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Pilot-Force Measurement with Inertia and Gravity Compensation

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Measuring pilot force on pilot control loaders used in flight simulators is difficult due to force errors introduced by pilot control loader inertia, simulator cab motion, and gravity. Attempts to correct this problem by using strain gauges near the grip handle or in gloves have proven impractical because the devices are sensitive to grip position. This paper describes a technique for measuring the pilot control loader pilot force with compensation for all inertial effects by incorporating an accelerometer located at a specific location for each particular pilot control loader axis. There are no additional requirements on the pilot, who is only required to operate the pilot control loader in a normal manner. The pitch axis on a McFadden wheel and column pilot control loader, used at the NASA Ames Research Center, was used to demonstrate the pilot-force measurement technique with compensation for inertial effects and gravity.

Nomenclature

a_{ACC}	=	accelerometer output, ft/s^2
F_A	=	actuator force, lb
F_{ACC}	=	accelerometer force, lb
F_C	=	Chatillon force-gauge output, lb
F_{FB}	=	force balance, lb
F_M	=	measured differential pressure transducer output force, lb
F_P	=	pilot force, lb
F_T	=	differential pressure transducer output force, lb
F_{TB}	=	differential pressure transducer output force bias, lb
g_{ACC}	=	accelerometer output, g
g_{OFFSET}	=	accelerometer output bias, g
I_A	=	pitch-column moment of inertia about the actuator axis, slug · ft^2
I_{CG}	=	pitch-column moment of inertia about the center of gravity, slug · ft^2
K	=	pressure-loop forward gain, V/V
l_A	=	actuator moment arm, ft
l_{ACC}	=	distance from actuator to accelerometer, ft
l_P	=	pilot moment arm, ft
l_{PCG}	=	distance from center of mass to applied pilot force, ft
l_{RCG}	=	distance from the actuator to the center of mass, ft
m	=	pitch-column mass slug
R_X	=	X-axis reaction force, lb
R_Z	=	Z-axis reaction force, lb
r_A	=	pitch-column radius of gyration about the actuator axis, ft
s	=	Laplace operator 1/s
T_A	=	torque about the actuator axis, lb · ft
T_{CG}	=	torque about the center of gravity, lb · ft
T_P	=	pilot torque about the center of mass, lb · ft
W	=	pitch-column weight, lb
θ	=	pitch-column angle from vertical radians

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I. Introduction

PILOT control loaders (PCLs) are commonly used in flight simulators to simulate the control forces a pilot would actually feel in the simulated vehicle due to air loads, feel devices, control surface actuators, and so forth. It is usually necessary to be able to measure the actual pilot forces used during a simulation because many aircraft handling-quality requirements specify pilot-force characteristics. Getting accurate force measurements with a force sensor or wired gloves [1] at or near the pilot grip is difficult, because the sensor is sensitive to the manner is which the grip is held. PCL drive torque is also commonly used as a measure of pilot force, but it is subject to inertia and gravity errors.

To provide compensation for the inertia and gravity errors, an accelerometer circuit was developed and installed on the pitch axis of a McFadden wheel and column assembly, as shown in Fig. 1. The circuit, comprising an integrated-circuit accelerometer and discrete components, was used to verify the concept of acceleration measurement compensation for the inertial and gravity effects in pilot-force measurement. A commercial accelerometer assembly was used for the final hardware configuration.

This paper describes a technique developed at the NASA Ames Research Center's Flight Simulation Laboratories for measuring pilot force in a pilot control loader (inceptor) using acceleration measurements. A brief description of the force-feedback control system used in the McFadden PCL is presented first. This is followed by an equation-of-motion analysis to provide the concept for the design and an explanation of the pilot-force circuit. Next, there is an explanation of how to establish the calibration and location for the accelerometer. An analog accelerometer test circuit is created to implement the inertia and gravity compensation, and the results of pitch-axis compensation for a McFadden wheel and column assembly are then presented. There is a discussion on the use of a commercial accelerometer and a final discussion on gravity and inertial force compensation as applied to the rudder pedals and collective.

II. Force-Feedback McFadden Pilot Control Loader

A simplified model for a single-axis McFadden PCL is shown in Fig. 2. Servo valve and actuator dynamics are represented as an ideal hydraulic actuator by the 1/s inside the PCL column block. The torque sensor block sums the pilot force with all acceleration and gravity forces. These two blocks represent the pilot control loader pitch-axis hardware. All of the other blocks are located in the McFadden analog controller. This model is used for all McFadden

