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~~NAVY AIR SYSTEMS COMMAND~~
~~WASHINGTON, D.C.~~
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**Report of the
First Piloted Aircraft
Powered Surface Control System
Symposium**

October 1949

**Bureau of Aeronautics
Airborne Equipment Division
Department of the Navy
Washington, D.C.**

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FOREWORD

This report contains the proceedings of the First Piloted Aircraft Powered Flight Control System Symposium. The Bureau of Aeronautics has felt the need for this type of meeting for some time, in view of the great problems associated with the design of flight control systems for high performance aircraft, especially since power boosted and power operated control systems became a necessity for high speed and heavy aircraft. This meeting was excellently responded to by the Aircraft Industry. The need for a medium of sharing of design information and techniques on flight control systems was recognized by all, and consequently all participants came well prepared, which resulted in a successful meeting. The Bureau of Aeronautics extends its appreciation for the excellent cooperation of all attending, especially those who prepared papers. In addition, the Navy's appreciation is extended to all companies participating for the time allowed their people in preparing papers and attending this symposium.

The Bureau of Aeronautics, Navy Department, invites comments on the proceedings of this symposium. Similar periodic symposiums on flight control systems are contemplated for the future. Appropriate time and places will be announced at a later date.

L. Morse Chatter,
Chairman, 1st Piloted Aircraft
Powered Surface Control System
Symposium

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WELCOME

By

Rear Admiral Lloyd Harrison

Assistant Chief, Bureau of Aeronautics Design and Engineering Group

Gentlemen, my purpose here is to welcome you to this conference and to this type of conference. I am not one of the people who could contribute anything in a technical way, of course, to the special things you are considering now, but I do want to indicate that I think this gathering is a very forward-looking affair and something we should have more of in the future. From reading the titles of the papers, it is clear that this has the technical standing of an interesting aeronautics meeting, although because of the nature of the material involved, it is probably not the sort of thing that should be published at this particular time.

The question of sharing information and progressing together as far and as fast as we can in a short length of time is an important one, and the technique for it is something that we should all be interested in developing. I find that in this field and also in other fields of so-called detailed design, i.e., detailed fields of design in aircraft areas, there is a wide need for sharing of information. A lot of the government's money, your money, the taxpayer's money is used in seeking from each company information that has repeatedly been sought by others.

Last month I made a short trip to England and I found that there had been a considerable amount of sharing, by the different manufacturers, of information. Each one knew the difficulties the other had been through and apparently had passed on quite a bit of information concerning their difficulties and how they had taken care of them. This in spite of the fact that there was strongly competitive spirit among the heads of the companies in engineering matters, as there is, and I hope will continue to be, in our country.

As I say, I have nothing to contribute technically to your meeting but I want to welcome you here. The space that you are using is something that we congratulate ourselves on, but it is in no sense a BuAer meeting; it's your meeting and I'm sure you are going to do useful things here. Let me welcome you again.

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OPENING

By
J. E. Sullivan

Director, Airborne Equipment Division

Gentlemen, I first want to thank each of you for coming here; in particular, those of you who have had to prepare papers. I find it very staggering as I think of the many design problems facing us in this high-speed, high-altitude era. In particular, we are very much concerned here in the Bureau on this question of control system design, for as you know, there are many unsolved problems in that field. I have high hopes, however, that this particular meeting will be a very definite contribution to the advancement of the art of aeronautics and I am certain that much worthwhile information will be developed. Therefore, in view of the importance of this meeting, I consider it a very definite, distinct privilege to open it.

