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Effects of Mass on Aircraft Sidearm Controller Characteristics

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ABSTRACT

When designing a flight simulator, providing a set of low mass variable-characteristic pilot controls can be very difficult. Thus, a strong incentive exists to identify the highest possible mass that will not degrade the validity of a simulation. The NASA Dryden Flight Research Center has conducted a brief flight program to determine the maximum acceptable mass (system inertia) of an aircraft sidearm controller as a function of force gradient. This information is useful for control system design in aircraft as well as development of suitable flight simulator controls.

A modified Learjet with a variable-characteristic sidearm controller was used to obtain data. A boundary was defined between mass considered acceptable and mass considered unacceptable to the pilot. This boundary is defined as a function of force gradient over a range of natural frequencies. This investigation is limited to a study of mass-frequency characteristics only. Results of this investigation are presented in this paper.

NOMENCLATURE

k	Force gradient, lbf/in or N/mm.
m	Mass, lb-sec^2/in or kg.
ω_n	Natural frequency, rad/sec. (This sidearm controller frequency is defined when damping and all nonlinear forces are removed, leaving only mass and force gradient.)

INTRODUCTION

The aircraft simulator designer is usually given the needed static force as a function of displacement for the primary controller, whether it is a center stick, wheel/column, or sidearm controller. Dynamic characteristics are often not included. When dynamic information is available, it is usually limited to natural frequency and damping ratio. Little is known of the effects on simulator fidelity of mismatched natural frequency between the simulator and the aircraft.

The factors determining natural frequency are mass, m, and force gradient, k. The classic equation relating them is as follows:[1]

$$\omega_n^2 = k/m \qquad (1)$$

In designing an all-electric, variable-characteristic flight simulator control such as a sidearm controller, force gradient is usually easy to model. However, mass (system inertia) can be very difficult to model. It is relatively easy to simulate high masses, but very difficult to simulate low masses. Some of the difficulties in developing low mass flight simulator controls have previously been described.[2,3] Thus, a strong incentive exists to identify the highest possible mass that will not degrade the validity of a simulation. This investigation attempts to do that.

In preparation for the flight experiments, technical publications were reviewed and interviews were conducted with several experienced test pilots and researchers to identify what was known regarding control mass. The technical publications indicated the following:

- Experiments that used effective masses ranging from 2.3 to 19.6 lbm (1.0 to 8.9 kg) had been performed.[4,5] However, these experiments only used mass to control natural frequency. The effects of the mass, per se, were not studied.
- Previous experiments showed that control system natural frequencies as low as 14 rad/sec resulted in pilot ratings similar to those given to control systems with natural frequencies as high as 26 rad/sec.[4]
- Human operators generally find it easier to fly aircraft using displacement controllers rather than force-operated controllers.[6] Accordingly, this experimental flight program was limited to using the controller in a displacement mode only.

The interviews indicated the following:

- The persons interviewed had no inputs regarding acceptable mass ranges.
- Control system natural frequencies at or above approximately 25 rad/sec are indistinguishable to the pilot.
- Frequencies from 16 to 25 rad/sec are generally acceptable to the pilot, although in certain cases the pilot may object to a frequency in the low end of that range. Some actual aircraft sidearm controllers have natural frequencies as high as 70 rad/sec.

Because of the unavailability of specific mass data, a brief flight program was conducted to obtain some preliminary data on the effects of sidearm controller mass on the handling qualities of an aircraft. This program was designed to identify the approximate boundary between masses high enough to be objectionable to the pilot and masses low enough that they are not objectionable. Because of the strong similarities between the characteristics of sidearm controllers and center sticks,[4,7] it may be possible to apply the data to center sticks as well.

Because pilot-operated flight controls have various nonlinear properties such as breakout, friction, and nonlinear gradients, frequency and damping are not precisely defined. The breakout region, for example, may have frequency and damping properties that are different from those of the linear region. Therefore, merely specifying frequency and damping can be inadequate for accurately modeling the dynamics of an aircraft control system. This investigation is limited, however, to looking at the overall frequency characteristic only, with emphasis on the mass.