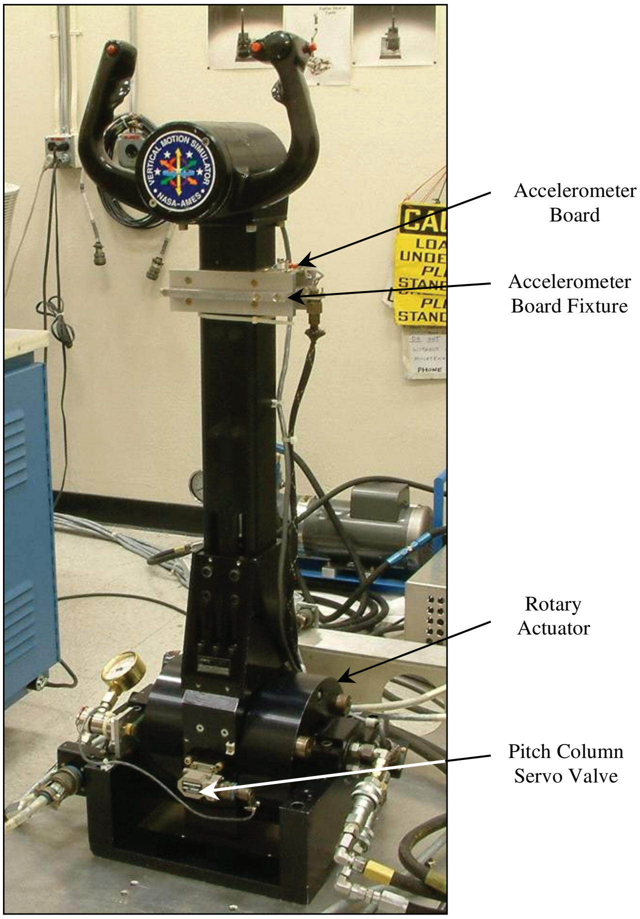

Fig. 1 Front oblique view of wheel and column showing the test accelerometer board fixture and servo valve locations.

pilot control loaders and includes the roll and pitch axis of a wheel and column, roll and pitch axis of a cyclic (or stick), roll and pitch axis of a hand controller, thrust axis of a collective, and yaw axis of rudder pedals. If the low-frequency compensation has been carefully done, this model holds well for frequencies up to about 30 Hz, depending on the particular McFadden pilot control loader. Attached to the PCL column is an accelerometer for which the output goes to the pilot-force circuit and is not used in any feedback loop.

McFadden PCLs normally obtain the pilot force by the use of a differential pressure transducer located at the base of the actuator. This transducer outputs all forces for the particular PCL axis, which includes the pilot force and all forces due to inertial effects and gravity, as implied by "all accelerations and gravity input" in Fig. 2. The transducer output becomes the force feedback. Also included (but not shown because the effects are negligible) are internal PCL viscous damping, spring gradient, and friction. There is virtually no friction effect because these actuators use hydrostatic bearings. Therefore, for all practical purposes, the total force feedback consists of pilot, cab-motion inertial, PCL inertial, and gravity forces. Force biases are neglected for the moment.

The force command shown in Fig. 2 is the sum total of all feedback force effects. These include the force feedback (pilot-force input, gravity, and all acceleration effects), damping force, and spring force. The acceleration effects include PCL motion and cab motion. The force command creates the acceleration command when scaled by the forward-loop gain K. The forward-loop gain K is used to vary the natural frequency of the pitch axis. The spring gradient and damping factor are not affected by this circuit gain.

Ignoring gravity and motion effects for the moment, actuator action occurs when the pilot inputs a force to create a force command. This, in turn, creates an acceleration command and is integrated to create a velocity command to the actuator servo valve to cause actuator motion. Steady-state zero motion (zero-velocity feedback) occurs when the spring force matches the force-feedback command and the acceleration and velocity commands are both zero. The spring gradient and damping factor blocks can be replaced by additional circuitry or computer (force-shaping computer) to create both linear and nonlinear effects that are required for pilot control loader force simulation and include force breakout, friction, stiction, electrical stops, dead zone, and so on. Figure 2 shows that gravity and cab-motion effects are both treated as force commands, no different from the pilot-force input. The pilot-force circuit presented in this paper will remove gravity and cab- and column-motion inertia effects from the force commands to give pilot force. Cab motion is not a serious problem for a lightweight control, but is significant for the heavier cyclic and wheel and column.

III. Analysis

Referring to Fig. 3, a test accelerometer was mounted to the PCL at a random location, l_{ACC}. Its axis is perpendicular to the pitch-column