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CONTROL SYSTEM DESIGN OBJECTIVES

By

L. Morse Chatter

Airborne Equipment Division, Bureau of Aeronautics

Since the inception of powered controls in piloted aircraft, i.e., power boosted and power operated surface control systems, very little progress has been made in refining design procedures or coordinating development so that all designers can utilize the most modern methods. We all know that a majority of the existing powered aircraft control systems were designed by the cut-and-try formulas. We also know that each prime contractor developed his own cut-and-try formula for his first powered surface controlled aircraft. It appears that most contractors proceeded along independent channels in developing these systems without realizing that when you're dealing with a design which has been formed by intuitive cut-and-try methods, only experience resulting from experimentation or actual usage produces the answer and the more experience the better the answer. Therefore for every new aircraft design underway the experiences of all aircraft designs that exist should be considered. This means pooling of design experiences and represents the major reason for this meeting.

Is this the answer to our control system design problems? Not completely, we want to go further. Had we pooled design experiences in the past, we may have better results today. But now in addition to cut-and-try know-how we want to go considerably further and try to eliminate cut-and-try techniques. Why? Let's examine the present picture of this cut-and-try control system design procedure and see where it hurts the most. Chronologically, the first effect is the cost of a complete or simulated mockup of the airplane control system and the cut-and-try designing to produce a satisfactory system in the mockup. Second, the experimental aircraft flights where the system again is usually unsatisfactory with additional delays, costs, and cut-and-try design; then finally, the production airplane where again everything usually goes sour and we find ourselves with an airplane control system which chatters, hunts, has high breakaway forces, poor centering characteristics, is sluggish, poor trimming characteristics or poor response.

This method of designing sounds primitive, but nevertheless exists on our modern high speed aircraft. I can name any number of airplanes where anywhere from 30 to 50 flights were necessary just to cut-and-try a satisfactory control system in the production airplane and in several instances it wasn't until the 21st and 80th production airplanes were delivered that the systems were made to perform acceptably but not satisfactorily. Some aircraft today are still flying with poor control system characteristics. This type of design, gentlemen, is very costly and very dangerous. Dangerous because production aircraft are delivered with control systems that are marginally acceptable. Costly, because of delay in producing a satisfactory system, the delay in producing an acceptable aircraft and the subsequent retroactive changes. Why does this condition exist? It exists because we at no time, from the preliminary to the final installation, know what the actual control system characteristics are. We have no mathematical picture of our system from which we can trouble shoot.

The solution - We must be able to apply more mathematical methods in our engineering work. The cut-and-try methods of the past will no longer suffice because the aircraft of today and tomorrow is gradually becoming a piloted missile and the

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engineering ingenuity that goes into a missile will have to go into our piloted aircraft if they are to be successful.

What do we have basically in this control system? We have a servomechanism, the design of which today has become a science in itself. What does the designer need to know? He needs a clear picture or appreciation of the fundamental principles involved in the functioning of the servomechanism and an accurate knowledge of the properties of which the mechanisms are composed. With this knowledge, an explicit solution to the problem rather than an intuitive or experiential one should be obtainable.

There are two mathematical methods available at present by which we can study and design powered control systems; those methods which give transient responses and those methods which give frequency responses. The transient response of a system show how various forces, signals and coordinates of the system vary as a function of time when the system is disturbed in some particular way. Unfortunately, depending on the complexity of the control system, the purely mathematical methods for obtaining a transient response are extremely laborious. However, it may warrant using a differential analyzer or other equation solving machines. Transient response has the advantage of also being applicable to non-linear systems. The disadvantage of the transient response is that it is a method for analysis and will not permit synthesis as readily as a frequency response, because the coefficients in the differential equations consist of such a heterogeneous mixture of the various physical parameters involved that the effect of any one parameter is not easily determined.

The frequency response of a system is based upon the concept that if a system is disturbed sinusoidally at some point all other points will respond sinusoidally at the same frequency after the transients have died out. Then when the ratio of the amplitudes and the phase difference between the disturbances and an output coordinate are both considered as a function of frequency, they yield information as to the stability, damping, and speed of response. Frequency response can be presented in several forms and in these forms is very helpful in designing the system because the effect of each component on the system is usually capable of graphic illustration. The disadvantage of the frequency response analysis is that it requires that all considerations be made by linear analysis, and we know that hydraulic systems are non-linear and cannot always be amendable to linear functions. However, there are several ways that we can overcome these deficiencies as will be discussed in this meeting.