VEHICLE DESCRIPTION

The flight program was conducted on a specially modified Learjet Model 25[8] (fig. 1) that was equipped with a hydraulically powered variable-characteristic sidearm controller located at the right-hand copilot's position (fig. 2). Because the controller was powered hydraulically, it had low inherent mass. It was controlled by a dedicated onboard computer that had the capability to model a wide range of natural frequencies. The aircraft also had variable-stability capability, but this feature was not used in this program. The aircraft dynamics used were those of the unaugmented Learjet. The left-hand controls were unmodified. The left seat was always occupied by an experienced safety pilot during the test flights. Either pilot could transfer control from one position to the other during the flight.

The sidearm controller had identical force and displacement capabilities in both axes. The length was fixed at 5.4 in. (137 mm). The maximum angular travel limits were ±20 deg (0.35 rad), which resulted in maximum linear travel limits of ±1.88 in. (47.8 mm). The controller could develop forces up to ±50 lbf (222 N). The gain of the electronic coupling between the sidearm controller and the aircraft control surfaces was variable, which allowed a wide range of aircraft response for a given force or travel. Commands to the aircraft control surfaces could be taken from either the displacement of or the force applied to the sidearm controller. However, during this experiment, all surface commands were taken from the displacement of the controller. The force stick capability was not used. The controller could be programmed with a number of feel

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Figure 1. The Calspan Learjet model 25.