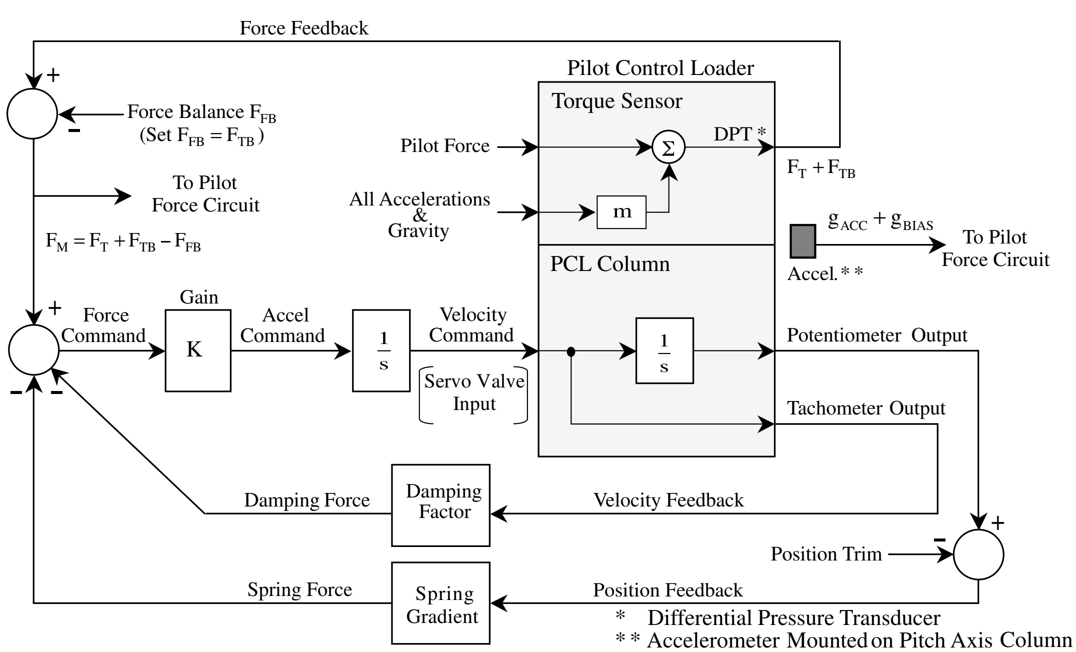

Fig. 2 Simplified McFadden PCL force-feedback translational model for a single axis.

vertical to measure tangential accelerations along the X axis. The equation of motion about the center of gravity for the pilot control loader pitch axis shown in Fig. 3 is

$$\sum T_{\mathrm{CG}} = \mathbf{I}_{\mathrm{CG}}\ddot{\theta} \tag{1}$$

Equation (1) can be expanded to

$$\mathbf{I}_{\mathrm{CG}}\ddot{\theta} = \text{pilot torque} + \text{actuator torque} + \text{reactive force torque} \tag{2}$$

The pilot torque and reactive torque are the torques about the center of mass due to forces F_P and R_X, respectively. The moment arm for R_Z is zero. The actuator torque is the torque about the actuator axis.

From Fig. 3, Eq. (2) can be rewritten as

$$\mathbf{I}_{\mathrm{CG}}\ddot{\theta} = l_{\mathrm{PCG}}F_P + T_A + l_{\mathrm{RCG}}R_X \tag{3}$$

An accelerometer at the center of gravity and aligned along the x axis will measure the following external forces:

$$F_{\mathrm{ACC}} = m a_{\mathrm{ACC}} \tag{4}$$

$$F_{\mathrm{ACC}} = F_P - R_X \tag{5}$$

Solving for the accelerometer output gives

$$a_{\mathrm{ACC}} = \frac{F_P - R_X}{m} \tag{6}$$

Moving the accelerometer to the location l_{ACC} (which will provide inertial and gravity compensation) gives

$$a_{\mathrm{ACC}} = \frac{F_P - R_X}{m} + (l_{\mathrm{ACC}} - l_{\mathrm{RCG}})\ddot{\theta} \tag{7}$$

Solving for the reaction force gives

$$R_X = F_P - m a_{\mathrm{ACC}} + (l_{\mathrm{ACC}} - l_{\mathrm{RCG}})m\ddot{\theta} \tag{8}$$

Substituting Eq. (8) into Eq. (3) gives

$$\mathbf{I}_{\mathrm{CG}}\ddot{\theta} = l_{\mathrm{PCG}}F_P + T_A + l_{\mathrm{RCG}}[F_P - m a_{\mathrm{ACC}} + (l_{\mathrm{ACC}} - l_{\mathrm{RCG}})m\ddot{\theta}] \tag{9}$$

Rearranging gives

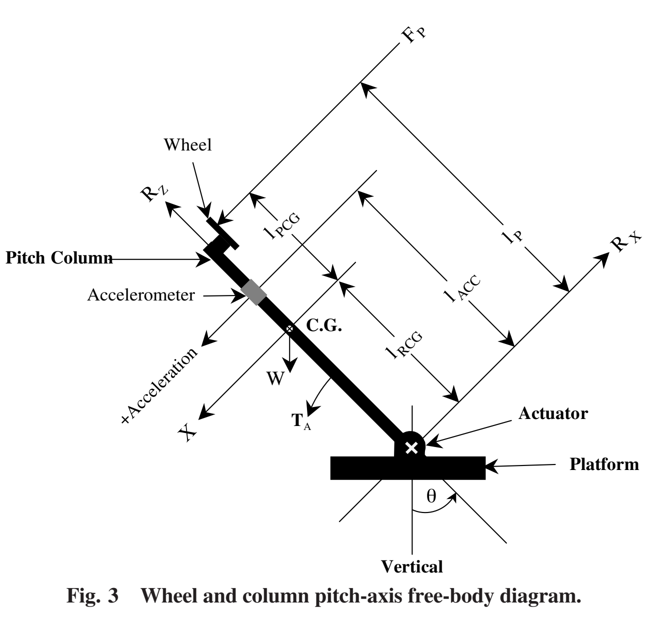

Fig. 3 Wheel and column pitch-axis free-body diagram.

