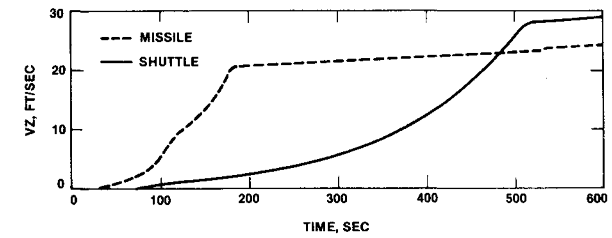

Fig. 2 Shuttle vs missile velocity error profiles for gyro mass unbalance drift (1 deg/h/g).

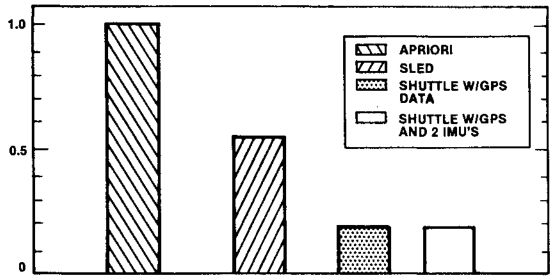

Fig. 3 Normalized composite IMU miss estimates.

venient times during Shuttle prelaunch preparation (NASA refers to this as "ship and shoot").

3) Use Shuttle power (and cooling if available).

4) Use the substantial Shuttle metric data available including Shuttle (multiple) IMU, GPS (Shuttle is configured for GPS receivers), and the test article multiple IMU data for boost IMU analysis.

5) Obtain zero-g data to evaluate biases and low-g performance.

6) Collect data during re-entry to obtain additional test results.

7) Remove modules after landing for post-test assessment.

This approach can make effective use of last-minute Shuttle space available on a cost-effective and noninterference basis with primary Shuttle payloads. Because it is the boost and reentry ΔV magnitudes that are important in generating the test data, the test concept is generally independent of the Shuttle mission profile and the test packages can fly on any Shuttle mission. These factors indicate that the AIRS test module will be a desirable Shuttle payload, filling small gaps in the full Shuttle payload capability left by large primary payloads.

The most notable advantage of the Shuttle relative to the rocket sled test is the total ΔV imparted. Because the Shuttle orbits, the total ΔV is about 15% greater than the ΔV on a ballistic missile trajectory; however, the acceleration level is less. Where a missile generates 7 to 8 (peak) gs, the Shuttle gives about 3.3 gs but for a much longer time. The consequences are that higher-order terms (e.g., g^2 and higher order) in the IMU model will not be as strongly propagated as velocity errors, but low-order terms in the IMU error model (biases and linear g-dependent terms) propagate to an equal or greater level on the Shuttle relative to a missile flight, as the longer time duration of the acceleration dominates. Figures 1 and 2 show velocity error propagation of typical IMU error terms.

Error analysis computations were based on the assumption of GPS data of the quality observed on two actual missile tests in 1980.[1] Figure 3 illustrates the relative level of post-test evaluation of total IMU error (for an additional, high-accuracy IMU) as a function of the instrumentation used (GPS or dual guidance data). These results show that with GPS data (of quality already demonstrated on missile flights), very effective observation of some major IMU errors can be achieved. Total error is evaluated to a level very close to the system's projected long-term capability. Thus, not only can certain systematic errors be identified, but anomalies or mismodeling in excess of the IMU error budget can be identified. The nondestructive nature of the test permits repeated testing in a variety of orientations so that candidate error sources can be extracted through optimal orientation selection.

Carrying multiple systems enhances test accuracy and increases test time on the IMU at low cost. The results are greatly superior to rocket sled testing. The test articles are recoverable after exposure to environments no more severe than those of the missile flight, which will lessen probability of environmentally induced failures. Opportunities to Shuttle-test IMUs before they actually fly on R&D test missiles are a method of further enhancing the role of the R&D tests.

The suitcase concept aims at modularity and minimum interference with Shuttle schedules , mission planning, and prime payloads. However, the package must meet Shuttle payload requirements and interface with Shuttle power and data sources.