Now we must go one step further in applying our mathematical tools; we must consider the control system and its mechanical, hydraulic and electrical components or individual loops as a function of the overall loop which is that of the airplanes response and stability. We can develop our boost systems, power control systems, synthetic feel systems, automatic pilot systems, stabilization systems, etc., but we must always examine at some stage its effect as a parameter of the overall airplane loop.

This conference was called for the expressed purpose of presenting the latest technique of control system design so that all designers can be brought to a par level of knowledge. We in the Navy believe that a concerted effort by all concerned with a planned program for future mutually acceptable investigations will progress the art and give us more and better airplanes for our money.

The symposium is divided into two parts. The first part containing papers on control systems which were designed by the intuitive cut-and-try techniques and the second part which contains papers on control systems which utilized mathematical aids.

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EXPERIENCES GAINED WITH POWER BOOST CONTROL SYSTEMS AT REPUBLIC AVIATION

By

R. Warner

Republic Aircraft, Farmingdale, L. I., N. Y.

Republic's entry into the field of power boost control systems is comparatively recent. The first application was designed for the F-84 aileron system in 1945. It was modified quite extensively after mechanical difficulties had been encountered during the early flights. Since then it has proved to be extremely satisfactory in service.

The overall design of the F-84 aileron system is based on attaining a wing tip helix angle of .09 at $.8 V_{max}$ at sea level. This is approximately equivalent to a rate of roll of 200° per second at 475 mph. Estimates indicated that this performance would require 30° total deflection of aileron surfaces of 24% wing chord and 43% wing semi-span. An effective aileron hinge moment coefficient slope $C_{H\delta}$ of $-.00015$ would have been required to attain this angular position with desirable pilot forces. Flight experience with the P-47 aileron was more than sufficient to discourage the design of an overhang balance for such refinement. Internal balance alone could not have been used because the required chord would restrict aileron deflection. Various types of tabs were ruled out because their characteristics were considered uncertain at the Mach numbers involved. In the end a hydraulic power boost unit was chosen as the most practical method of reducing the control forces for normal operation.

However, we were anxious to provide limited rolling performance in event of failure of the boost system. Internal balance was selected for this purpose. A 30% aileron chord balance was the largest that could be used without restricting aileron travel. Estimates of the aileron hinge moment coefficients were made from wind tunnel data for similar surfaces. These indicated a control force in the neighborhood of 500 lbs. for the design condition. Later more refined estimates of aileron performances and control force without boost were made from wind tunnel data for an F-84 model. Figure 1 shows this result for sea level. The maximum boost ratio was selected at 10.8 to 1 to place the design condition within the pilot's ability. Variable boost ratio was incorporated to allow him to select the ratio suited to any particular operation.

The aileron system of the present airplane is shown in Figure 2. It is a conventional rod and bell crank arrangement with the power boost unit located adjacent to the stick. The arrangement of the original system was quite similar, but the details, particularly those of the power boost unit, were different. Redesign had been undertaken before the initial flight tests but when these disclosed poor centering characteristics, slightly jerky operation of the surface, and a tendency for easier operation in one direction than the other, this work was speeded. It was fairly evident that the major difficulties were the result of excessive friction and play throughout the system. Effort was directed towards reducing these quantities to a minimum. A comprehensive laboratory program was undertaken to trace the origin and determine how to guarantee the desired operation. Each joint in the system was analyzed carefully. Self aligning anti-friction bearings were substituted in every joint and some