$$(l_{\mathrm{PCG}} + l_{\mathrm{RCG}})F_P = -T_A + l_{\mathrm{RCG}} m a_{\mathrm{ACC}} + [\mathbf{I}_{\mathrm{CG}} - (l_{\mathrm{ACC}} - l_{\mathrm{RCG}})l_{\mathrm{RCG}} m]\ddot{\theta} \tag{10}$$

The pilot torque moment-arm length can be expressed as

$$l_P = l_{\mathrm{PCG}} + l_{\mathrm{RCG}} \tag{11}$$

Then solving for pilot torque gives

$$l_P F_P = -T_A + l_{\mathrm{RCG}} m a_{\mathrm{ACC}} + [\mathbf{I}_{\mathrm{CG}} - (l_{\mathrm{ACC}} - l_{\mathrm{RCG}})l_{\mathrm{RCG}} m]\ddot{\theta} \tag{12}$$

$$l_P F_P = -T_A + l_{\mathrm{RCG}} m a_{\mathrm{ACC}} + (\mathbf{I}_{\mathrm{CG}} + l_{\mathrm{RCG}}^2 m - l_{\mathrm{ACC}} l_{\mathrm{RCG}} m)\ddot{\theta} \tag{13}$$

The moment of inertia of the pitch column about the actuator is

$$\mathbf{I}_A = \mathbf{I}_{\mathrm{CG}} + l_{\mathrm{RCG}}^2 m = r_A^2 m \tag{14}$$

Substituting Eq. (14) into Eq. (13) gives

$$l_P F_P = -T_A + l_{\mathrm{RCG}} m a_{\mathrm{ACC}} + (r_A^2 m - l_{\mathrm{ACC}} l_{\mathrm{RCG}} m)\ddot{\theta} \tag{15}$$

And solving for pilot force gives

$$F_P = -\frac{T_A}{l_P} + \frac{l_{\mathrm{RCG}}}{l_P} m a_{\mathrm{ACC}} + \left(\frac{r_A^2 - l_{\mathrm{ACC}} l_{\mathrm{RCG}}}{l_P}\right) m\ddot{\theta} \tag{16}$$

The actuator torque is

$$T_A = F_A l_A \tag{17}$$

Substituting Eq. (17) into Eq. (16) gives

$$F_P = -F_A \frac{l_A}{l_P} + \frac{l_{\mathrm{RCG}}}{l_P} m a_{\mathrm{ACC}} + \left(\frac{r_A^2 - l_{\mathrm{ACC}} l_{\mathrm{RCG}}}{l_P}\right) m\ddot{\theta} \tag{18}$$

Defining the expression $F_A(l_A/l_P)$ to be the force output F_T, Eq. (18) therefore becomes

$$F_P = -F_T + \frac{l_{\mathrm{RCG}}}{l_P} m a_{\mathrm{ACC}} + \left(\frac{r_A^2 - l_{\mathrm{ACC}} l_{\mathrm{RCG}}}{l_P}\right) m\ddot{\theta} \tag{19}$$

Let

$$\frac{l_{\mathrm{RCG}}}{l_P} m a_{\mathrm{ACC}} + \left(\frac{r_A^2 - l_{\mathrm{ACC}} l_{\mathrm{RCG}}}{l_P}\right) m\ddot{\theta} = F_{\mathrm{ACC}} \tag{20}$$

Substituting Eq. (20) into Eq. (19) gives the equation for the pilot-force circuit:

$$F_P = -F_T + F_{\mathrm{ACC}} \tag{21}$$

The pilot force Eq. (19) can be implemented when the following conditions have been met: 1) calibrating the differential pressure transducer, which measures F_T, after force balancing ($F_{\mathrm{TB}} = F_{\mathrm{FB}}$); 2) scaling the accelerometer, which establishes the value for $(l_{\mathrm{RCG}}/l_P)m$; and 3) locating the accelerometer that sets $l_{\mathrm{ACC}} = r_A^2/l_{\mathrm{RCG}}$ to eliminate the $\ddot{\theta}$ inertial term in Eqs. (19) and (20).

IV. Pilot-Force Circuit

The pilot-force circuit was implemented using Eq. (21) and is illustrated in Fig. 4. The output of the accelerometer g_{ACC} is scaled in units of g (32.2 ft/s^2) and is biased to half-scale. The bias and scale block removes the bias term and rescales g_{ACC} to a_{ACC} in ft/s^2. The term $(l_{\mathrm{RCG}}/l_P)m$ in the second block is the coefficient associated with the second term on the right side in Eq. (19). The output F_P is an open-loop measurement and is not fed back to close any feedback loop or used for pilot-force shaping. Therefore, the pilot-force circuit cannot affect the stability of the PCL.

V. Implementing the Pilot-Force Circuit

The test fixture that holds the accelerometer circuit shown in Fig. 1 can be mounted anywhere on the pitch column. The axis of the accelerometer must be set perpendicular to the pitch-column axis and the correct sign of the accelerometer output will be determined during scaling.