A complete package would contain the IMU, computer, data-recording unit, and power-cooling and data-interface units. The IMU calibration can be performed as much as several days prior to launch or as close as several hours before launch.

Conclusion

Testing high-precision IMUs on the Shuttle offers a test capability not duplicated on any other dynamic test. The Shuttle can substantially increase the test time where the "real" flight tests are limited in number, can fly multiple units on a noninterference basis with the Shuttle's primary missions, and can provide high-quality metric test data for performance assessment in an environment remarkably similar (in the sense of total ΔV delivered) to that of the missile. As a nonprimary payload, the incremental cost to the Shuttle program should be low, and the concept will adapt well to relatively short-notice changes in Shuttle payload availability.

Specific interface and packaging issues remain to be assessed. However, the IMU support requirements, weight/volume constraints, and timelines are not at variance with known Shuttle requirements, and use of an existing design payload support module will simplify this problem.

Reference

[1]Barkley, R. L. and Hietzke, W., "GPS Instrumentation Performance as an ICBM Guidance Systems Evaluator," *AIAA Guidance and Control Conference Proceedings,* Aug. 1982, p. 28.

Some Effects of High-Rate Springs in Elevator Control Systems

M.E. Eshelby*
Cranfield Institute of Technology
Cranfield, Bedfordshire, England

Introduction

A CONVENIENT, simple, and inexpensive means of increasing the controls-free longitudinal static stability of an aircraft with manual flying controls is to install a nose-

Received Jan. 27, 1983; revision received March 17, 1983.
Copyright © 1983 by M.E. Eshelby. Published by the American Institute of Aeronautics and Astronautics with permission.

*Lecturer in Applied Mechanics of Flight, College of Aeronautics. Member AIAA.

down spring in the elevator control circuit; the installation is shown diagramatically in Fig. 1. The principle of the spring is well known.[1-3] It provides a constant mechanical control hinge moment in a nose-down sense which has the effect of increasing the slope of the curve of elevator hinge moment coefficient to trim with lift coefficient, which is used as a measure of the controls-free static stability of the aircraft. The control force bias caused by the spring is overcome by the trim tab so that the pilot is still able to fly the aircraft to a zero control force datum. Weights can also be used for this purpose, but they also contribute to the maneuverability of the aircraft in terms of its control force per g, and this may not be necessary.

As a means of correcting an understable aircraft in the controls-free sense, the spring is simple to install, easy to adjust, and low in cost. It eliminates the need for relatively expensive modifications to the aircraft control system or the control balance parameters. For these reasons the spring is often used by light aircraft manufacturers to achieve an acceptable controls-free static stability. In theory, the spring should provide a constant, mechanical, control hinge moment, independent of the control deflection. To achieve this, a low-rate spring is required so that control deflections do not alter the spring load significantly; traditionally, a bungee cord was used as the spring. In some cases, however, high-rate springs have been used which have produced a variable hinge moment contribution as the control surface moves, causing a nonlinear increment to the static stability trim curves.[4] In this Note some of the effects of the use of a high-rate spring in an elevator circuit are considered.

The Theory of the Nose-Down Spring

In the ideal system, the spring should produce a constant increment to the control hinge moment such that the overall control hinge moment H' is given by

$$H' = H_s + qS_\eta \bar{c}_\eta C_H \tag{1}$$

which in coefficient terms becomes

$$C'_H = H_s / qS_\eta \bar{c}_\eta + C_H \tag{2}$$

Now, from the aircraft lift in level flight,

$$q = W/SC_L \tag{3}$$

so that, from Eqs. (2) and (3),

$$C'_H = \frac{H_s SC_L}{WS_\eta \bar{c}_\eta} + C_H \tag{4}$$

The controls-free static stability is determined by the rate of change of elevator hinge moment coefficient to trim with lift coefficient, thus, by differentiating Eq. (4) with respect to C_L, gives the stability criterion

$$\frac{\mathrm{d}C'_H}{\mathrm{d}C_L} = \frac{H_s S}{WS_\eta \bar{c}_\eta} + \frac{\mathrm{d}C_H}{\mathrm{d}C_L} \tag{5}$$

This is shown in Fig. 2.