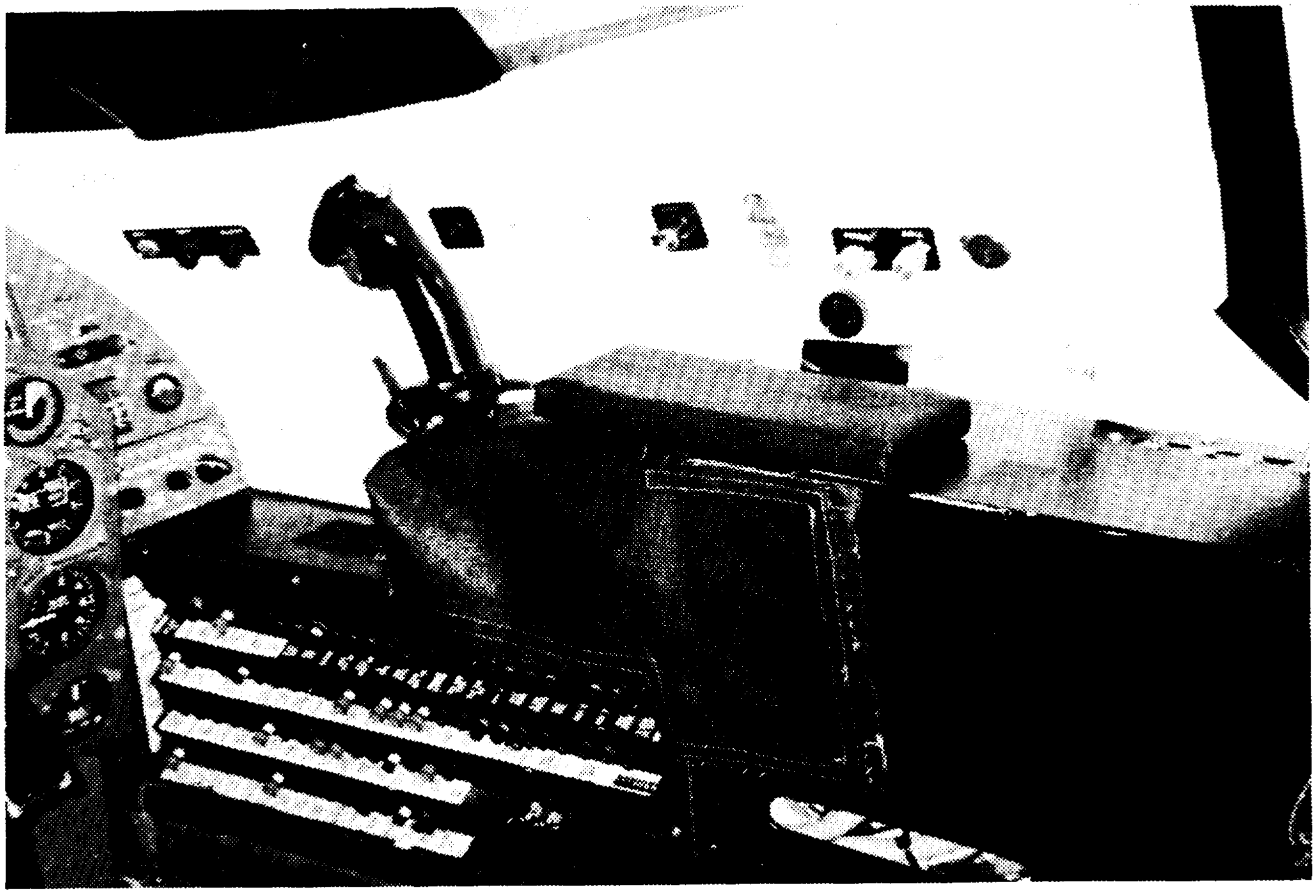

Figure 2. Sidearm controller.

characteristics, including both linear and nonlinear force gradients, damping, natural frequency, breakout, and friction.

The sidearm controller could also be decoupled from the aircraft during flight. Therefore, it was possible to evaluate the "feel" of the controller in a fixed base environment with the safety pilot flying the aircraft straight and level and then evaluate it again with it coupled to the aircraft.

FLIGHT TEST PROCEDURE

The flights were conducted at Calspan Advanced Technology Center in Buffalo, New York, on February 25 and 26, 1993. Two experimental flights were conducted using two test pilots. Pilot 1 is a highly skilled professional test pilot with a wide range of aircraft experience. This experience includes piloting the F-16, which has a high-gradient, high-frequency sidearm controller. Pilot 2 is a private pilot with experience in light aircraft who had one hour of prior familiarization in a Learjet.

Both flights were designed to cover a range of force gradients and natural frequencies on the sidearm controller. This range included simulated controller masses from 7.2 to 384 lbm (3.3 to 174 kg) and was selected to explore the effects of sidearm controller mass at both high and low force gradients.

The flight design called for experimenting with a range of force gradients and frequencies during up-and-away flight (250 kn or 460 km/hr at an altitude of 10,000 to 15,000 ft or 3,000 to 4,500 m). Maneuvers included pitch and roll rate inputs and coordinated turns. Each pilot requested various force sensitivity settings and selected a preferred value. This value was held constant for most data points to prevent changes in that variable from affecting the results. During this investigation, force sensitivity was held constant by simultaneously varying the force gradient and the ratio between stick position and surface deflection.

From the up-and-away data, each pilot selected four settings to use during approaches and touch-and-go landings. The landing settings were intended to help define the boundary between low frequency (high mass) that adversely affected the pilot and high frequency (low mass) that did not affect the pilot.

The damping ratio was maintained at a constant 0.7, and breakout forces were held at a constant 0.25 or 0.5 lbf (1.1 or 2.2 N) level, according to the preference of each pilot. Friction was left at 0 lbf (0 N).

The determination of the degree of acceptability of controller mass was made solely by each test pilot. Where the mass was a noticeable factor in handling qualities, each pilot indicated this fact with a negative comment.

Pilot 1 flew first and selected force sensitivities that would provide full control authority at 30 lbf (133 N) in pitch and 9 lbf (40 N) in roll. In the pilot's opinion, this combination created control harmony with the responses of the Learjet. Pilot 1 preferred the high force gradients combined with relatively small control travel, suggesting that these preferences resulted from prior F-16 experience. Accordingly, pilot 1 flew the majority of the data points at high gradients and extremely high mass and less points at low gradients with low mass.