A. Calibrating the Differential Pressure Transducer

Force calibration of the differential pressure transducer output F_M (see Fig. 2) is done by first setting the pilot control loader pitch axis to vertical, using position trim with a high force gradient (spring coefficient). With $F_P = 0$, F_T should also be zero in the vertical position. First adjust the force balance, shown in Fig. 2, on the McFadden controller to give a zero output ($F_{\mathrm{FB}} = F_{\mathrm{TB}}$) for F_M, which removes the bias term F_{TB}. Under these conditions, Eq. (19) reduces to

$$F_P = -F_T \quad \text{where } a_{\mathrm{ACC}} = 0, \qquad \ddot{\theta} = 0 \tag{22}$$

Second, a value of F_P is applied using an external force gauge to the pilot control, and the gain on the differential pressure transducer is adjusted to give the correct F_T scaling. The preceding steps are part of the normal PCL calibration process.

B. Scaling the Accelerometer

Scaling the accelerometer consists of first setting the pilot control loader pitch axis to some angle θ. This is done by setting in a zero force gradient and turning off all other force effects except for the electrical stops and turning off the gravity-compensation circuit if there is one is use. This is only so that gravity can be used to make the pilot control come to rest against the electrical stop.

With the pitch axis held steady at a pitch angle θ, Eq. (19) reduces to

$$0 = -F_T + \frac{l_{\mathrm{RCG}}}{l_P} m a_{\mathrm{ACC}} \quad \text{where } F_P = 0, \qquad \ddot{\theta} = 0$$
$$a_{\mathrm{ACC}} = g \sin \theta_C \tag{23}$$

With F_T calibrated, the accelerometer scale factor or gain $(l_{\mathrm{RCG}}/l_P)m$ shown in Fig. 4 and Eq. (23) is adjusted until the output is satisfied (the pilot-force output F_P is equal to zero). Because the PCL is not moving, the accelerometer is only reading effects due to gravity. Adjusting the gain in this static position will simultaneously compensate for gravity affects and scale the accelerometer for inertial forces. If the signs of the accelerometer and differential pressure transducer inputs to the pilot-force circuit are different, change the sign of the accelerometer output from the accelerometer test circuit. The vertical location of the accelerometer on the stick is not important at this point because the accelerometer gives the same reading regardless of location. This scaling procedure avoids having to determine m, l_{RCG}, and l_P values.

C. Locating the Accelerometer

The final step is to determine the accelerometer location. First set in a force gradient, damping factor, and position trim that will bring the pilot control to its center of travel position. It is not necessary to set the pilot control arm to a vertical position. Connect a sinusoidal generator to the position trim input on the McFadden analog controller. Set the pilot control loader pitch axis into a low-frequency oscillation (e.g., 2 to 3 Hz) with an amplitude that stops just short of either electrical stop. Under these conditions, Eq. (19) reduces to

$$0 = -F_T + \frac{l_{\mathrm{RCG}}}{l_P} m a_{\mathrm{ACC}} + \frac{r_A^2 - l_{\mathrm{ACC}} l_{\mathrm{RCG}}}{l_P} m \ddot{\theta} \quad \text{where } F_P = 0 \tag{24}$$

The second term on the right side, $(l_{\mathrm{RCG}}/l_P)m$, corrects for both gravity and inertial force errors in the differential pressure transducer output F_T once the accelerometer location l_{ACC} has been set. The accelerometer location l_{ACC} is adjusted until the pilot-force-circuit output is zero. By moving the accelerometer up or down the column, the accelerometer output is altered to compensate for acceleration due to inertial force $m r_A^2 \ddot{\theta}$ of the pilot control. When r_A^2 equals $l_{\mathrm{ACC}} l_{\mathrm{RCG}}$, the pilot-force-circuit output will go to zero. Because the accelerometer gain $(l_{\mathrm{RCG}}/l_P)m$ was not changed, the pilot-force circuit is now compensating for both gravity and inertial affects. This completes the adjustments of the pilot-force circuit and Eq. (19) now becomes

$$F_P = -F_T + \frac{l_{\mathrm{RCG}}}{l_P} m a_{\mathrm{ACC}} \quad \text{when } l_{\mathrm{ACC}} = \frac{r_A^2}{l_{\mathrm{RCG}}} \tag{25}$$

The accelerometer is at its final location. Examine the pilot-force-circuit output F_P at different frequencies to confirm the location. The pilot-force-circuit output should remain at zero for all frequencies within both the pilot and simulator cab frequency range. A small error may remain, but this is due to internal viscous damping and possibly the pitch column not being perfectly balanced over center. As it was for the accelerometer scaling procedure, this accelerometer location technique avoids having to determine r_A and l_{RCG} values.

VI. Wheel and Column Test Setup

Figure 1 shows a McFadden wheel and column outfitted with an accelerometer test fixture mounted on a testbed (platform for testing McFadden actuators). The accelerometer board fixture allows simple vertical adjustment of the accelerometer board to find the proper location for the accelerometer. The fixture, despite its appearance, does not add any appreciable mass to the pitch column. In this front oblique view, the pitch-column servo valve can be seen at the bottom of the assembly. The pitch-column differential pressure transducer is located on the backside at the bottom of the assembly and is not visible in Fig. 1.

