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Rolling Tail Design and Behavior as Affected by Actuator Hinge Moment Limits

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Experience with the B-1 airplane has illustrated some problems that can be encountered with rolling tails. Stabilizer actuators large enough for pitch control can generate large tail rolling moments and high loads in the tail support structure. At high speeds, undesirable behavior of the flight control system can be encountered if the actuator hinge moment limit is reached. The measures used to avoid or deal with such problems on the B-1 are explained. The paper is presented as a case history to show the various interrelated consequences arising from the design decision to use a rolling tail, with particular attention to the effects of the actuator hinge moment limit.

Introduction

As a high-performance bomber, the B-1 was designed for low-altitude flight at high subsonic speed, and for supersonic flight at high altitude. Its configuration is shown in Fig. 1. The design was based on use of a variable sweep wing, with a range of sweep angles from 15 to 67.5 deg. For longitudinal stability and control, an all-moving horizontal tail was selected. For roll control, a combination of a rolling tail and spoilers was selected. (A rolling tail is one that generates rolling moments by differential deflection of the right and left stabilizers.) In high-speed flight, with the wings swept back, roll damping and inertia are low. For this condition, the rolling tail provides substantial roll control effectiveness. With the wings forward, however, the rolling tail alone is not adequate, and so the spoilers are needed for roll control in cruise and low-speed flight. The stability and control augmentation functions were assigned to the rolling tail because of the aerodynamic nonlinearities of the spoilers. Also, roll trim was assigned to the rolling tail to avoid the drag that would result from deflecting spoilers for roll trim. Another consideration was that the rolling tail could provide a sort of vernier control for small stick deflections, so that a dead band could be used in the spoiler control. This avoids possible drag due to small steady spoiler deflections.

Thus a number of considerations during the design process led to the use of the rolling tail. This meant some complication of the control system and the necessity of designing the tail support structure for substantial tail rolling moments. These disadvantages were believed to be manageable and were considered to be outweighed by the necessity of meeting the overall design requirements for the roll control system.

The B-1 design is used as an example in the discussion that follows to illustrate some problems that can be encountered with rolling tails. In the case of the B-1, these problems have been successfully avoided or dealt with. The discussion is presented as a case history which is thought to be interesting and instructive. It outlines some of the detailed design considerations that arose from the choice of a rolling tail. These include control system design, actuator sizing and structural loads. Particular attention is paid to the effect of reaching the stabilizer hinge moment limit. (This is the point at which the aerodynamic hinge moment is equal to the maximum hinge moment that the stabilizer actuators can produce.) The possibility of undesirable control system behavior on reaching the hinge moment limit is discussed in terms of analytical studies, simulations and flight test results. Measures used to avoid or deal with these potential problems are presented. The discussion illustrates the need in the original design to strike a balance among considerations of aerodynamic control effectiveness, structural loads and control system design. It also shows how this balance can be disturbed by later design decisions and changes in the underlying aerodynamic design data.

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Control System Description

The B-1 flight control system provides both symmetrical and antisymmetrical control of the horizontal stabilizers. Figure 2 is a simplified schematic of the portion of the system that converts pitch and roll commands into right and left stabilizer commands. The behavior of this part of the system is of interest when the hinge moment limit is reached.

Longitudinal stick motion is transmitted through a push-rod and cable system to the pitch master servo shown in Fig. 2. An electrical signal proportional to stick displacement is also generated and fed to the pitch SCAS servo. The pitch SCAS servo provides stability augmentation by responding also to aircraft pitch rate and normal acceleration. The mechanical sum of the outputs of the two pitch servos is the total pitch command to the tail.

Lateral stick motion generates an electrical signal which goes to the roll SCAS servo. This servo provides stability augmentation by responding also to roll rate. The roll SCAS servo output is the roll command to the tail.

The mixing linkage shown in Fig. 2 generates the right and left stabilizer commands. These commands go to the servo valves which operate the right and left stabilizer hydraulic actuators.

The override bungees are devices for limiting the loads in the control linkages. Springs in these devices yield when the loads reach preset values. Loads can build up in the linkages if the actuator servo valves are bottomed. This can occur if the stabilizer is against its mechanical stop or if it has reached its hinge moment limit.

