

THE LIGHT TOUCH

by

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Performance is certainly the first consideration when judging the relative merits of sailplanes. Performance is readily measured and an excellent literature is available due to the work of Bikle, Zacher, Johnson, and others. The acid test of competition frequently confirms the results of engineering tests and sailplanes with superior performance are rapidly recognized and therefore thrive and improve the breed.

Handling qualities (or stability and control or flying characteristics) are less definite. They tend to be difficult to measure and most of the literature is qualitative, emphasizing adjectives rather than numbers. There have been successful competition sailplanes with poor handling qualities. But there is another aspect that must be mentioned: handling qualities are related to safety of flight much more so than is performance. Furthermore, as handling qualities improve, the joy of flying increases. Nobody flying an unresponsive, heavy-handed glider ever identified himself with a seagull. So this is a subject worthy of our attention.

Let us first look at the current literature. Frank G. Irving's "An Introduction to the Longitudinal Static Stability of Low-Speed Aircraft" (Ref. 3) is an excellent source of information on the physics and algebra for at least the pitch axis. The "OSTIV Airworthiness Requirements for Sailplanes" (Ref. 2) and the related SSA draft proposal to FAA "Joint Airworthiness Requirements for Gliders" (Ref. 7) present the current state of requirements. (It is interesting to note that the FAA does not have an FAR on glider characteristics. Reference 7 is a proposal to fill that void). Bennett's "Pilot Evaluations of Sailplane Handling Qualities" (Ref. 1) reports a significant experiment in which seven well qualified pilots evaluated six high performance sailplanes. Their opinions were carefully recorded on the numerical Cooper-Harper scale which allowed a statistical analysis. The result was an in-depth comparative description of the characteristics of the test fleet. The experiment included an effort to measure certain stability and control parameters but this did not succeed which leads us to the experiments to be reported here.

Flight control is usually divided into two elements: longitudinal or pitch control using the elevator and lateral-directional or roll-yaw control using the rudder and ailerons. This report will deal only with the longitudinal case although it is clearly recognized that lateral-directional control is extremely important. The reason for selecting the pitch

axis for study is that important pitch characteristics can be measured in steady flight conditions whereas the most important lateral-directional problems occur in rolling and yawing maneuvers that cannot reach steady state.

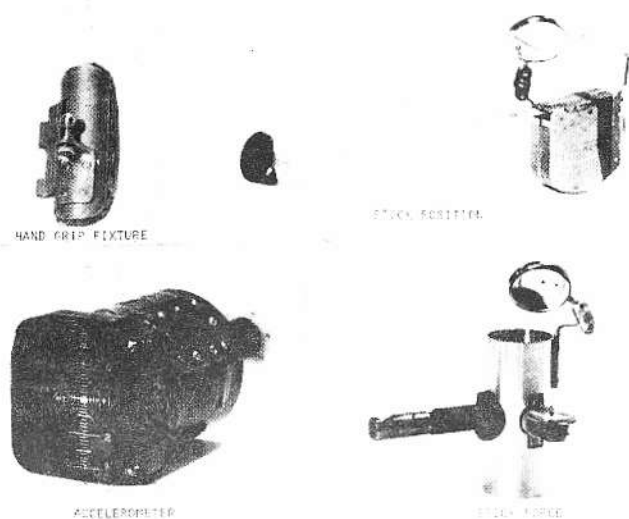
Figure 1 lists the quantitative longitudinal requirements from Reference 2, the OSTIV requirements. Reference will be made to this list throughout this report.

FIGURE 1 OSTIV REQUIREMENTS

REFERENCE 2		RELATED REF. 7 PARAGRAPH
PARAGRAPH		
2.163	STICK FRICTION NO MORE THAN 1.5 kg	22.683
2.412	FRICTION SHALL NOT CONCEAL STABILITY CHARACTERISTICS. RETURN TO TRIM WITHIN 0.2 VSTALL WHEN STICK FORCE SLOWLY RELEASED	22.173
2.43	POSITIVE LONGITUDINAL STABILITY. STABLE STICK MOTION	22.173
2.44	STICK FORCE GRADIENT NO LESS THAN 0.5 kg/g AT 1.4 VSTALL	22.155
3.63	ELEVATOR SYSTEM COMPLIANCE NO GREATER THAN 50% OF SEMITHROW UNDER 30 kg FORCE. (NO MORE THAN .0083 PER kg ON FIGURE 8 SCALE)	22.411

A set of instrumentation was built and used to measure the elevator control system and the longitudinal static and maneuvering stability of several gliders. This report presents the results of these tests.