Pilot 2 flew next and found that the force sensitivities selected by pilot 1 were highly satisfactory. Pilot 2 preferred the low force gradients combined with increased control travel, perhaps the result of previous flight experience. Pilot 2 repeated a representative sampling of the data points flown by pilot 1 and reached similar conclusions. Pilot 2 flew the majority of the data points around the low gradient and low mass conditions. Because this was a major region of interest, pilot 2 flew several conditions where the control travel was very large compared to the aircraft response in an attempt to artificially exaggerate any mass effects.

RESULTS AND DISCUSSION

Table 1 lists the test conditions flown. The values for mass were computed using equation 1. Table 1 also gives pilot comments relevant to mass characteristics. If no comment is given, mass was not a factor in the pilot's evaluation. Comments regarding other control characteristics, such as excessive motion, are not included because they do not apply to the issue of control mass.

Figures 3 and 4 show mass plotted as a function of force gradient. Lines of constant natural frequency are shown for reference. From the pilot comments, a shaded region was added that divides the graph into two regions. The upper region is where control mass affected the pilot's ability to control the aircraft, and the lower right region is where mass was not apparent to the pilot.

Between approximately 10 and 30 lbf/in (1.75 and 5.25 N/mm), the dividing region between high and acceptable mass appears to be close to the 20 rad/sec line, as suggested by the interviews and available data.[4] However, there is a significant departure from this line at both high and low force gradients.

At low gradients below 10 lbf/in (1.75 N/mm) (fig. 3), the adverse effects of mass seem to disappear at a mass level between 7 and 8 lbm (3 and 3.6 kg), regardless of gradient or natural frequency. Perhaps the pilot's hand and arm can easily control that amount of mass without significant impediment. Thus, a mass no greater than 7 lbm (3 kg) would be acceptable for either a flight simulator or an aircraft whose control movements are no more aggressive than those of a Learjet. This mass is independent of the actual force gradient used. It is reasonable to assume that a mass somewhat lower than 7 lbm (3 kg) may be needed for highly maneuverable aircraft that are controlled more aggressively than the Learjet, but it was not possible to test that assumption in this experiment. These data do suggest, however, that there will always be a nonzero mass level that can be tolerated by the pilot without adverse effects.

At low force gradients below 10 lbf/in (1.75 N/mm), a low natural frequency is acceptable to the pilot. Because of the similarities between sidearm controllers and center sticks, it is reasonable to assume that this conclusion would also apply to center sticks. Further flight testing would be needed to confirm this assumption. These data suggest that, for low force gradient controls, specifying the maximum mass level would be more meaningful than specifying a minimum natural frequency.

At high force gradients above 30 lbf/in (5.25 N/mm) (fig. 4), a natural frequency lower than 16 rad/sec is acceptable to the pilot, perhaps because the motions are too small for mass to be a significant factor. The effective mass at the most extreme point translates into 384 lbm (174 kg), a very high number. No practical sidearm controller, either aircraft or simulator, would be designed with such a large mass. Thus, the data

Table 1. Sidearm controller experiment data.

Force gradient		Mass		Force at full authority		Natural Frequency	Comments related to mass, if any
lb/in	n/mm	lbm	kg	lb	N	rad/sec	
Pitch axis							
3.98*	0.70	7.7	3.5	30	133	14.1	
7.95*	1.39	7.7	3.5	30	133	20.0	
7.95*	1.39	12.0	5.4	30/15**	133/67**	16.0	
7.95*	1.39	48.0	21.8	30	133	8.0	Feels like a pendulum
15.9	2.78	6.8	3.1	30	133	30.0	
15.9	2.78	24.0	10.9	30	133	16.0	Can feel mass
15.9	2.78	96.0	43.5	30	133	8.0	Feels sloppy
31.8	5.57	48.0	21.8	30/60**	133/267**	16.0	
31.8	5.57	192	87	30	133	8.0	Weird for landing
63.6	11.1	384	174	30	133	8.0	Mass not noticeable
Roll axis							
2.39*	0.42	7.2	3.3	9	40	11.3	
4.77	0.83	7.2	3.3	9/18**	40/80**	16.0	
4.77	0.83	28.8	13.1	9	40	8.0	Feels like a pendulum
9.54	1.67	7.2	3.3	9	40	22.6	
9.54	1.67	14.4	6.5	9/18**	40/80**	16.0	
19.08	3.34	28.8	13.1	18/36**	80/160**	16.0	Sluggish
38.2	6.69	57.7	26.2	18	80	16.0	
38.2	6.69	230	104	9	40	8.0	Mass not noticeable