It should be noted that the effect of the spring on the control hinge moment is independent of speed and thus is not directly equivalent to an increase in the controls-free neutral point obtained by altering the aerodynamic balance parameters of the control.[4]

The basic aircraft static stability, controls-free, is given by the term $\mathrm{d}C_H/\mathrm{d}C_L$, while the overall static stability, controls-free, $\mathrm{d}C'_H/\mathrm{d}C_L$, which includes the constant contribution from the spring, would be the measured trim curve slope based on control forces to trim at various speeds.

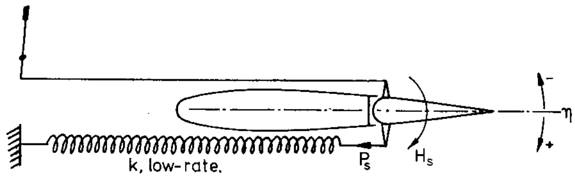

Fig. 1 Elevator control circuit with nose-down spring.

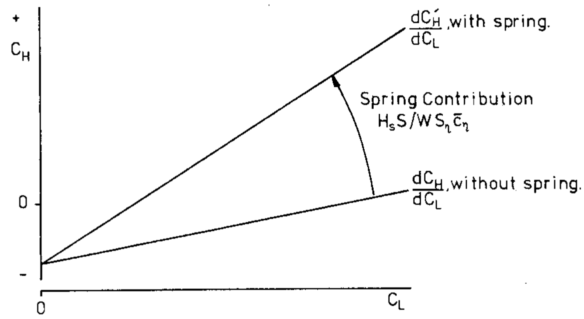

Fig. 2 Effect of the spring contribution to the controls-free static stability trim curves.

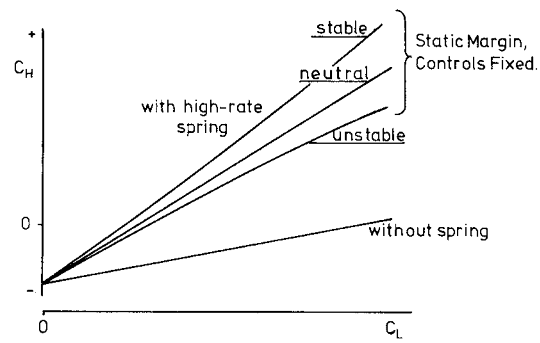

Fig. 3 Effect of the controls-fixed static margin on the controls-free static stability trim curves through a high-rate spring.

The Effect of a High-Rate Spring

If the spring is of high rate, then any deflection of the elevator control will produce a change in the length of the spring and therefore the load it applies to the control. The spring load will be a function of the control position such that

$$P_s = P_{s0} - (k/m_s)\eta \tag{6}$$

where P_{s0} is the spring load at datum elevator position $\eta = 0$; k is the spring stiffness; and m_s is the spring to elevator gearing.

Now the hinge moment produced by the spring load through the gearing to the control is given by

$$H_s = P_s / m_s \tag{7}$$

so that, from Eqs. (4), (6), and (7), the overall hinge moment coefficient becomes

$$C'_H = = \left\{ P_{s0} - \frac{k}{m_s}\eta \right\} \frac{SC_L}{m_s WS_\eta \bar{c}_\eta} + C_H \tag{8}$$

Differentiating Eq. (8) with respect to lift coefficient, and noting that the control deflection η is a function of C_L through the controls-fixed static stability, gives the controls-free static stability criterion,

$$\frac{\mathrm{d}C'_H}{\mathrm{d}C_L} = Am_s P_{s0} - Ak\eta - AkC_L \left(\frac{\mathrm{d}\eta}{\mathrm{d}C_L} \right) + \frac{\mathrm{d}C_H}{\mathrm{d}C_L} \tag{9}$$

where $A = S/m_s^2 WS_\eta \bar{c}_\eta$.

This shows that the overall controls-free static stability expression contains four terms:

1) dC_H/dC_L, which is the basic aircraft static stability, controls-free, without the nose-down spring.

2) Am_sP_{s0}, this is the datum spring contribution with the elevator control set in the neutral position, $\eta=0$, and would be the intended spring contribution necessary to bring the static stability up to the required level.