FIGURE 2 INSTRUMENTATION



Instrumentation

The test instrumentation is shown on Figures 2 and 3. First, a flexible steel metric tape was supported by hinges between the instrument panel and a hand grip fixture lashed to the control stick. A mirror allowed precise reading of the stick position. Next, a compact spring scale was connected to the fixture using a ball-socket. If the pilot controlled the glider with his hand on the spring scale housing he could read the applied force on the dial of the spring scale. The third instrument was a sensitive accelerometer that could either be temporarily fastened to an appropriate surface with tape or semi-permanently mounted in a standard 3 1/8 inch instrument hole.

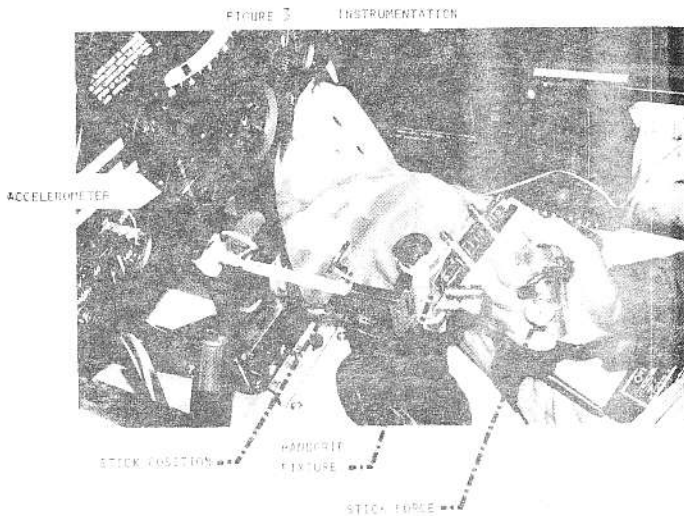


FIGURE 3 INSTRUMENTATION

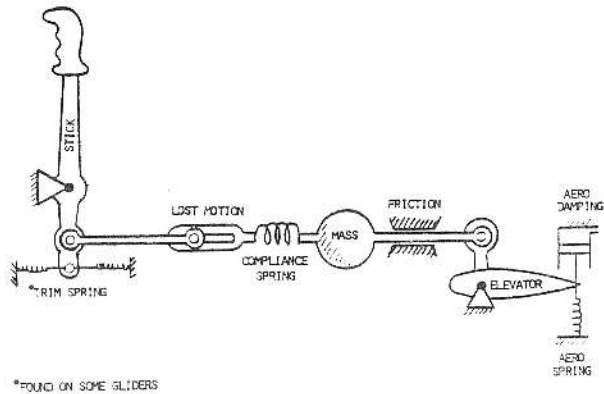
g were probably close to the truth and seemed compatible with the unknown weight and airspeed errors.

Ground Tests

Figure 3A shows the mechanical properties of a manual elevator control system. The forces of interest to the static ground tests described here are lost motion, compliance, friction and travel.

FIGURE 3A ELEVATOR CONTROL SCHEMATIC

(LOST MOTION, COMPLIANCE, MASS AND FRICTION ARE DISTRIBUTED THROUGHOUT THE SYSTEM. THEY ARE NOT CONCENTRATED AS SHOWN ON THE SKETCH.)



If the control stick is carefully cycled through its full stroke while recording force and position, a closed hysteresis curve such as that shown on Figure 4 will be generated. The width of the curve is total stick travel and the vertical thickness is static friction. Now, if the elevator is restrained and a push and pull force then applied while recording force and position, a "Z" shaped curve will be generated such as the example shown in Figure 4. The two nearly vertical branches of the curve are separated at the center by the lost motion of the system. The slope of the branches is the compliance.

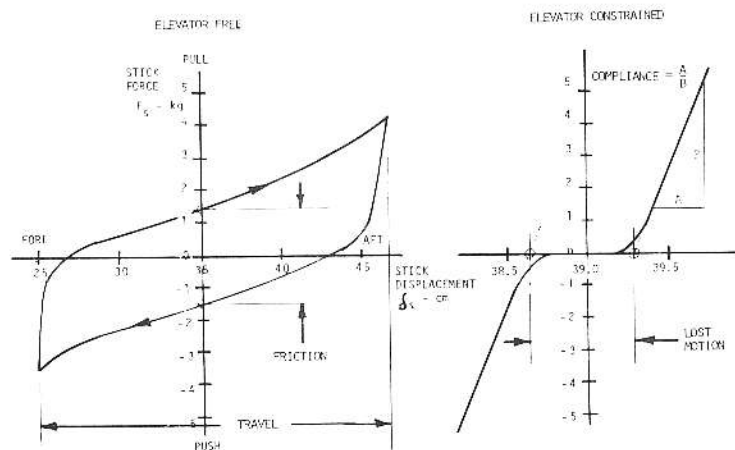
The design criteria for the instruments were:

1. No interference with flight safety
2. Easy to install and remove
3. Cheap
4. Sufficient precision for the task

All of these goals were met. The FAA agreed with the first. It takes about five minutes to install the equipment. The position measuring device was made from an inexpensive pocket tape. The spring scale comprised a cylindrical spring in a cylindrical housing with a conventional .001 inch dial indicator measuring spring deflection. The spring was calibrated by reducing its wall thickness and length on a lathe until the dial indicator read kilograms-force. The accelerometer was also specially made. It was a horizontal 8 inch piano wire supporting a tiny plastic bob which was viewed through an instrument glass. Compass oil was used for damping and the system was calibrated by simply rotating it to the plus one g, zero g and minus one g positions and making linear extrapolations to higher values.

The requirement for precision was modest since it was impractical to weigh the test aircraft or calibrate their airspeed systems. Assumed stick position error of 1 mm, stick force error of 250 gm and acceleration error of 0.1

FIGURE 4 IDEAL MECHANICAL CHARACTERISTICS



Note: Instrument panel is zero displacement.

Figures 5 and 6 show these measurements for a Blanik L-13 and a Pilatus B-4. The Blanik was trimmed with an aerodynamic tab and its hysteresis curve was essentially a flat rectangle while the Pilatus used a trim spring that inclined the hysteresis loop to the slope of the trim spring rate.

FIGURE 5 BLANIK MECHANICAL CHARACTERISTICS

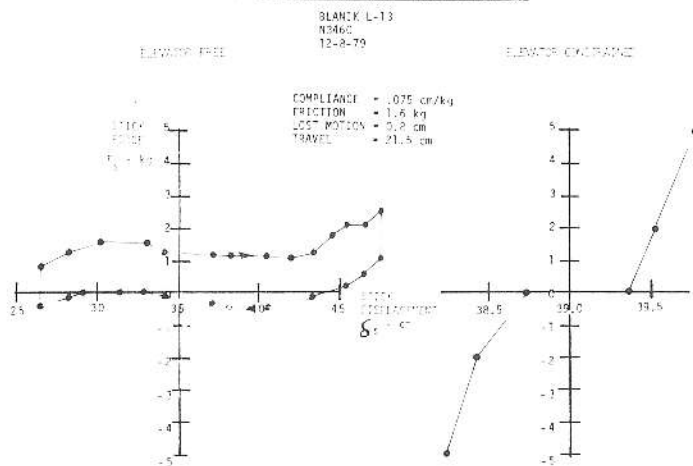


FIGURE 6 PILATUS MECHANICAL CHARACTERISTICS

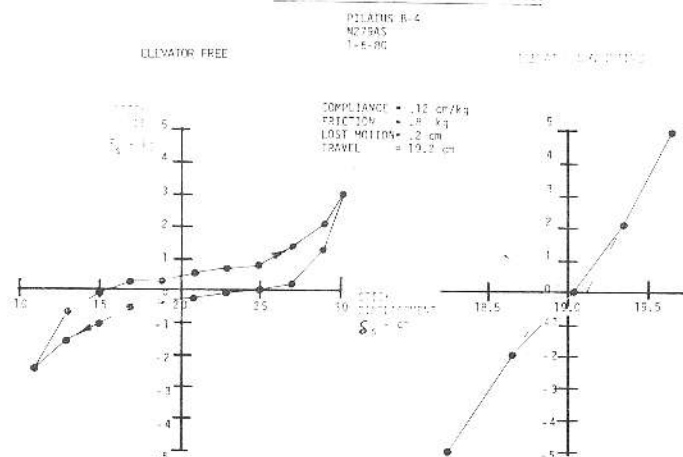


Figure 7 summarizes the ground test measurements of nine sailplanes including two Blaniks and the Pilatus. An indication of the accuracy of the ground tests is seen by comparing the data of the two nearly identical Blaniks. The measured difference in friction was qualitatively apparent to the careful observer.