In the course of a dynamic maneuver, it is possible for the aerodynamic hinge moment to build up to a value greater than the maximum hinge moment that the actuators can produce. In this case, there are relief valves that will open to limit the hinge moment by allowing the stabilizer to back off.

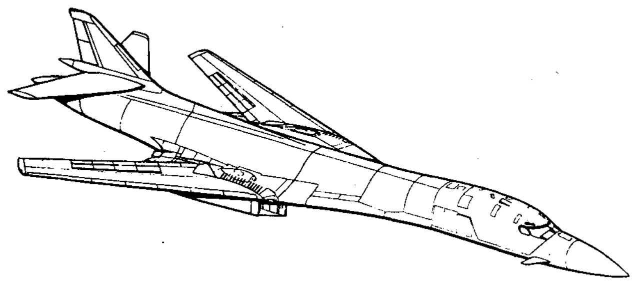


Fig. 1 The USAF/Rockwell B-1 bomber.

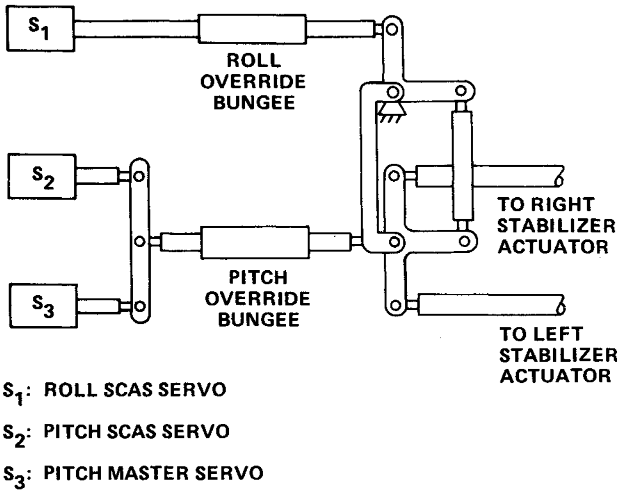


Fig. 2 Control system mixing linkages.

Actuator Sizing

The stabilizer actuators must first of all be adequate for pitch control. One view of this requirement is the following. The horizontal tail is put on the airplane to stabilize and control the wing/fuselage combination. In the aft portion of the allowable c.g. range, the wing/fuselage combination is normally unstable. The tail supplies stability, and it must always be able to generate enough tail lift to overcome the unstable tail-off moment. The actuators, in turn, must provide sufficient hinge moment to position the tail to the angle that produces the necessary tail lift. Thus the requirement is that the actuators be big enough to manage the unstable tail-off pitching moments. At the forward c.g. limit, the wing/fuselage combination is normally stable. Here, the requirement is that the actuators be big enough to trim the airplane over the desired range of angle of attack.

Next consider roll control. The actuators must be designed for specified roll maneuvers and rolling pullouts. In a rolling pullout, the higher hinge moment will occur on the stabilizer for which the hinge moments due to roll and pitch control inputs are additive. In the case of the B-1, a rolling pullout design condition determined the maximum required hinge moment for one stabilizer. The actuators were sized accordingly. Now while the critical design condition had the maximum hinge moment on only one of the stabilizers, the maximum tail rolling moment that could be generated would occur if the full available hinge moment were applied to both stabilizers. In other words, the actuators could readily develop excess tail rolling moments. Either the tail support structure had to be designed for these moments, or some means would have had to be found for limiting the capability of generating tail rolling moments. It was decided to design for the maximum tail rolling moment that the actuators could produce.

Possible hydraulic system failures also need to be accounted for. For the B-1, full mission capability is required with a single failure, and the ability to get home safely is required after a second failure. To meet these requirements, the airplane has four independent hydraulic systems. If the actuators can do their job with one hydraulic system failed, then they have excess capacity in the normal situation of no failure. In the pitch case, this means an extra margin above the requirement for adequate control. In the roll case, however, it means large tail rolling moments for structural design.

To summarize, the selection of actuator size for a rolling tail needs to balance several considerations. First, the actuators must be large enough to insure against running out of pitch control and to meet rolling pullout design requirements. However, they should be no larger than necessary because excess capacity means excess tail rolling moments for structural design. But also, they must be adequate in case of failure of a hydraulic system.

