oriented such that the plane of its dihedral angle with the horizontal is always vertical [i.e., the control fins are in the plus (+) configuration].

The results for the MK-84 bombs with the guidance law implemented are as shown in Fig. 2. In summary, the circular error probable (CEP) for the MK-84 was 82.9 ft uncontrolled and 9.1 ft controlled. Similar simulations for the smaller MK-82 bombs resulted in comparable numbers. The CEP for the MK-82 was 79.4 ft with no control and 8.1 ft controlled.

Conclusions and Remarks

The model reference adaptive control algorithm was successfully utilized for guidance and control of iron bombs from release to impact. The results of the present simulations indicate that it is possible to terminally guide bombs with relatively inexpensive instrumentation, independent of the aircraft flight control system. Furthermore, the error of dispersion is reduced tremendously, thus creating an attractive means of solving the problem of random effects on bombs released from aircraft. The same algorithm will apply to other release conditions (such as toss or dive bombing) just as well; however, it might involve more complex mathematics and, thus, require more computations.

Acknowledgments

The various valuable suggestions of the reviewers are thankfully acknowledged.

References

[1]Ausman, J. S., "Dispersion and Separation Disturbances for MK-82 Bombs Released from A4 and A7 Aircraft," Marine Aviation Detachment PMTC, Pt. Mugu, Calif. Feb. 1980.

[2]Ausman, J. S., "Theoretical Analysis and Experimental Measurements of Separation Disturbances in Weapon Delivery Systems," *Aircraft/Stores Compatibility Symposium Proceedings*, Vol. I, Sept. 1975, pp. 53-86 (compiled by JTCG/MD WP #12).

[3]Puckett, A. E. and Ramo, S. (ed.), *Guided Missile Engineering*, McGraw-Hill Book Co., New York, 1959.

[4]Axelband, E. I., "Missile Guidance and Control," Paper presented at 'Avionic Systems Engineering' UCLA Short Course Program, University of California, Los Angeles, July 1981.

[5]Matko, D. and Bremsak, F., "On the Equivalence of Parameter Adaptive and Model Reference Systems," *International Journal of Control*, Vol. 30, No. 2, 1979, pp. 203-211.

[6]Kirk, D. E., *Optimal Control Theory: An Introduction*, Prentice Hall, Englewood Cliffs, N. J. 1970.

[7]Panossian, H. and Leondes, C.T., "Observers for Optimal Estimation of the State of Linear Stochastic Discrete Systems," *International Journal of Control*, Vol. 37, No. 3, 1983, pp. 645-655.

Use of Differential Pressure Feedback in an Automatic Flight Control System

David W. Levy* and Jan Roskam†
University of Kansas, Lawrence, Kansas

Introduction

THIS Note outlines a feasibility study performed to evaluate the performance of a system whereby a control surface is positioned using differential pressure across that surface as the feedback variable. In nearly all airplanes equipped with automatic flight controls, control surfaces are positioned via feedback of surface position. Since control power is often linearly related to position, this type of feedback works well. However, in many instances, it is found necessary to schedule the feedback gain with flight attitude, dynamic pressure, Mach number, or a combination thereof.

Since the purpose of any control deflection is to create a pressure differential across a surface, it is logical to consider positioning a control surface by direct feedback of this differential pressure. This method may simplify control laws. Since differential pressure is also a function of airspeed and angle of attack, it may as well allow for control of these variables.

The goal of the study documented herein was to build a simple, low-cost demonstration system and to evaluate its performance through frequency response testing. First, the pressure profile characteristics of the test surface were determined and a suitable pressure sensor arrangement selected; then closed-loop dynamic tests were conducted.

System Description

The differential pressure (ΔP) command system drives the control surface to a position such that the desired differential pressure is achieved between the two pressure sensor locations. One application is illustrated by the simplified pitch attitude hold block diagram shown in Fig. 1. The ΔP command loop merely replaces a conventional position command loop. It is the ΔP command loop that has been tested and is discussed in this Note.