FIGURE 7 GROUND TEST DATA SUMMARY

	FRICTION (kg)	LOST MOTION (cm)	TOTAL STICK TRAVEL (cm)	COMPLIANCE (cm/kg)
DIAMANT 16.5 N363P	2.3	0.3	21	.07
PRUE STD N66675	0.5	< 0.1	14	.09
PHOENIX N264K	0.9 0.7*	0.2	27 28*	.19
LIBELLE # 3016 N4156A	0.2	< 0.1	17.5	.12
C-11 N1749	1.3	0.3	26	.13
ALCOR	1.8	0.1	20	.49
BLANIK N4659	2.3	0.6	23	.28
BLANIK N346C	1.6	0.8	22	.278
X-8 CP-PVL	0.75	< 0.1	21	.29
PILATUS 3-4 N279AS	0.80	0.2	19	.12
OSTIV REQUIREMENT	1.5	MUTE	MUTE	[See Fig. 8]

*PHOENIX A PER G. ENVELOPES

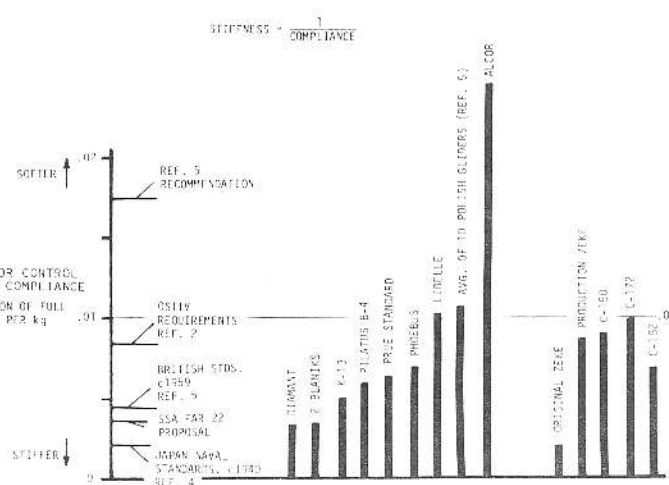
It is seen that the friction varies through a wide range with most of gliders having less friction than the maximum allowed by the OSTIV requirements. It is the author's opinion that the instances of high friction encountered were associated with maintenance practices.

A criterion for acceptable lost motion is not mentioned in either Reference 2 or 7. The author believes that this characteristic is undesirable, small values can be irritating and excessive lost motion can interfere with precise flight control. It is seen on Figure 7 that most of the gliders tested had only a few millimeters of slop. A practical limit for airworthy control systems should probably be about 5% of full stick travel. This criterion should also be acceptable even for side-stick controllers which may have as little as 5 to 7 cm of total travel.

Total travel is listed in the third column of Figure 7. If a side-stick control had been included in this list the travel values would have ranged through nearly six factors (5 cm to 28 cm). Neither of the requirements documents (References 2 and 7) mentions stick travel and it appears that this is a variable available to the designer for tailoring stick forces by changing elevator-stick gearing and stick length and accepting whatever travel results within very flexible limits.

Values for compliance are shown on the last column of Figure 7 in units of cm per kg. A wide variation is noted. A maximum value for this quantity is specified in both References 2 and 7 in units equivalent to fraction of total stick travel per kg. The test data are presented in these units on Figure 8 which also shows five different limitations placed on this parameter by different authors.

FIGURE 8 CONTROL SYSTEM STIFFNESS



It seems to the author that the smallest possible value of compliance would be ideal. Evidence opposing this view is given in Reference 4 which describes the history of the Mitsubishi A-1 (or Zeke, or Zero) fighter. The elevator control system was initially designed to the very stiff requirements of the Japanese naval standards. Test pilots reported that

the airplane was overly sensitive in pitch at high speed which led to a revision of the elevator control system in which the compliance was increased several fold resulting in an increase of stick-travel-per-g at high speed. This led to improved rating by the test pilots and the modification was retained throughout the long production run.

Compliance values before and after the modification of the Zeke are shown on Figure 8 and compared to the measured value of compliance for three popular Cessna models. The author draws the conclusion that the original Japanese standard was too severe for high speed flight and that the OSTIV standard of about 1% of full travel deflection per kg is about right. Examination of the glider compliances tends to support this view. A corollary conclusion is that the SSA FAR22 proposal (Ref. 7) is also too severe. The author retains his opinion that zero compliance is ideal in the absence of other factors.

Fight Test Preliminary Remarks

Only one basic flight test can be conducted with the instrumentation described in this report: airspeed and load factor are stabilized and stick force and position are read and recorded. A number of variations of this test allows determination of several very important characteristics. However, there is no hope of measuring transient or oscillatory conditions with this primitive instrumentation.