Tail Support Structure

The tail and its support structure must first of all be designed for the symmetical tail loads that are required to balance the tail-off moments and to maneuver the airplane in pitch. Also, the design must consider gust loads and unsymmetrical loads due to sideslip. Finally, the structure must be designed for the antisymmetrical loads due to differential stabilizer deflection.

At a given flight condition, the maximum load that can be developed on one stabilizer depends on the maximum hinge moment that can be applied by its actuators. Each stabilizer is designed to take the maximum load in either direction, regardless of what the load is on the other stabilizer. When it comes to designing the tail support structure, however, there is a basic difference between the symmetrical and antisymmetrical cases. In the symmetrical case, the resultant of the loads on the two stabilizers is a vertical force, while in the other case the resultant is a rolling moment.

On the B-1, the horizontal tail is mounted on the vertical tail. The vertical tail structure below the horizontal tail can readily be designed to take forces in the vertical direction, but it provides only a small base for resisting tail rolling moments. The more critical nature of the antisymmetrical case is illustrated in Fig. 3. The structure below the horizontal tail has to have added strength to handle the tail rolling moment that results from the use of differential stabilizer deflection.

If the tail had been mounted down on the fuselage, the tail rolling moment would have gone directly into the fuselage structure instead of being imposed on the vertical tail structure. In fact, at an early stage of the B-1 design, the tail was on the fuselage. Then wind tunnel tests showed that for aerodynamic reasons the tail had to be moved up to its present location. This design change increased the structural penalty associated with the use of differential stabilizer for roll control. So it is seen that carefully balanced design decisions can be disturbed by subsequent design changes.

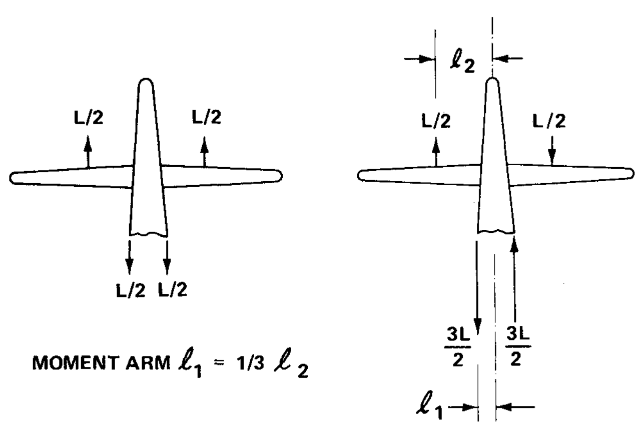


Fig. 3 Symmetrical vs antisymmetrical tail support loads.

Tail Planform Change

Another change that occurred in the course of the design program was an increase of 10 deg in the horizontal tail sweep angle. This change was made to reduce tail drag. The need for making this change came up after the design of the actuators and the tail support structure had been frozen. The location of the hinge line with respect to the tail root section was frozen, and so the increase in sweep angle moved the tail aerodynamic center aft with respect to the hinge line. This had two main effects. For longitudinal control, it reduced the amount of tail load that could be generated by given hinge moments applied symmetrically by the actuators. This reduced the margin between available and required tail loads. For lateral control, it reduced the amount of tail rolling moment that could be generated by given hinge moments applied antisymmetrically by the actuators. This reduced the antisymmetrical design loads for the tail support structure. This is another example of a design change that altered the balance of the original overall design.

Calculation of Design Hinge Moments

The stabilizer actuators, as previously discussed, are sized to provide adequate capacity for the design maneuvers. Thus the design hinge moments need to be calculated with good accuracy. This involves a number of considerations. First, for equilibrium in pitch, the tail load must balance the tail-off pitching moment. The tail-off characteristics are not always easy to estimate, and are best determined from wind tunnel tests. Absolute values of moment coefficients are needed, not just moment curve slopes. Thus all applicable corrections to the wind tunnel data must be properly applied. Also, the effects of the propulsion system on airframe pitching moments have to be accounted for. From the balancing tail load, the hinge moment is determined. This requires estimating the location of the tail aerodynamic center, which gives the moment arm of the tail lift about the hinge line. Also, there may be a finite hinge moment at zero tail lift to be accounted for. (The B-1 tail has a symmetrical airfoil section, but variation in local flow angle across the span of this swept-back tail gives an appreciable hinge moment at zero lift.) Hinge moments due to longitudinal and lateral maneuvering tail loads are determined by the tail lift curve slope and aerodynamic center location. The main point to be noted is that the actuator sizing depends directly on knowledge of the airframe aerodynamic characteristics, including in particular, the tail-off moment coefficients.