3) $-Ak\eta$, which depends on the position of the elevator control. From Fig. 1 it can be seen that as the elevator moves to a more positive setting, the extension of the spring, and hence its load, will be reduced, thus reducing its contribution to the controls-free static stability trim curve. Any contribution to the aircraft pitching moment which must be balanced by the elevator control to attain the state of trim will alter the elevator position to trim and hence the spring load. For example, a forward shift of center of gravity will be trimmed out by a more negative elevator angle, which will tend to increase the spring contribution to the controls-free static stability. Similarly, any change in configuration, such as flap setting, which may contribute to the pitching moment equation will also effect the spring load.

4) $-AkC_L(d\eta/dC_L)$, which is the contribution to the controls-free static stability from the controls-fixed static stability. Since the slope of the curve of elevator angle to trim with lift coefficient is negative for controls-fixed static stability, a stable aircraft will impart an increase to the controls-free static stability through the spring. Figure 3 shows the effect of the controls-fixed static stability on the controls-free trim curves.

Conclusion

The objective of the nose-down spring is to increase the slope of the trim curve of the elevator hinge moment to trim against lift coefficient. Ideally, it should be equally effective throughout the speed range of the aircraft and should not vary significantly with airframe configuration changes or center of gravity location. This can be achieved by the use of a low-rate spring, such as a bungee cord, so that minor changes in its length will not materially affect the spring load. To achieve the necessary datum spring load, a low-rate spring will need to be extended to a considerable length and it may be too long for convenient installation in an aircraft. As a consequence of this, shorter, high-rate springs have been used which lead to the secondary contributions described here.

References

[1] Auterson, E.I. and Lyon, H.M., "The Effect of Combined Springs and Weights on Longitudinal Stability and Maneuverability," Royal Aircraft Establishment, Farnborough, U.K., Report Aero 1804, March 1943.

[2] Goldberg, J.H., "Effects of Spring and Inertia Devices on the Longitudinal Stability of Aircraft," Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, Technical Report 53-350, July 1953.

[3] Irving, F.G., "An Introduction to the Longitudinal Static Stability of Low-Speed Aircraft," *International Series of Monographs in Aeronautics and Astronautics,* 1st ed., Vol. 5, Pergamon Press, New York, 1966, Chap. 8, pp. 82-89.

[4] Eshelby, M.E., "The Influence of Short Springs on Longitudinal Static Stability," Cranfield Institute of Technology, Cranfield, Bedfordshire, England, Report Aero 29, March 1975.

From the AIAA Progress in Astronautics and Aeronautics Series...

EXPLORATION OF THE OUTER SOLAR SYSTEM—v. 50

Edited by Eugene W. Greenstadt, Murray Dryer, and Devrie S. Intriligator

During the past decade, propelled by the growing capability of the advanced nations of the world to rocket-launch space vehicles on precise interplanetary paths beyond Earth, strong scientific interest has developed in reaching the outer solar system in order to explore in detail many important physical features that simply cannot be determined by conventional astrophysical observation from Earth. The scientifically exciting exploration strategy for the outer solar system—planets beyond Mars, comets, and the interplanetary medium—has been outlined by NASA for the next decade that includes ten or more planet fly-bys, orbiters, and entry vehicles launched to reach Jupiter, Saturn, and Uranus; and still more launchings are in the initial planning stages.

This volume of the AIAA Progress in Astronautics and Aeronautics series offers a collection of original articles on the first results of such outer solar system exploration. It encompasses three distinct fields of inquiry: the major planets and satellites beyond Mars, comets entering the solar system, and the interplanetary medium containing mainly the particle emanations from the Sun.

Astrophysicists interested in outer solar system phenomena and astronautical engineers concerned with advanced scientific spacecraft will find the book worthy of study. It is recommended also as background to those who will participate in the planning of future solar system missions, particularly as the advent of the forthcoming Space Shuttle opens up new capabilities for such space explorations.

251 pp., 6x9, illus., $15.00 Member $24.00 List

TO ORDER WRITE: Publications Dept., AIAA, 1290 Avenue of the Americas, New York, N.Y. 10019