The purpose of the flight tests was to measure longitudinal stability. The requirements listed on Figure 1 are concerned with stability. There are four measures of stability that can be determined from variations of the basic flight test:

1. The change of stick position with speed in steady level flight (one g), $d\delta_s/dv$
2. The change of stick force with speed in steady level flight, dF_s/dv .
3. The change of stick position with load factor at constant speed, $d\delta_s/dn$
4. The change of stick force with load factor at constant speed, stick force per g, dF_s/dn .

Of course steady level flight is a descending flight path in a glider. Flight at steady load factor greater than one g can only be attained in a steady turn and that was the maneuver used in this case.

Stability increases as the center-of-gravity (cg) moves forward. A most interesting result can therefore be obtained from the basic flight test by repeating it at two or more cg locations and extrapolating to the cg where stability is zero. This is called the neutral point (NP) for tests in steady level flight and the maneuver point (MP) for tests with the load factor greater than 1.0g.

The difference between the angle of attack on the wing and the tail during curved flight tends to increase maneuvering stability in comparison to the static stability measured in steady level flight. Therefore, the MP is aft of the NP. The difference between NP and MP is independent of load factor in the case of symmetrical pull-ups in the vertical plane. This is not true for the case of load factor generated by flying a steady turn in which case the difference between NP and MP varies with load factor.

In the present test this was dealt with by flying all maneuvers at either 1.0g or 1.5g. The bank angle for 1.5g is 48.2°. It is easy to judge a 45° bank so that the 1.5g load factor could be approximated by using bank angle reference. However, it was much easier and more accurate to fly the condition using a precision accelerometer as reference.

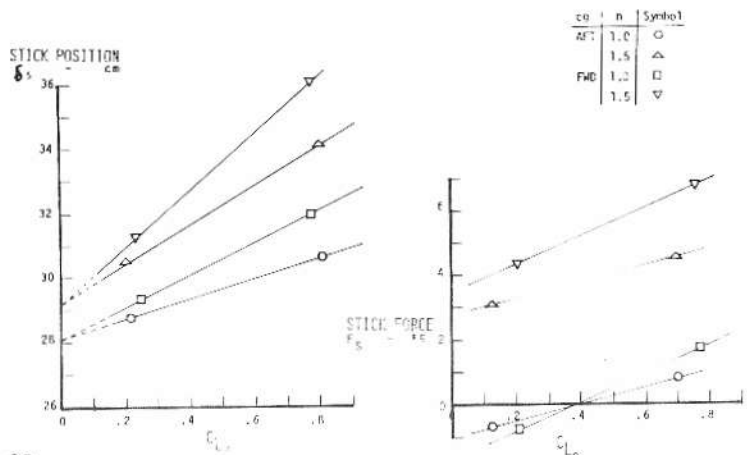
It should be clear to the reader at this point that no attempt was made to measure elevator-to-stick gearing, elevator/stabilizer geometry or to gather any of the other data required for a aerodynamic analysis. This study was limited by practical considerations to measurements at the pilot-airplane interface. The author intends to check the results for at least one glider by computing the theoretical values but that remains to be done in the future.

One further introductory comment before we turn to the flight data. The author uses the terms "stick position stability" and "stick force stability" rather than the conventional "stick-fixed stability" and "stick-free stability" as a matter of personal preference.

Flight Test Data

Figure 9 shows an idealized representation of the type of data that was recorded. Four curves are shown on each of the two position and force plots: the four combinations of two test load factors and two cg loadings. The stick position curves are straight lines radiating from the zero C_L value. The zero stick position shifts due to pitch damping at the increased 1.5g factor. The stability curves are steeper for the accelerated case.

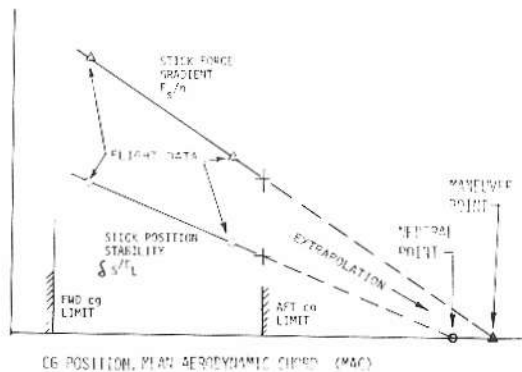
FIGURE 9 IDEAL LONGITUDINAL STABILITY



The stick force curves intersect at the trim condition in the 1.0g case. The 1.5g curves are parallel to their 1.0g counterparts with the forward c.g. pair of curves separated farther than the aft c.g. pair. Stick force per g is independent of speed or lift coefficient in this ideal case but it varies strongly with c.g. position.