Figure 5 shows a close-up of the accelerometer test board with the ADXL05 accelerometer. The axis of the accelerometer is aligned with the pitch-column motion. The use of 1% resistors provides for a sufficiently precise scale-factor setting, and a potentiometer is used to set the bias voltage. Whereas the test board is a relatively large assembly, commercial versions containing all components are available in considerably smaller packages. An example of a commercial version is described later in this paper.

VII. Confirming the Pilot-Force Circuit

To confirm that the pilot-force circuit really does generate pilot force, apply force to the pitch column at the pilot grip position with an external force gauge, as shown in Fig. 6, and compare this with the pilot-force-circuit output. The pilot grip position or pilot torque

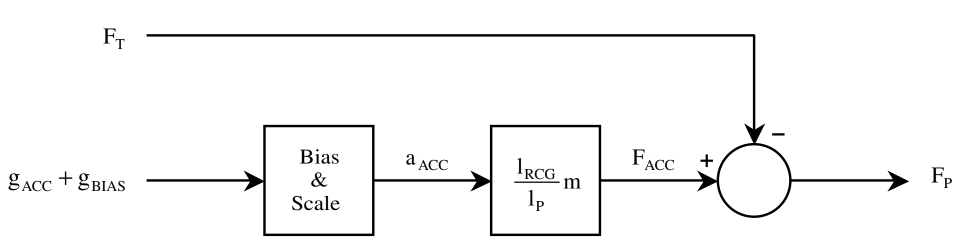

Fig. 4 Pilot-force circuit.

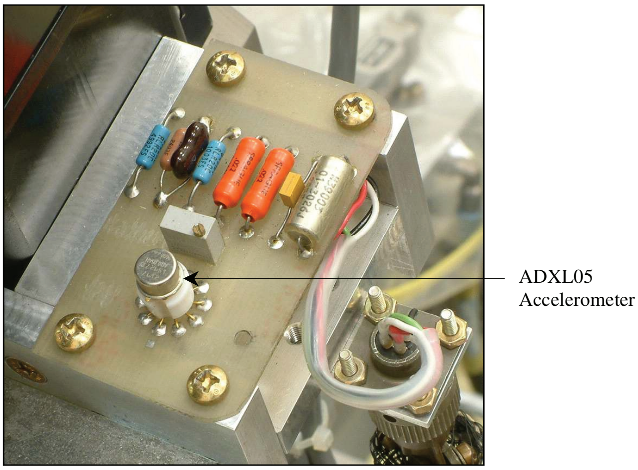

Fig. 5 Test accelerometer board.

moment arm is defined as the distance from the pitch axis to the pilot's middle finger on the grip. The external force gauge used for this test is a Chatillon model DFGS50, which has an analog output signal. A storage oscilloscope was used to capture the external force-gauge test signal F_C, the pilot-force-circuit output F_P, the differential pressure transducer force F_T, and the accelerometer force F_{ACC} [Eq. (20)].

Fig. 6 Handheld external force-gauge measurement.

For this particular test, the PCL was configured for a simple force gradient. However, testing with any of the nonlinear characteristics, such as force breakout or friction, could also be done. The external force-gauge output was directly connected to a storage oscilloscope. An approximately 1-Hz motion was applied with the force gauge for a few seconds and then suddenly removed (hands-off). This is representative of pilot inputs during a critical maneuver such as flare. For this test, the pilot control was held forward of the center position because the force gauge was not mechanically connected to the pilot grip to push and pull simultaneously.

Figure 7 shows the results of testing with the external force gauge. The top trace is the external force-gauge signal output F_C. The second trace is the output F_P of the pilot-force circuit. The third trace is the total force output F_T from the differential pressure transducer, and the fourth trace is the accelerometer output F_{ACC} after scaling to force. All forces are scaled to 12.5 lb per vertical division. The pilot-force-circuit output is the difference between the differential pressure transducer and the scaled accelerometer outputs. Note that when the force gauge is removed from the pilot control (denoted by hands-off), both the force gauge and pilot-force circuit show a zero force output, whereas the differential pressure transducer output F_T shows both gravity and inertial force effects.

The improvement in pilot-force measurement that the pilot-force circuit provides depends on the mass of the pilot control, the frequency of the column input, and the cab-motion effects. Considerable improvement is made when the pilot control mass is high, as it is with the wheel and column pitch axis. Compare the top two traces in Fig. 7. There is very little difference between the handheld force gauge and the pilot-force-circuit output. Compare either of these two traces to the third trace, the differential pressure transducer output F_T. Here, a considerable difference is seen. F_T is normally used to represent pilot force. A measure of the pilot-force error in F_T is seen in the last trace F_{ACC}, which is the accelerometer output scaled to force. It represents the error between the differential pressure transducer output force output F_T and the pilot force F_P. Note that when the external force gauge is removed from the pilot control (hands-off or $F_P = 0$), F_{ACC} and F_T match. Obviously, lower mass pilot controls and lower input frequencies will have less error.