Figure 2 shows the ΔP command system flow diagram. The pressure transducer selected was a commercially available piezoresistive type with a range of 0-1 psid. Its response characteristics were good, but only positive pressures could be sensed. A second sensor, with the input ports reversed, was needed to sense negative pressures. The rectifier circuit blocks the signal output by either sensor when it is below its usable range and passes the valid signal. The end result is an effective range of -1 to $+1$ psia. The signal conditioner allows for pressure or position feedback modes, lead-lag compensation if required, and monitor positions to prevent a hardover condition in the pressure feedback mode. Standard amplification methods are used to drive the actuator. The actuator is an electromechanical jack screw and is semireversible. It has a stalled output of 400 lb.

Pressure Profile Study

To determine the best location for the pressure transducer, baseline data were obtained through wind-tunnel testing on the pressure distribution around the airfoil as a function of angle of attack and flap deflection. All wind-tunnel tests were in the University of Kansas 3×4 ft low-speed wind tunnel and are completely documented separately.[1] Angle of attack α and flap deflection δ limits were ± 8 and ± 20 deg, respectively. The static pressures at 13 chordwise locations on both sides of the surface were read from a slant-tube manometer board for each combination of α and δ. After applicable corrections were made, the data were reduced to differential pressure coefficient form,

$$\Delta C_P = (P_{\text{lower}} - P_{\text{upper}})/\bar{q} \tag{1}$$

The differential pressure at each chordwise location is found to be a linear function of angle of attack and flap deflection. The data can be further reduced by deriving the following coefficients:

$$C_{P_\alpha} = \frac{\partial(\Delta C_P)}{\partial \alpha}; \qquad C_{P_\delta} = \frac{\partial(\Delta C_P)}{\partial \delta} \tag{2}$$

Submitted Aug. 9, 1982; revision received July 25, 1983.

*Project Manager, Flight Research Laboratory; presently, Aerospace Engineer, Kohlman Systems Research, Inc., Lawrence, Kan. Member AIAA.

†Ackers Distinguished Professor of Aerospace Engineering, Flight Research Laboratory. Associate Fellow AIAA.

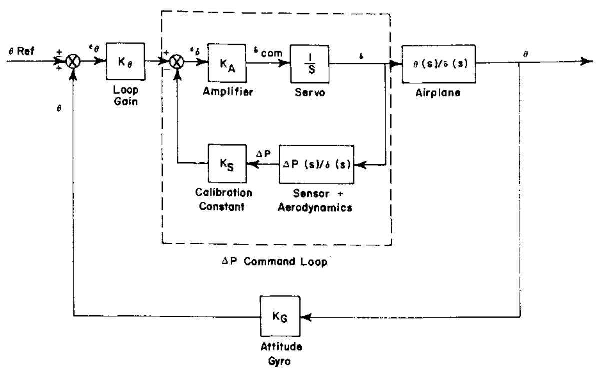

Fig. 1 Pitch attitude hold block diagram with ΔP command.

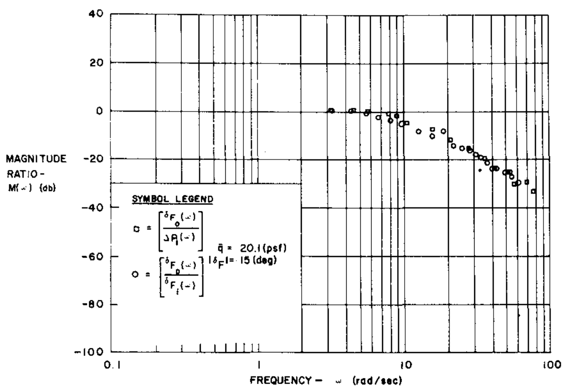

Fig. 2 System flow diagram.

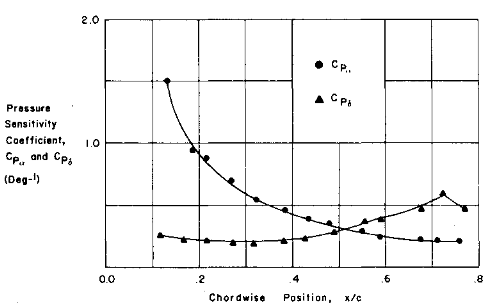

Fig. 3 Pressure sensitivity profile.