Figure 10 shows the extrapolation of these idealized data to determine the neutral point and maneuver point. The slopes of the stick position stability data for the one g case are plotted on a cg scale and extrapolated to the zero value of slope to determine the cg position for neutral static stability or the neutral point (NP). Similarly, the stick force gradients are plotted and extrapolated to the zero stick force gradient point or maneuver point (MP). In truth, the maneuvering stick position data yield the stick-fixed MP while the stick force data give the stick-free MP. The difference between these two terms is small compared to the accuracy of this kind of data and is neglected in this analysis.

FIGURE 10 METHOD OF COMPUTING NEUTRAL POINT



Figures 11A and 11B plot the Blanik L-13 flight data and substantial difference is seen between theory and test. At high speeds aeroelastic forces may distort the glider geometry and at low speeds the aerodynamics tend to become non-linear. Uncertainties about the airspeed calibration and errors in setting up the flight conditions and recording the data all add noise to the signal. The straight lines overlaying the data points on the position stability plot are the author's opinion of a reasonable linearization of those data. The stick force curves were read at the C_L corresponding to 1.4Vs when solving for the MP in accordance with the OSTIV requirements.

The resulting extrapolations show for the Blanik a .54MAC NP and a .55MAC MP with an uncertainty of at least several per cent MAC. Since the aft cg limit of this glider is .38MAC, the static margin is approximately .16MAC. The stick force gradient at this aft limit and 1.4Vs is about 6.0 kg per g.

FIGURE 11a BLANIK LONGITUDINAL STABILITY

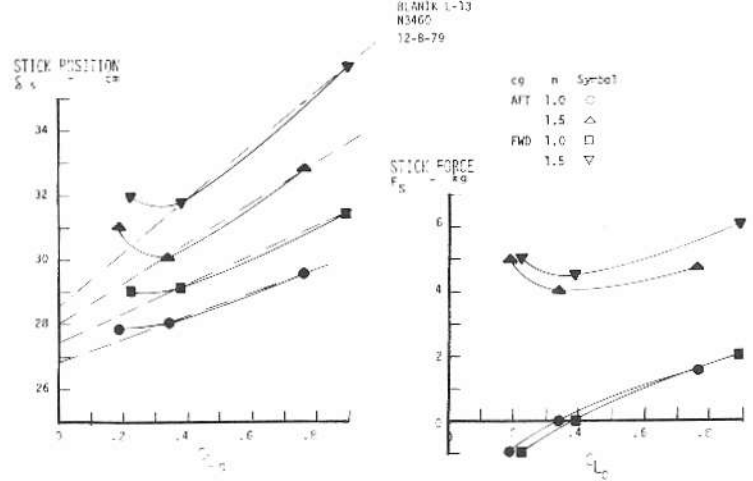
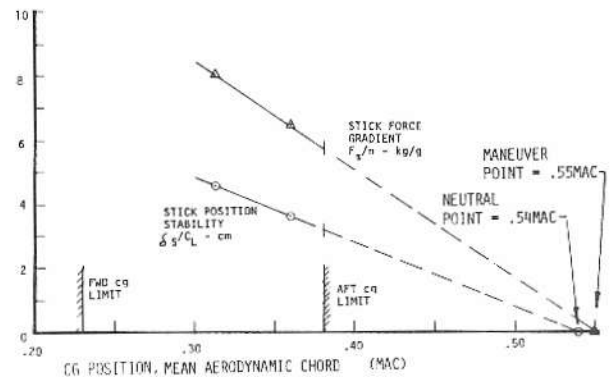


FIGURE 11b BLANIK LONGITUDINAL STABILITY



Figures 12A and 12B show the flight data for the Pilatus B-4. In this case the cg was moved .17MAC between the two loadings compared to only .05MAC for the Blanik. The confidence in the accuracy of the Pilatus extrapolation to the NP is therefore much higher than for the Blanik. The large non-linearities seen at the high speed end of the Blanik data are missing from the Pilatus results lending a further increase in confidence to the computed value of the Pilatus NP.