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F-84 AIRPLANE ESTIMATED AILERON PERFORMANCE AT SEA LEVEL

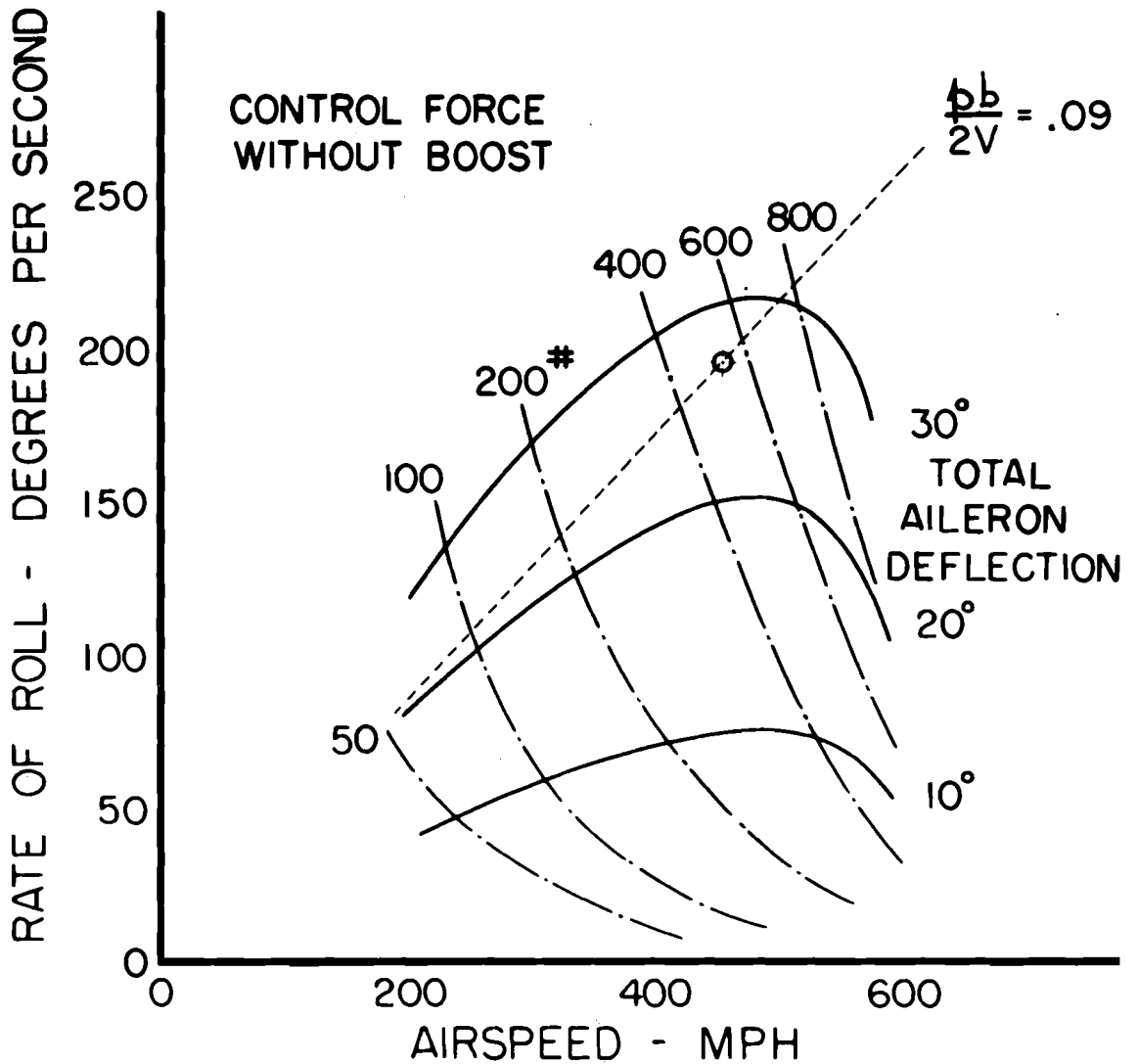


Fig. 1