Hinge Moment Limiting in Roll Maneuvers

B-1 flight test experience showed undesirable effects caused by reaching the stabilizer hinge moment limit in lateral-directional maneuvers. The particular instance that first showed this behavior came during some lateral-directional stability-and-control testing at a Mach number of 0.85 at 5000 ft. The airplane was at a relatively light weight and an aft c.g. (5% ahead of the aft limit). The yaw damper was turned off so that the Dutch roll mode was lightly damped. The maneuver was initiated with a rudder pedal doublet input. This caused an oscillatory rolling and yawing motion with abnormally large sideslip angles. The roll SCAS responded by providing differential stabilizer proportional to roll rate. The magnitude of the motion was great enough to drive the left stabilizer and then the right stabilizer to the hinge moment limit. What this did was to cause an uncommanded response in pitch, with the load factor going up to about 1.7. Figure 4 presents time histories of the principal quantities that show this behavior.

To explain this occurrence, consider the point at which the right stabilizer reaches its hinge moment limit at a deflection of about +5.8 deg. The actuator cannot move it any further. Meantime, the left stabilizer keeps moving. In so doing, it produces a more negative rolling moment, and also a nose-up

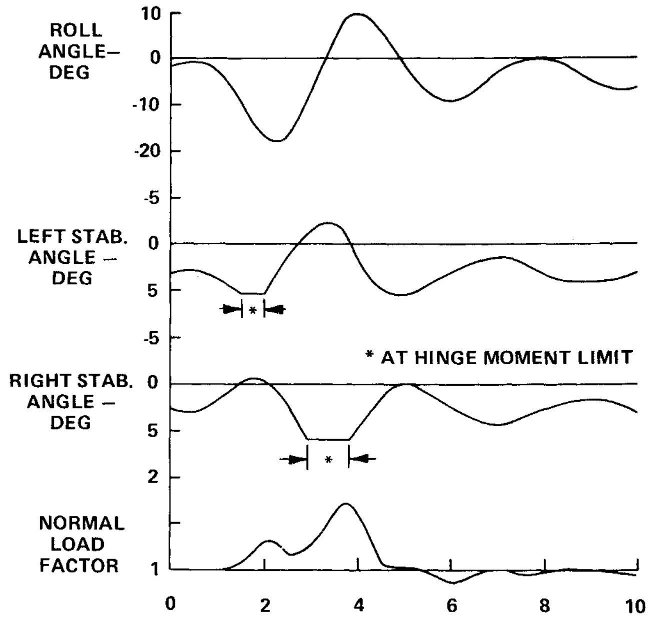


Fig. 4 Uncommanded pitch response in a lateral maneuver—flight 1-21.

pitching moment. It is this pitching moment that causes the uncommanded response in normal load factor. Just before time 4.0 in Fig. 4, the roll command drops to a value where the right stabilizer comes off the hinge moment limit and normal control system operation resumes.

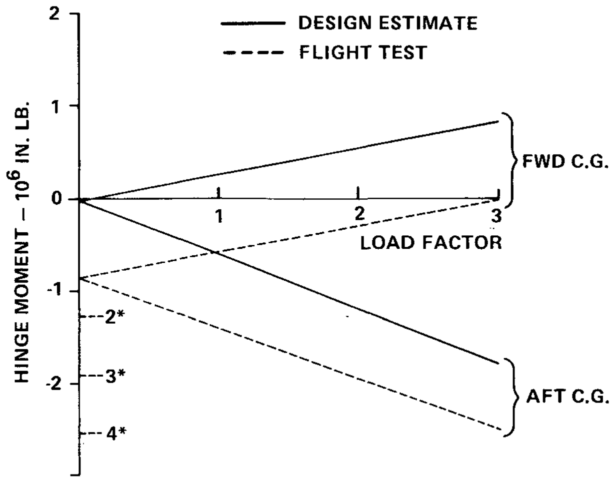
Now refer to Fig. 2 and consider that the roll override bungee is set to yield more easily than the pitch bungee. It appears that if the right stabilizer is stalled, if the pitch command is constant, and if the pitch bungee does not yield, then no further roll command can get through to the left stabilizer. Instead, the output of the roll SCAS servo should be taken up by yielding of the roll bungee. There are two difficulties with this argument. The first is that when the stabilizer stalls, the linkage is free to keep moving until the actuator servo control valve is bottomed. The left stabilizer responds normally to this linkage motion. The second trouble arises from the fact that there is considerable flexibility in the pitch linkage, primarily from a nonlinear gearing unit downstream of the pitch master servo. Once the control valve is bottomed, loads start to build up in the linkage. While the pitch bungee does not yield in response to these loads, the pitch linkage does, because of its flexibility. This permits motion of the left stabilizer until the linkage loads build up to the point where the roll bungee finally yields.