*Data points where controller motion was so large that full aircraft control authority was not available. That is, the sidearm controller ran out of travel before the aileron or elevator was at full deflection.
**Two different force sensitivities were used. That is, the gain of the coupling between the controller and the aircraft control surface was changed to allow full control deflection to occur at two different force levels. Because the controller force gradient and natural frequency were not changed, this variation served as a cross check to look at other force sensitivities.

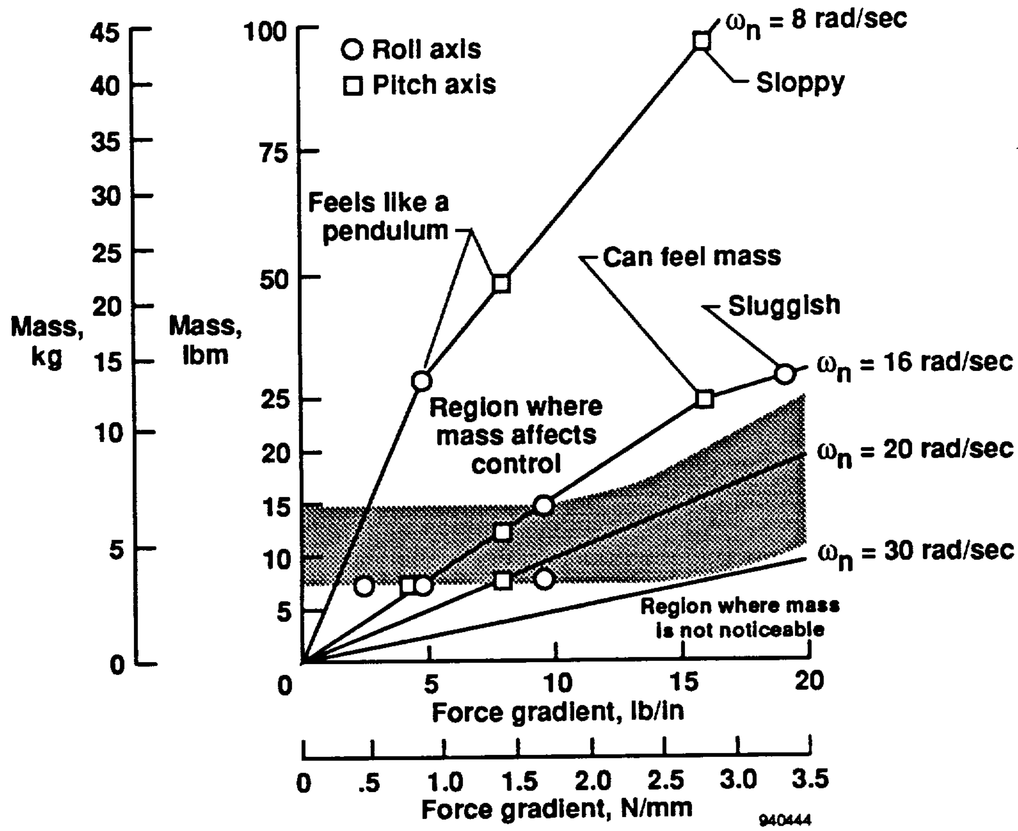

Figure 3. Mass as a function of force gradient (low gradients).

