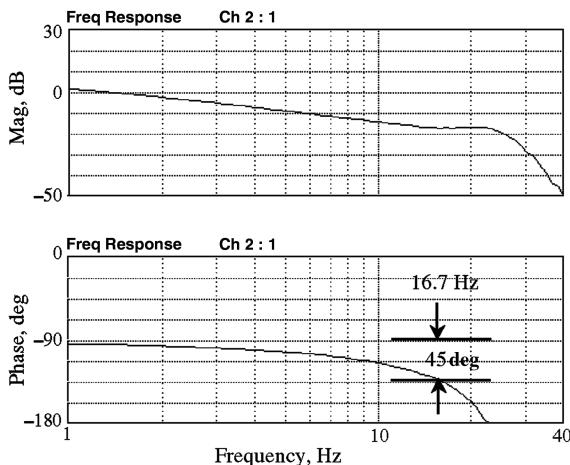


Fig. 13 Pitch position potentiometer output to velocity frequency response plot without compensation.

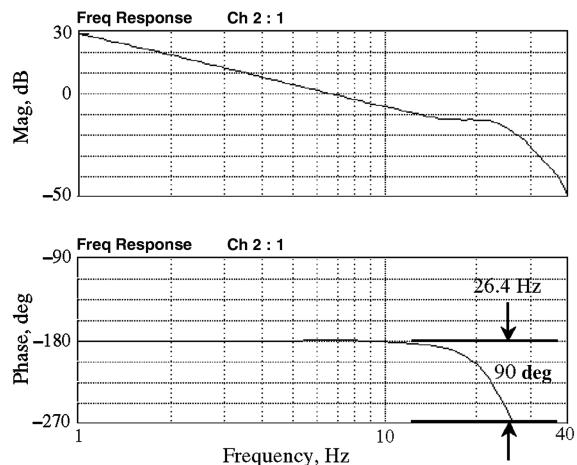


Fig. 14 Pitch position potentiometer output to acceleration command frequency response plot with compensation.

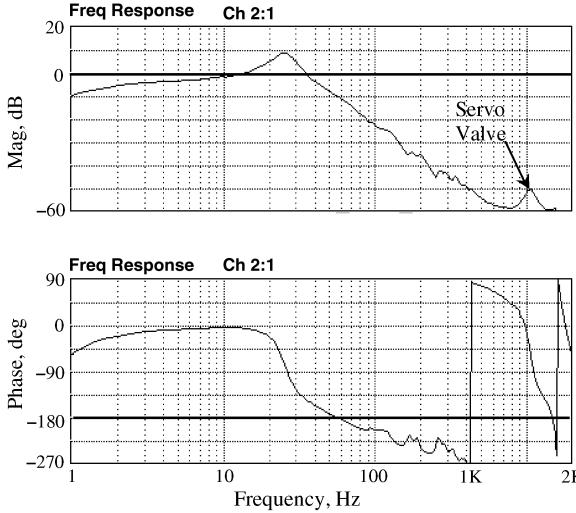


Fig. 15 Force feedback open-loop frequency response before tuning.

modifying the response to achieve the required performance. Measuring the force feedback open-loop response requires that the force gradient and damping factor, as shown in Fig. 3, be set to zero. However, the PCL position would drift so as to make this approach impractical. Instead, a small amount of force gradient and damping factor are used to keep the PCL centered and stable. This only affects the frequency response plot typically up to just a few Hertz. This is not a problem as the frequency range of interest for tuning starts at about 50 Hz and extends to about 1.5 kHz. This means that Bode plots represent the force feedback open-loop response.

A baseline frequency response plot (i.e., without frequency tuning) of the force feedback open loop is shown in Fig. 15. To ensure stability during this test, the loop gain is kept sufficiently low by decreasing the gain in the feed-forward path (Fig. 3). The example frequency response plot illustrated in Fig. 15 has the 0 dB and  $-180^\circ$  deg lines marked for reference. This plot shows that increasing the loop gain by about 10 dB will cause instabilities or oscillations around 55 Hz. A third-order lead-lag compensator will be used to improve the phase response between 55 and 400 Hz.

There is a resonant frequency at slightly over 1 kHz (Fig. 15), and the phase-lead compensation at lower frequencies will amplify this resonant frequency. Phase-lead compensation at this frequency is not practical because of the extreme phase lag roll-off. Therefore, a notch filter will be necessary to suppress this resonant frequency. Adding an ordinary second-order notch filter, with its significant phase lead