The point that is illustrated is that in the design of a rolling tail control system, detailed attention must be given to system behavior when one stabilizer stalls at its hinge moment limit. It must be remembered that, in high-speed flight, it takes very little movement of the unstalled stabilizer to produce appreciable pitch response, particularly with aft c.g. locations.

Hinge Moments Required to Trim

Comparison of flight test data with predictions showed that for the low-altitude, high-speed (LAHS) flight regime, stabilizer angles to trim are more positive than predicted, and accordingly, stabilizer hinge moments to trim are more negative than predicted. The comparison is shown in Fig. 5, where hinge moment for trim is plotted against load factor for forward and aft c.g. positions. Also shown are the actuator hinge moment limits with four, three, and two hydraulic systems operating.

Some comments on Fig. 5 may be helpful. Because hinge moment is directly related to tail load, positive hinge moments can be associated with down tail loads and negative hinge



*HINGE MOMENT CAPACITY WITH INDICATED NUMBER OF HYDRAULIC SYSTEMS OPERATING

Fig. 5 Hinge moments for trim—estimated vs flight test.

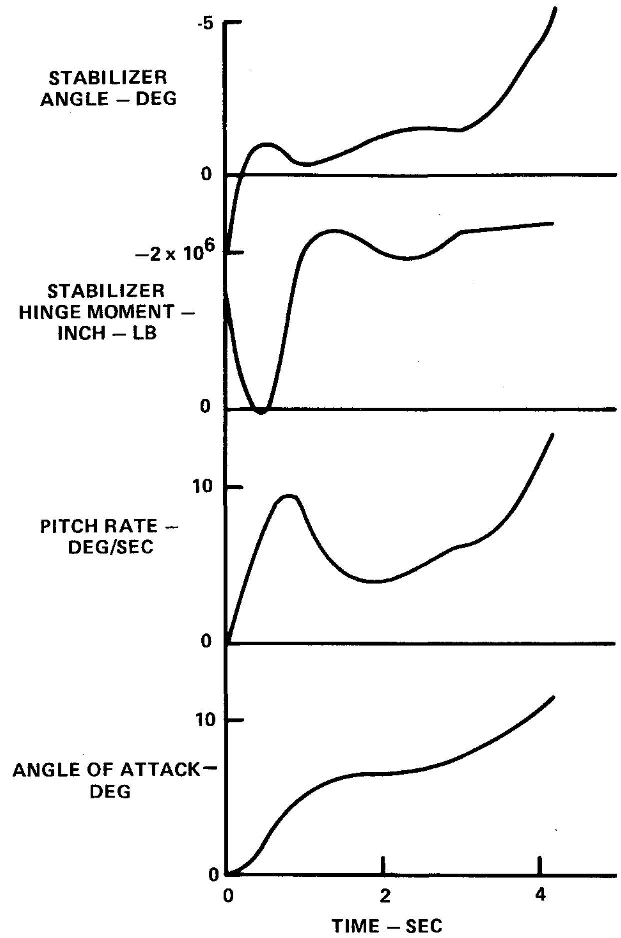


Fig. 6 Pitch control divergence at hinge moment limit (from ASD hybrid computer).

moments with up tail loads. At the forward c.g., the wing/fuselage combination is stable and so an increasing down tail load is required to trim at increasing load factors. At the aft c.g., the tail-off moments are unstable. An increase in angle of attack means a more positive (nose-up) moment of the wing/fuselage combination. Thus, an increased up tail load is required to maintain equilibrium. Accordingly, in Fig. 5, the forward and aft c.g. curves have slopes of opposite sign.