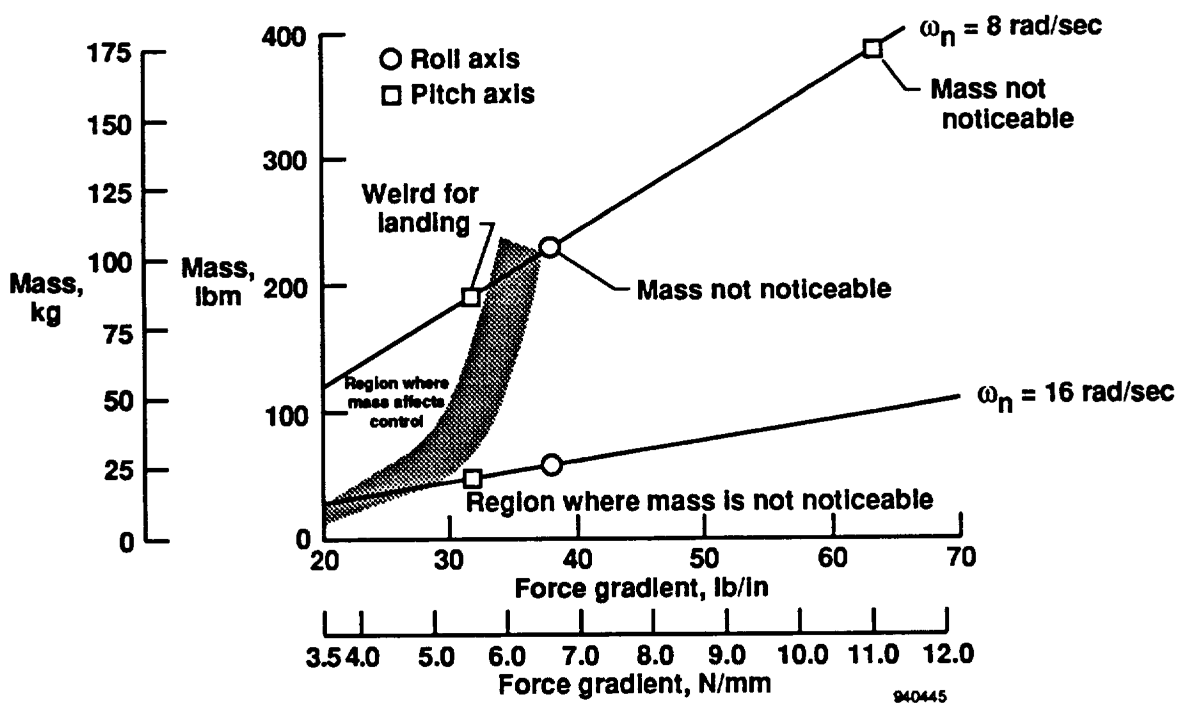

Figure 4. Mass as a function of force gradient (high gradients).

suggest that high force-gradient controllers can be designed essentially without regard to mass or natural frequency.

These data (table 1) suggest that at the low mass, low force-gradient conditions, a given mass seems to be about equally acceptable or objectionable in both the pitch and roll axes. It is possible that a more detailed study could show that there is a modest difference in the maximum acceptable mass in the two axes, but this difference is not likely to be large.

One unexpected phenomenon was found during this flight program, and it has significant implications for control system design. The sidearm controller settings were as follows:

	Gradient		Mass		Natural Frequency
	lbf/in	N/mm	lbm	kg	rad/sec
Pitch	7.95	1.39	48	21.8	8.0
Roll	4.77	0.83	28.8	13.1	8.0

When the aircraft control surfaces were electronically coupled to the sidearm controller, the controller felt like a pendulum. That is, it felt like there was a long arm underneath the control with a weight on the end. The controller bobbled around as the aircraft moved, creating unwanted control inputs during maneuvers. The presence of this effect as confirmed by both pilots. However, the effect disappeared when the control was electronically uncoupled from the aircraft and simply moved without a corresponding aircraft response.