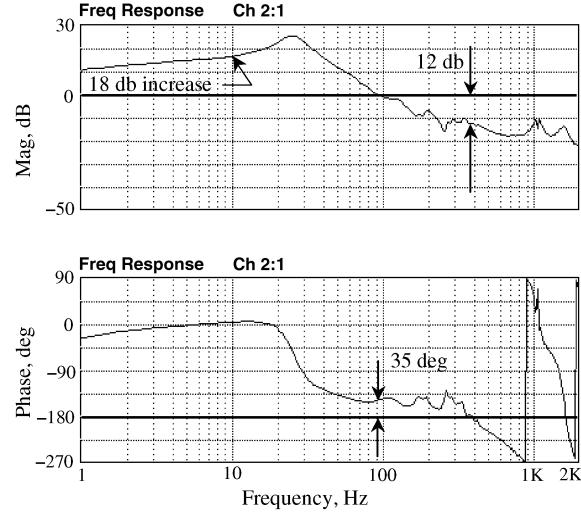


Fig. 16 Force feedback open-loop frequency response after tuning.

at lower frequencies, will counteract the phase-lead compensation. To minimize this effect, a variable depth notch filter of the form shown in Eq. (4) is used.  $K_A$  is an attenuation factor scaled from 0 to 1 and will not be determined until the phase-lead compensation has been added to the force feedback open-loop response and the resulting high frequency is measured. The second-order variable depth notch filter for the servo valve resonant frequency was set at 1.14 kHz with a coefficient of 2.0 for damping ratio and a notch depth  $K$  of 0.125 or  $-18$  dB.

The third order phase-lead compensator was set at  $135^\circ$  maximum at 400 Hz. In this example, all the phase lead of  $45^\circ$  deg for each first-order phase-lead compensator was applied at a single frequency of 400 Hz. For other PCL systems it has been necessary to apply first-order phase lead at different frequencies to properly shape the frequency response. After achieving the desired phase response, the gain in the feed-forward path is increased until there is no noticeable change in the natural frequency or mass of the pilot control. This is the optimal gain setting. The final force feedback open-loop frequency response, after applying the notch filter and third order phase-lead compensator, is shown in Fig. 16. Note the gain and phase margins of 12 dB and  $35^\circ$  deg, respectively. Also note that the force feedback open-loop amplitude response was increased by approximately 18 dB from the baseline Bode plot at 10 Hz. This increase in loop gain increases the natural frequency of the wheel and column pitch axis. Temporarily increasing the loop gain by another

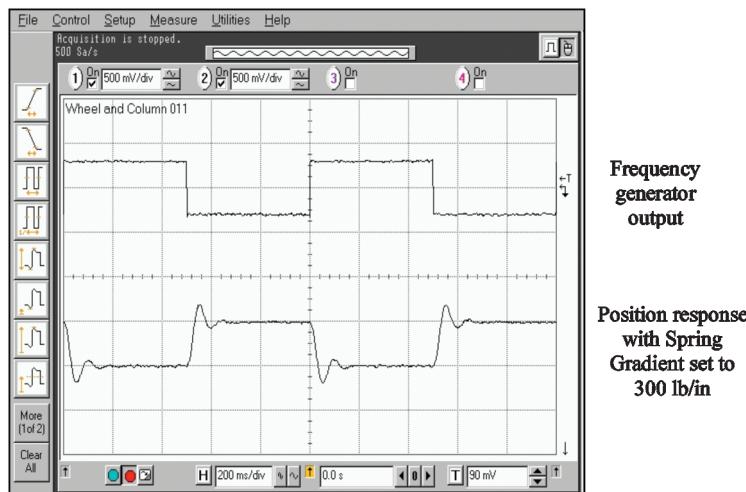


Fig. 17 Nonlinear damping factor position response example.

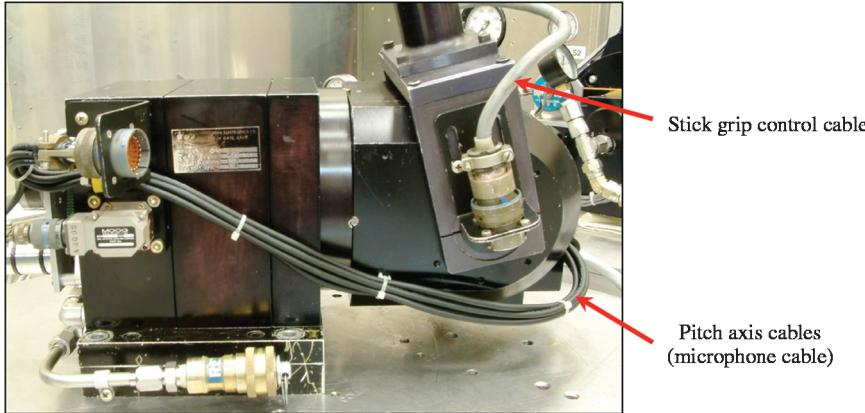


Fig. 18 Cyclic cable layout.

6 dB does not show any appreciable change in the natural frequency. Therefore, the final loop gain increase of 18 dB at 10 Hz is optimal and requires no further improvement.