The flight test curves in Fig. 5 show a substantial shift in the negative hinge moment direction. The slopes of the curves are in agreement with design estimates, and so the difference can be associated with the hinge moment or tail load at zero lift. This implies that the source of the difference is the tail-off zero-lift pitching moment coefficient.

The design estimate curves of Fig. 5 indicate a reasonably well-balanced situation, with the hinge moments covering a range of positive and negative values. The flight test curves, however, are biased substantially in the negative direction. This means that it is easier than intended to reach the negative hinge moment limit when the center of gravity is aft.

The overall point is that a discrepancy in an aerodynamic parameter (tail-off C_m at $C_L = 0$) resulted in a reduced margin between the hinge moments required to trim and the hinge moment capacity of the actuators.

It should be remarked that the hinge moment margin is of concern only for the low-altitude, high-speed condition. The margin is improved if the dynamic pressure is decreased, and also it is better at supersonic Mach numbers where the aircraft aerodynamic center is farther aft.

Hinge Moment Limiting in Symmetrical Maneuvers

Since it was found to be easier than expected to reach the hinge moment limit, a study was made of symmetrical maneuvers in the LAHS flight condition. In this case, there is no roll control and so the discussion is just as applicable to simple, all-moving tails, as it is to rolling tails. The main concern is what happens when both stabilizers reach the hinge moment limit at the same time. (Actually, as noted briefly below, this can also occur in unsymmetrical maneuvering with a rolling tail.)

The situation that is found to be of concern is at aft c.g. locations where the tail-off moment curve is unstable. In terms of Fig. 5, the question is what happens if the load factor is increased sufficiently so that the hinge moment reaches the negative hinge moment limit.

At the aft c.g. locations, as seen in Fig. 5, the hinge moment becomes more negative as the load factor is increased. This can be understood in terms of the increasing up tail load required to balance the unstable nose-up tail-off pitching moment. It can also be said that in a pull-up at an aft c.g., the effect of stabilizer deflection on hinge moment is more than counterbalanced by the effect of the increasing angle of attack. This is not a peculiarity of the B-1; rather, it is typical of airplanes with all-moving tails for aft c.g. locations.

Now suppose that in a symmetrical pull-up maneuver both stabilizers reach the hinge moment limit. To recover, the pilot moves the stick forward to make the stabilizer trailing edge go down. But because the limit has been reached, the actuators cannot move the stabilizers in this direction. If the pilot moves the stick back, the stabilizer trailing edge will move up without difficulty, but the airplane will then trim at a higher angle of attack and at an increased load factor, which makes the hinge moment more negative and the situation worse. Likewise, a roll input can only make things worse. Therefore, control of the airplane is jeopardized unless, in the course of the maneuver, Mach number and dynamic pressure fall off appreciably. If the negative hinge moment increases to the point where the actuator relief valves open, the air loads will force the trailing edge up. This leads to an uncommanded pitch-up.

A somewhat more complex situation involving a rolling tail and unsymmetrical maneuvering also deserves mention. Suppose the airplane is maneuvering near the hinge moment limit. A roll command may stall one stabilizer and produce an uncommanded pitch response. If the resulting increase in angle of attack causes both surfaces to reach the hinge moment limit, then control of the airplane may be lost.

Several simulation programs were run to support the analysis of this situation. Figure 6 shows the results of one run which was made on the hybrid computer of the Air Force

Aeronautical Systems Division at Wright-Patterson Air Force Base. The conditions represented are the following: 1) maximum design gross weight; 2) c.g. near aft limit; 3) altitude 500 ft; 4) Mach number 0.85; 5) one hydraulic system failed; and 6) abrupt symmetrical pull-up. At time $t = 0$, it is assumed that the stick is abruptly moved aft and held at a new position. The stabilizer, starting at 2.5 deg, moves rapidly in the trailing-edge-up direction. It then continues to move as it responds to the pitch rate and normal acceleration feedback of the SCAS. The stabilizer hinge moment is initially relieved but then builds up as the angle of attack increases. Pitch rate and angle of attack respond normally to the stick input. The maximum capacity of the actuators is 1.9×10^6 in.-lb, so after time $t = 1$, they cannot move the stabilizer in the positive direction. During the time from $t = 1$ to $t = 2$, the trailing edge moves up in response to the SCAS, but from $t = 2$ to $t = 3$, it cannot move as it should in the other direction. Finally, the effect of increasing angle of attack brings the hinge moment to the point where the relief valves open: 2.25×10^6 in.-lb. The stabilizer then moves trailing edge up and the airplane responds with an uncontrollable pitch-up.