While a similar effect has been previously reported with low damping ratios under 0.3,[5] this current result is surprising in two ways. First, it occurred with the damping ratio set relatively high (0.7). Second, tests performed at the same natural frequency and damping ratio but at force gradients higher than those shown in the table above did not exhibit this problem. Thus, frequency and damping characteristics alone do not predict control system behavior in an aircraft. This effect underscores the fact that it may be unwise to select control system characteristics in a fixed-base environment. The behavior in an actual moving aircraft could prove to be rather different from that which is intended.

CONCLUDING REMARKS

A brief flight program was conducted to determine the maximum acceptable mass of an aircraft sidearm controller as a function of force gradient. A modified Learjet with a variable-characteristic sidearm controller was used by two pilots to obtain data. The program identified the approximate boundary between masses high enough to be objectionable to pilots and masses low enough that they are not objectionable. Large variations in force gradient and control travel were included in the program.

From the test data obtained, it can be concluded that a sidearm controller with a mass no greater than approximately 7 lbm (3 kg) would be acceptable for either a flight simulator or an aircraft whose maneuvers are no more aggressive than a Learjet. This mass is independent of the actual force gradient used. In this experiment, it was not possible to identify a mass that would be acceptable for a highly maneuverable aircraft that required more aggressive control inputs than a Learjet. It is reasonable to assume that a somewhat lower mass would be acceptable.

At low force gradients below 10 lbf/in (1.75 N/mm), a low natural frequency is acceptable. A similar conclusion may apply to center sticks as well, but further flight test would be required to confirm this.

At force gradients between 10 and 30 lbf/in (1.75 and 5.25 N/mm), a natural frequency of 20 rad/sec or more is acceptable.

At high force gradients above 30 lbf/in (5.25 N/mm), a low natural frequency below 16 rad/sec is acceptable. Because the combination of high force gradient and low natural frequency occurs only when mass is very high, this condition is unlikely to arise in an actual aircraft or flight simulator.

No significant differences in acceptable mass characteristics were found between the pitch and roll axes.

There is a significant risk associated with choosing controller characteristics in a fixed-base environment. The resulting motions of an aircraft can have unexpected influences on the feel of a control and can even cause extraneous inputs. Flight controller characteristics should always be verified in actual flight.

Dryden Flight Research Center
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DEFINITIONS

Angular travel	The angular deflection of the sidearm controller handgrip.
Breakout	The minimum force required to overcome the centering forces in the control and begin to produce a response from the aircraft.
Damping	The force in a control system that is proportional to the velocity of the handgrip.
Force	The linear force applied at the reference point.
Force gradient	The ratio, in lbf/in or N/mm, of the stick force to the travel. This term is defined only when force is proportional to travel.
Force sensitivity	The ratio of stick force to control surface deflection in lbf or N per unit deflection. Maximum control surface deflection was arbitrarily chosen to be unity, so the force sensitivity is numerically equal to the force required to obtain maximum control surface deflection (maximum control authority). Note that force sensitivity is unrelated to the force gradient.
Friction	The static force required to overcome the drag forces in the control system. This force is sometimes referred to as hysteresis.
Length	The distance from the reference point to the actual pivot point of the sidearm controller. For the controller used in this investigation, the length is 5.4 in. (137 mm).
Linear travel	The deflection of the sidearm controller handgrip measured along the arc described by the reference point.
Mass	The apparent mass of the sidearm controller handgrip. This is felt by the pilot as system inertia. The mass as defined here is equivalent to a system that has only a single point mass located at the reference point. In an actual sidearm controller system, the mass includes the effects of all moving parts, including both the handgrip itself and any linkages operated mechanically by the handgrip. Any artificial modifications of the mass caused by powered actuators are also included.
Pound-mass	One pound-mass is defined as that mass that exerts a downward force of one pound in Earth's gravitational field. It is calculated by multiplying the mass, *m*, by the acceleration caused by the Earth's gravity, which is 386.4 in/sec^2 (32.2 ft/sec^2 times 12 in/ft).
Reference point	The point on the sidearm controller where the center of the pilot's middle finger contacts the handgrip. This is the point where forces and displacements are measured.

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