FIGURE 12a PILATUS LONGITUDINAL STABILITY

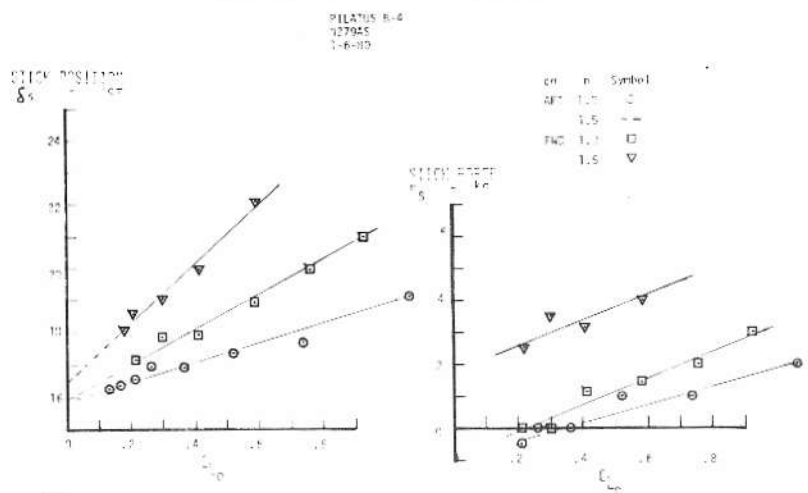
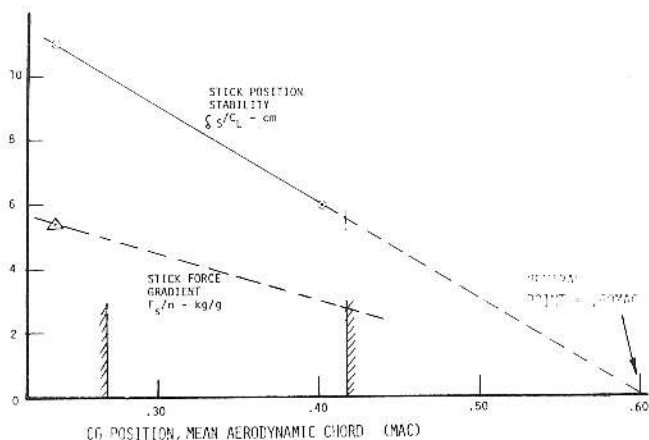


FIGURE 13 RELATIVE LONGITUDINAL STABILITY



Looking at Figure 7 it is seen that several of the gliders had system friction greater than that allowed by the requirement. Turning to Figure 13, half of the gliders flown failed the "return to trim" requirement although satisfying the friction requirement. The positive static stability requirement was met by all of the gliders flown although this was not demonstrated at the aft limit for the gliders flown without cg variation. The stick force gradient requirement was also met by all of the gliders flown (with the same stipulation concerning those flown at only one cg). Five of the nine gliders ground tested satisfied the stiffness (compliance) requirement as seen on Figure 8.

Difficulty was encountered in stabilizing the aft cg, 1.5g maneuvering condition in the Pilatus and the MP was therefore not computed. The stick force gradient at the aft cg limit was estimated from the forward cg maneuvering data by using the conservative assumption that the MP and NP were equal.

Conclusions

Requirements can be examined from two viewpoints. The first considerations are "What is required for flight safety? Is a glider airworthy?" These are the concern of requirements having legal weight such as the FARs. One would expect that characteristics affecting flight safety would have Cooper-Harper ratings of 3.5 or better. The other viewpoint is "What is required for elegance, what are the qualities that make flight more enjoyable, and why is one glider more pleasant to fly than another?" Favorable answers to these questions are probably associated with Cooper-Harper ratings of 1.5 or better.

The Pilatus NP was estimated to be .60MAC, equivalent to a .18MAC static margin. The stick force gradient at the aft limit and at 1.4V_S was estimated to be 2.7kg/g.

Six different gliders were flown and the test results are summarized on Figure 13. The table is incomplete since the cg was varied only on the Blanik and the Pilatus. The first four columns show the criteria for longitudinal stability that were measured. The next column repeats the static friction measured during the ground tests and the last column shows the "return to trim" error computed from the static friction and the stick force stability term.

Compliance with the OSTIV requirements can be examined by reference to Figures 1, 7, 8 and 13.

With respect to safety, the author is of the opinion that the OSTIV requirements (those listed on Figure 1) are adequate. The "return to trim" requirement (2.412) may be too severe. The addition of a maximum value for lost motion would be appropriate, say, no more than 5% of full stick travel. Otherwise, the OSTIV list is necessary and sufficient to describe airworthy longitudinal characteristics.