Several remarks should now be made to put this problem into perspective as far as the B-1 is concerned. There has been no instance in the flight test program in which both stabilizers were close to reaching their hinge moment limits. The simulation studies show that there is only a limited region of low-altitude, high-speed flight in which the problem can be encountered within the flight envelope. Within this LAHS region, the problem can be encountered only at aft c.g. locations and at heavy gross weights, and it affects a significant part of the weight-c.g. envelope only after one hydraulic system has failed. The measures taken to recognize and deal with the problem are discussed in the following section.

Corrective Measures

In the lateral case, the undesired characteristic is an uncommanded pitch response to lateral stick deflection when one surface reaches its hinge moment limit. What is needed is an arrangement such that when one surface stops moving because of reaching the limit, the other one stops also. Various ways of doing this have been studied, and one way has been selected for use in the B-1. To explain the principle of this method, it is noted first that at low hinge moments the stabilizer deflection rate is proportional to the control valve opening. To detect the approach to the hinge moment, a stabilizer rate measurement is compared to a valve deflection measurement. The difference between the two measurements is a measure of slowing of the stabilizer motion due to the hinge moment. This difference signal is fed to a circuit which reduces the roll channel gain as the difference signal increases. The gain reduction inhibits the motion of the unstalled stabilizer. This scheme has been evaluated on a moving-base flight simulator and has given satisfactory results. It has not yet been tested in flight.

The longitudinal case has been handled by defining restrictions on the weight/c.g. envelope. The restriction cuts off the aft c.g./heavy-weight corner of the envelope. These restrictions were determined by several simulation studies, including evaluation by engineering pilots on a moving-base simulator. The restrictions were found to be necessary only below 10,000 ft. They do not limit the ability to perform any of the airplane's missions. Since the occurrence of a hydraulic system failure is not predictable, the restrictions are based on the assumption of one hydraulic system having failed.

Another approach to the longitudinal case has been studied. The idea in this case is to incorporate camber in the horizontal tail. This will alter the hinge moment at a given tail load. In terms of Fig. 5, this is a way of shifting the flight test curves back up to the location of the design estimate curves. This restores the intended margin between the operating hinge moments and the negative hinge moment limit.

Concluding Remarks

The above discussion has illustrated the interrelated aspects and consequences of an original design decision, in this case the decision to use a rolling tail. The need for roll control effectiveness was balanced against penalties in the areas of structural loads and control system complication. The balance was disturbed at an early stage of the program when the horizontal tail was moved up from the fuselage onto the vertical tail and later when the tail sweep angle was increased. The design balance was further affected when it was found that the flight test hinge moments were biased in the negative direction from the design estimate. Further control system complication and certain c.g./weight restrictions were needed. With these corrective measures, the airplane is fully capable of accomplishing its missions. It is seen that the ability to accommodate the effects of changes in assumptions and design data can be an important and valuable attribute of the original design.

With respect to rolling tails specifically, several points have been made. Tail rolling moments are likely to be critical in designing the tail support structure. Stabilizer actuators large enough to provide an adequate margin for pitch control are likely to provide excess roll control. The effects of reaching the hinge moment limit with one or both stabilizers need to be examined carefully and in detail.

This is an example of a case in which the control system design was basically dependent on a particular item of aerodynamic design data, namely, the zero-lift tail-off pitching moment coefficient. This coefficient proved to be different from the design estimate. The result was that a good part of the intended margin between actual hinge moments and the hinge moment limit of the actuators was lost.

A comment can be made about the use of "active control technology" to get along with tail surfaces of reduced size, in general. If the control surfaces must be active to keep the airplane stable, then they must never reach the limit of their authority. Some of the considerations discussed above are very much applicable to this case.

Acknowledgement

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