These quantities are plotted in Fig. 3. On the basis of these data, the hinge line is the best sensor location for the sensitivity to flap deflection. To control the angle of attack, the sensor should be located at $0.10-0.15\ x/c$.

Frequency Response Testing

The purpose of frequency response testing is to determine the transfer function of the pressure feedback path. If all system components except the actuator are considered to be pure gains, then the pressure change to flap deflection transfer function can be derived. This is done by first measuring the actuator characteristics with conventional position feedback, and then measuring the response with pressure command. The feedback path transfer function can then be isolated.

Pressure and position command frequency sweeps were conducted at four flap deflection amplitudes ($|\delta_F|=5$, 10,

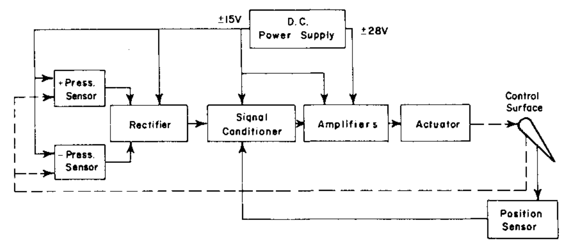

Fig. 4 Position and ΔP command bode plots for $|\delta_F|=15$ deg and dynamic pressure = 20.1 psf.

15, and 20 deg) and dynamic pressures of 12.1-32.2 psf. Three pressure port locations were tested: $x/c=0.641$, 0.668, and 0.747 (hinge line is at $x/c=0.700$). Figure 4 shows the Bode plots of the results for pressure and position feedback for $|\delta_F|=15$ deg. Complete documentation is contained in the final project report.[2]

It is seen that both pressure and position command systems are dominated by the first-order break at 7-10 rad/s due to the actuator slew rate. Dynamic pressure had no effect on the frequency response. These results are valid for incompressible flow only, as Mach effects are not considered here.

Conclusions

It is feasible to position a control surface by feeding back the differential pressure across that surface. Inherent in the system is a gain proportional to the dynamic pressure. The bandwidth of the system tested is limited by the actuator response rather than a lag in pressure change. Due to the limited actuator capabilities, high-frequency (including unsteady aerodynamic) effects could not be isolated from the data. A theoretical study[3] suggests that aerodynamic lags would not occur below frequencies of 50 rad/s for this installation.

From the pressure profile study it appears that angle of attack can also be controlled using the same concept. This has already been used in flight controls and flight test applications with sensors mounted in a probe or nose boom.[4,5]

It must be realized that the system discussed herein will be subject to all of the problems associated with pressure sensor installations in aircraft. They must be heated and kept free of rain and dirt. In addition, shock waves associated with transonic or supersonic applications must be taken into account.

Acknowledgment

This study was performed under NASA Grant NAG 4-5 (CRINC/FRL 4900), sponsored by NASA Dryden Flight Research Center during the period Aug. 25, 1980 to Jan. 15, 1982.

References

[1] Hrabak, R.H. et al., "A Program to Evaluate a Control System Based on Feedback of Aerodynamic Pressure Differentials, Interim Report," Pt. 1, NASA CR-164684; Pt. 2, NASA CR-16485; Aug. 1981.

[2] Levy, D.W., Finn, P.D., and Roskam, J., "A Program to Evaluate a Control System Based on Feedback of Aerodynamic Pressure Differentials, Final Report," NASA CR-163466, Dec. 1981.

[3] Lan, C.E., "The Induced Drag of Oscillating Airfoils in Linear Subsonic Compressible Flow," Flight Research Laboratory, University of Kansas Center for Research, Lawrence, Kan., Rept. KU-FRL-400, June 1975.

[4] Larson, T.J. et al., "Wind Tunnel Investigation of an All Flush Orifice Air Data System for a Large Subsonic Aircraft," NASA TP-1642; May 1980.

[5] Larson, T.J. and Siemers, P.M. III, "Subsonic Tests of an All Flush Pressure Orifice Air Data System," NASA TP-1871, June 1981.