FIGURE 13 FLIGHT TEST DATA SUMMARY

- NOTES:
 1. DATA CORRECTED TO AFT CG LIMIT, 1.4 V_{STALL}, MAX WEIGHT
 2. CG LOCATION UNKNOWN WHERE NOTED
 3. COMPUTED TRIM ERROR, $\Delta V = \frac{F_r}{2(F_s/\Delta V)}$

	STABILITY			STATIC MARGIN	FRICTION	RETURN TO TRIM ERROR (NOTE 3)
	STICK POSITION	STICK FORCE	STICK FORCE GRADIENT			
	$\frac{ds}{dv}$	$\frac{dF_s}{dv}$	$\frac{dF_s}{dn}$	MAC	F _r	$\Delta V/V_{stall}$
	cm/mph	kg/mph	kg/g		kg	
BLANIK N3460	.090	.06	5	.14	1.6	.36
K-8 CF-PVL	.089	.05	--	(NOTE 2)	0.75	.22
LIBELLE N161D	.070	.05	2	(NOTE 2)	0.2	.06
K-13 N1749	.020	.06	5	(NOTE 2)	1.3	.31
PHOENIX A N264K	.055	.011	0.6	(NOTE 2)	0.6	.70
PILATUS B-4 N279AS	.064	.073	2.7	.18	0.8	.14
OSTIV REQUIREMENT	> 0	> 0	> 0.5	> 0	< 1.5	< .20

It is tempting to write a list of criteria for elegance. The author believes the ideal system would totally lack friction, lost motion, compliance and mass. All of the forces would be linear and light. The stick force gradient would be more than 1 kg/g but less than 3 kg/g. Since a very low stability gradient would provide adequate signalling of speed changes with such a high quality mechanical system, the static margin could range between 5 and 10% MAC.

Of course, the zero values suggested of the ideal system are not practical. However, a realistic system probably could be built with no more 0.1 kg friction, 1 mm lost motion and 0.3% full travel per kg compliance. The mass of the system should be as low as possible consistent with structural safety. (The compliance and mass criteria tend to be in opposition, a very rigid system is apt to be heavy.)

Caveat

The testing reported here was exploratory and the resulting data should be considered tentative. The purpose of this report was to stimulate more testing of this type, it was not intended to categorize the gliders tested. These were not calibrated tests such as would be performed for certification and substantial errors may be present in the data. The gliders were all flown in the condition they were encountered except for the installation of the test instrumentation. Some of the gliders were tied down outdoors with no protection from the elements and others were in superb competition condition. The state of the maintenance undoubtedly affected some of the characteristic measured.

The ideal criteria listed under "conclusions" infers that low static margins may be desirable. This is an area where there are very strong opposing factors. For example, the favorable attributes of reduced static margin are:

1. Improved maneuverability, lower stick force gradient.
2. Reduced dependence on the trim system since the stick force change with speed is low.
3. Improved performance. L/D varies with static margin and is maximum at a very low value of stability.

The unfavorable consequences of decreased static margin are:

1. Increased difficulty maintaining steady flight with respect to airspeed and load factor, especially in rough air.
2. Increased possibility of encountering a stall during low speed flight and increased severity of the consequences of a stall such as a greater spin tendency and more difficult spin recovery.

If the c.g. is moved behind the neutral point (negative static margin) things can become much worse. Flight will tend to be oscillatory and in an extreme case a disturbance can cause divergence with complete loss of control and possible structural failure depending on speed.

During the course of these tests the author had the unusual experience of flying with the cg near its maximum fore and aft limits on consecutive flights within an hour. He was surprised by the dramatic difference in the ability to fly the test conditions caused by the approximate doubling of static margin. At the forward limit airspeed and load factor were simultaneously controlled with ease. At the aft limit (in smooth air) most attempts to set up a steady 1.5g condition failed throughout the speed range.

References

1. Bennett, A. G. Jr., "Pilot Evaluations of Sailplane Handling Qualities," Mississippi State University, NA3A CR 2960, 1978.
2. "OSTIV Airworthiness Requirements for Sailplanes," December 1966.
3. Irving, F. G., "An Introduction to the Longitudinal Static Stability of Low-Speed Aircraft," Pergamon Press, London, 1966.
4. Horikoshi, Jiro, "A Research on the Improvement of Flying Qualities of Piloted Airplanes, Reduced Stiffness Concept Applied to Elevator Control System" Institute of Space and Aeronautical Science, University of Tokyo, 1965.
5. Aleksandrowicz, R. and Lucjanek, W., "Sailplane Stiffness Measurements," Warsaw Polytechnic School, Swiss Aero Review, 1959.
6. Phillips, W. H., "Preliminary Measurements of Flying Qualities of the Japanese Mitsubishi OO Pursuit Plane," NACA MR, May 5, 1943.
7. "Joint Airworthiness Requirements for Gliders," SSA draft proposal to FAA, 1979.
8. Pilot's flight handbooks and weight and balance documents of reported aircraft.