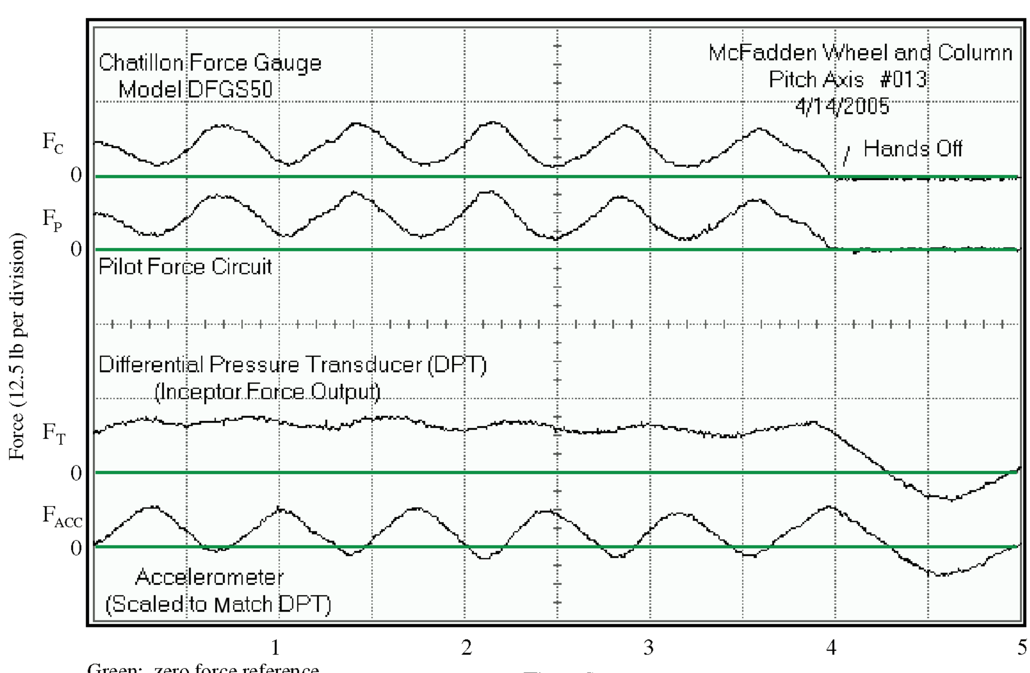

Fig. 7 Oscillograph of force measurements.

VIII. Using a Commercial Accelerometer

A commercial Crossbow accelerometer (model CXL04LP1) was purchased and installed to replace the test accelerometer and is shown in Fig. 8. The Crossbow accelerometer uses the same technology as the Analog Devices (model ADXL05) accelerometer so that the same signal-conditioning circuit can be used. However, the scaling for the Crossbow accelerometer is different, and it was necessary to change the scaling in the pilot-force circuit to reflect this.

IX. Additional Notes

A. Setting the Vertical Position

The PCL pitch-column nominal position was set to vertical during force scaling and dynamic testing. During calibration, the column itself may or may not be vertical. In other words, the pitch column is in a vertical position when it is in mechanical balance over center. However, just setting the pitch column to visual vertical gave good results, especially when considering that it would be somewhat difficult to determine the exact mechanical balance position. This must be done with the hydraulic supply turned off and fluid removed from the actuator. This much simpler approach is preferable when there is only a small error, if any, introduced by simply making the accelerometer axis perpendicular to the pitch-column visual vertical.

B. Application to Rudder Pedals

The distance from the actuator to the accelerometer, as stated in Eq. (25), is

$$l_{\mathrm{ACC}} = \frac{r_A^2}{l_{\mathrm{RCG}}} \tag{26}$$

This means that a single translational accelerometer would not work directly on rudder pedals (or a wheel), where the center of gravity is at its axis of rotation and hence l_{RCG} is equal to zero. It would be necessary to install either a rotational or two translational accelerometers. A rotational accelerometer would only require scaling while oscillating the rudder pedals. Translational accelerometers would be installed on each rudder pedal arm perpendicular to each arm but facing in opposite directions. In this manner, the sum of the two accelerometers would cancel translational accelerations and gravity, but not angular accelerations. The pilot-force circuit shown in Fig. 4 for the pitch column would have to be modified slightly to sum the outputs of both accelerometers. The accelerometers may be located at any equal distance from the axis of rotation and then scaled by oscillating the rudder pedals and adjusting the circuit gain until the pilot-force-circuit output is zero.

C. Application to Collective

Application of the pilot-force circuit to a collective is not as straightforward as the wheel and column pitch-axis example. The collective arm cannot be conveniently set to a vertical position to establish the force-balance value F_{FB} (see Fig. 2) to null out F_{TB}. A two-point measurement process, as illustrated in Fig. 9, will provide sufficient data to calculate the correct differential pressure transducer outputs T_{P1} and T_{P2} for both angular positions θ_1 and θ_2. The force-balance potentiometer can then be adjusted to give the correct output at either of the positions. The collective can then be moved to the other position as a check to see that the computation and adjustment are correct.

Fig. 8 Commercial accelerometer installation.