#### D. Setting Nonlinear Damping Compensation

The purpose of the NDC, as shown in Fig. 10, is to provide the damping needed to stabilize the nonlinear circuits. This is accomplished by coupling some velocity feedback with position feedback. The damping factor used for the normal spring gradient setting may not be sufficient to keep the PCL stable when the nonlinear circuits, such as force breakout, friction, stiction, or the electrical stops, are used. These nonlinear circuits required very large spring gradients. The lack of sufficient damping will cause oscillations when the pilot control is in any one or combination of these nonlinear circuits. The amount of NDC required is small and does not cause any noticeable damping at low force gradients. But, when the NDC has been set properly, the high force gradients in the nonlinear functions also increase the coupled velocity feedback to provide sufficient damping.

The procedure for determining NDC is started by setting the spring gradient to 300 lb/in.. Connect a low-frequency square wave generator to the position trim input. Set the amplitude of the square wave and damping factor on the front panel of the McFadden analog controller to give approximately 2 in. of total travel of the pilot control. The NDC is adjusted until the position response is slightly underdamped as shown in Fig. 17. It might be tempting to set the NDC for a critically damped response but this will result in a poor simulation of a stop. An underdamped response, as shown in Fig. 17, gives a more crisp feeling. Another consideration is that a slightly underdamped response means a lower velocity feedback loop gain, which lowers the possibility of velocity loop oscillations.

When done properly, the end result is a smooth and noise-free operation of the pilot control when the nonlinear circuits are used. There is also an increase in the maximum spring gradient capability without adding any significant damping at low spring gradient settings.

This completes the tuning procedures. The pilot control should have smooth motion with no turnaround bump. The position output to acceleration command input should be a good approximation of a second-order integrator in the pilot's frequency response range, and the PCL should have the highest natural frequency capability for any spring gradient setting. Finally, the pilot control should be stable for any combination of nonlinear functions.

## VII. Other Improvements

### A. Cabling

The cabling used to interface the transducers and PCL controls (switches, buttons, etc.) with the outside world have produced some special problems of its own. Cables that must move with the control add additional problems as explained in the following sections.

#### 1. Cable Drag

This is a condition in which the movement of the control drags a cable around to follow its motion. An example would be the cable that connects to the grip control cable shown in Fig. 18. Cable drag can add additional force requirement to the control and is most noticeable when the control is programmed for low force conditions. Attaching the cable to the control at its axis can lower cable drag effects. This becomes more complicated for a two-axis control, but compromises can be made when the cable is very flexible as discussed next.

#### 2. Cable Stiffness

The stiffness of a cable can add additional forces to a pilot control if the cable is required to bend with the motion of the pilot control. This is particularly noticeable when the pilot control is programmed for low force conditions. The solution was to use an available microphone cable that was made to be extremely flexible so that it would lie flat on the floor as it followed the microphone user (Fig. 18).

### B. Vacuum System

The PCL uses hydrostatic bearings to provide a virtually friction-free motion. A vacuum recovery system is required for returning oil from the hydrostatic bearings to the hydraulic pump. If a vacuum pump is used with more than one actuator system (e.g., a fighter stick and a collective), then vacuum gauges should be installed at each actuator vacuum port. A vacuum gauge installed at the vacuum pump is not the same as a vacuum gauge installed at the actuator vacuum port because of the effect of oil in the return lines. It is best to install gauges at all vacuum ports and the vacuum pump.

If two or more PCL actuators are connected to a single vacuum pump, and the vacuum is not equal at each vacuum input port, it may be necessary to install needle valves to control the amount of oil flow from the actuator with the highest vacuum reading in order to improve the vacuum on the other actuators. This can be difficult, but it helps to have the needle valves located the same distance from each actuator.

It also helps to keep the vacuum return lines as short as possible and to locate the vacuum pump below the level of the actuators. In general, it takes a minimum of 5 in. of Hg vacuum at the input vacuum port on the PCL actuator for the recovering system to work properly. The vacuum pump itself should be able to draw close to 30 in. of Hg.

## VIII. Conclusions

Optimizing the performance of the PCLs used at the Vertical Motion Simulator has resulted in a greatly improved simulation capability. Improving the precision of the position and velocity feedback transducers allowed larger position and velocity loop gains and greater bandwidth in the PCL. Furthermore, increasing the maximum force gradient on all standard McFadden pilot control

loaders from 200 to 300 lb/in. has produced sharper force breakouts and stiffer simulated position stops. The McFadden rudder pedals can now achieve force gradients of 1000 lb/in.. An improved differential pressure transducer has minimized force drift and an improved servo valve has resulted in higher pilot control frequency response and smoother motion. Optimization of the analog controller tuning has enabled higher pilot control frequency bandwidth and larger natural frequencies. When combined, these improvements have resulted in pilot control simulations with better performance through greater pilot control natural frequencies and smoother and precise simulation of nonlinear functions.

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