1. Analysis

With the collective arm at its first location θ_1 and not on a mechanical stop (e.g., near full lift), the differential pressure transducer output from Eq. (19) is

$$F_{T1} = \frac{l_{\mathrm{RG}}}{l_P} mg \sin\theta_1 \quad \text{where } \theta = \theta_1, \qquad F_P = 0$$
$$a_{\mathrm{ACC}} = g \sin\theta_1 \tag{27}$$

From Fig. 2:

$$F_{T1} = F_{M1} - F_{\mathrm{TB}} + F_{\mathrm{FB}} \tag{28}$$

Substituting Eq. (28) into Eq. (27) gives

$$F_{M1} = +\frac{l_{\mathrm{RCG}}}{l_P} mg \sin\theta_1 + F_{\mathrm{TB}} - F_{\mathrm{FB}} \tag{29}$$

Similarly, with the collective arm at its second location θ_2 and not on a mechanical stop (e.g., near minimum lift), the differential pressure transducer output is

$$F_{T2} = \frac{l_{\mathrm{RG}}}{l_P} mg \sin\theta_2 \quad \text{where } \theta = \theta_2, \qquad F_P = 0$$
$$a_{\mathrm{ACC}} = g \sin\theta_2 \tag{30}$$

From Fig. 2:

$$F_{T2} = F_{M2} - F_{\mathrm{TB}} + F_{\mathrm{FB}} \tag{31}$$

Substituting Eq. (31) into Eq. (30) gives

$$F_{M2} = +\frac{l_{\mathrm{RCG}}}{l_P} mg \sin\theta_2 + F_{\mathrm{TB}} - F_{\mathrm{FB}} \tag{32}$$

Subtracting Eq. (29) from Eq. (32) gives

$$F_{M2} - F_{M1} = \frac{l_{\mathrm{RCG}}}{l_P} mg(\sin\theta_2 - \sin\theta_1) \tag{33}$$

Solving for the gravity-force term in Eq. (33) gives

$$\frac{l_{\mathrm{RCG}}}{l_P} mg = \frac{F_{M2} - F_{M1}}{\sin\theta_2 - \sin\theta_1} \tag{34}$$

Substituting Eq. (34) into Eqs. (27) and (30) gives

$$F_{T1} = (F_{M2} - F_{M1}) \frac{\sin\theta_1}{\sin\theta_2 - \sin\theta_1} \quad \text{for } \theta = \theta_1 \tag{35}$$

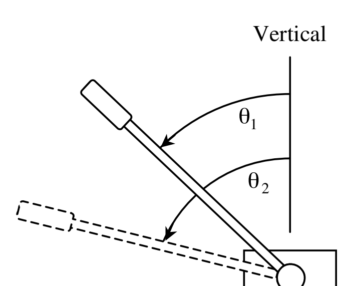

Fig. 9 Collective two-point measurement.

$$F_{T2} = (F_{M2} - F_{M1}) \frac{\sin\theta_2}{\sin\theta_2 - \sin\theta_1} \quad \text{for } \theta = \theta_2 \tag{36}$$

Equations (35) and (36) represent the differential pressure transducers outputs for two collective arm positions when the collective arm is balanced at vertical.

2. Procedure

First, calibrate the collective differential pressure transducer output as would normally be done with the collective arm typically at its center of travel and setting the force balance in Fig. 2 on the McFadden controller to remove any F_M force bias. The collective arm is now balanced at its center of travel. Then use position trim and a high force gradient on the McFadden controller to move the control arm to near the upper end of travel. In this first position, measure the differential pressure transducer output as F_{M1} and its angular position from vertical as θ_1. Now move the collective arm using the position trim to a position near the other stop. In this second position, measure the differential pressure transducer output as F_{M2} and its angular position from vertical as θ_2. Calculate the correct differential pressure transducer output for each position using Eqs. (35) and (36).

With the collective arm still at the second position, adjust the force-balance potentiometer on the McFadden controller to give the force readout calculated by Eq. (36). As a check, move the collective arm to θ_1 and check to see that the force readout matches the value calculated with Eq. (35). The end result is that the collective is now balanced for a collective arm at vertical. With the collective arm balanced for vertical, there will, of course, be a gravity-force effect in its normal center of travel position. This can be corrected with a gravity-compensation circuit in the force shaping computer. As a side note, the measured values F_{M1} and F_{M2} and the angles θ_1 and θ_2 can be used to calculate the accelerometer scale factor $(l_{\mathrm{RCG}}/l_P)mg$ in Eq. (34).

X. Conclusions

Acceleration measurement is a technique that can be used to remove gravity and all inertial effects from the differential pressure transducer output of a McFadden PCL allowing for a true pilot-force measurement. The practical application used in this report is the pitch column on a McFadden wheel and column PCL, which has a relatively high mass. Because this technique does not involve strain gauges near or in the pilot grip or gloves, the pilot can handle the pilot controls in a normal fashion. Good compensation can be obtained even when the accelerometer is not exactly at the correct location. The technique used to scale and locate the accelerometer avoids determining several unknown parameters, making the implementation of acceleration measurement simple and straightforward.

Reference

[1] Morgan, G. A., "A Device for Measurement of Control Column Forces in Aircraft," Aircraft Research and Development Unit, Rept. ADA140876, Edinburgh, Australia, Mar. 1984.