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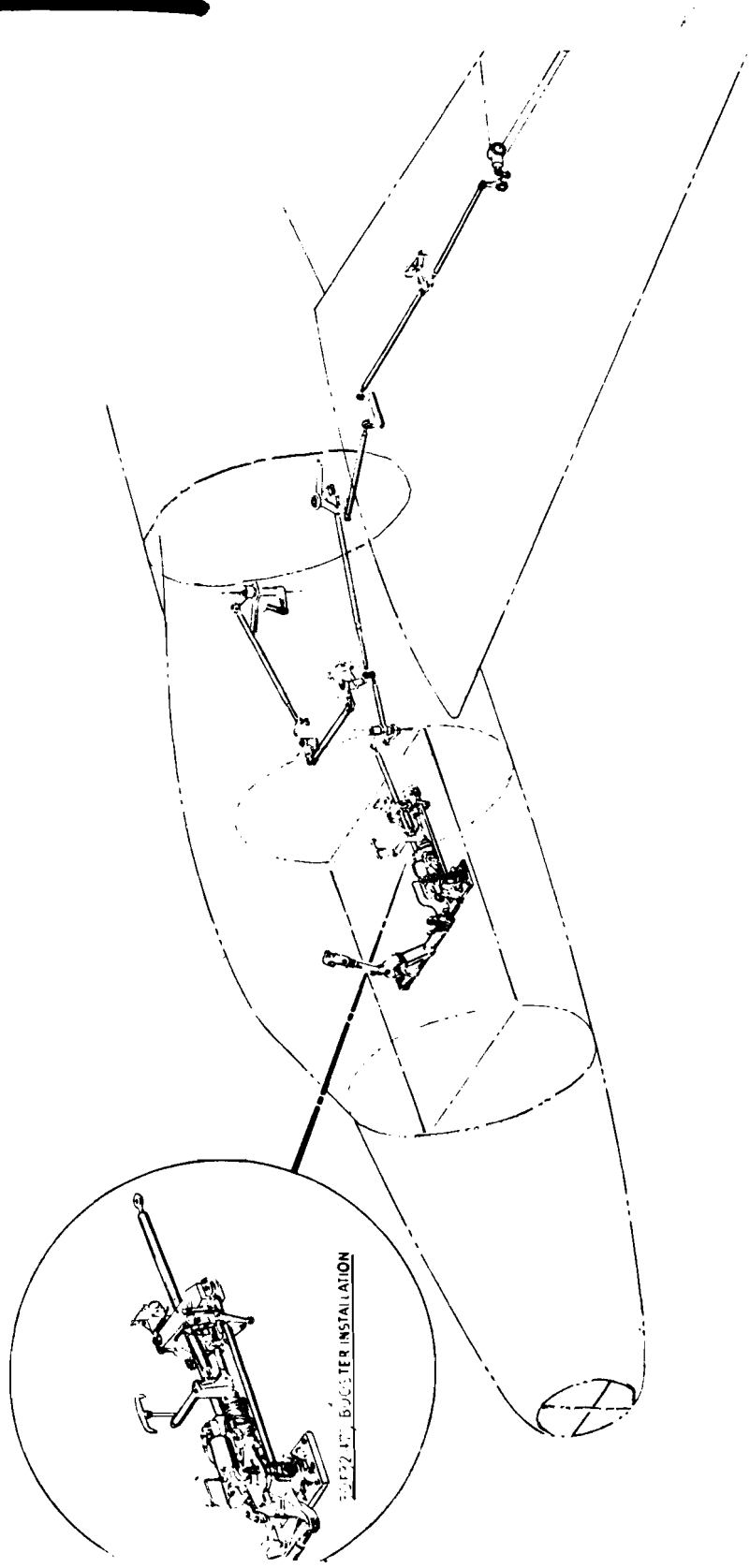


Fig. 2

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MECHANICAL ARRANGEMENT AT BOOST UNIT

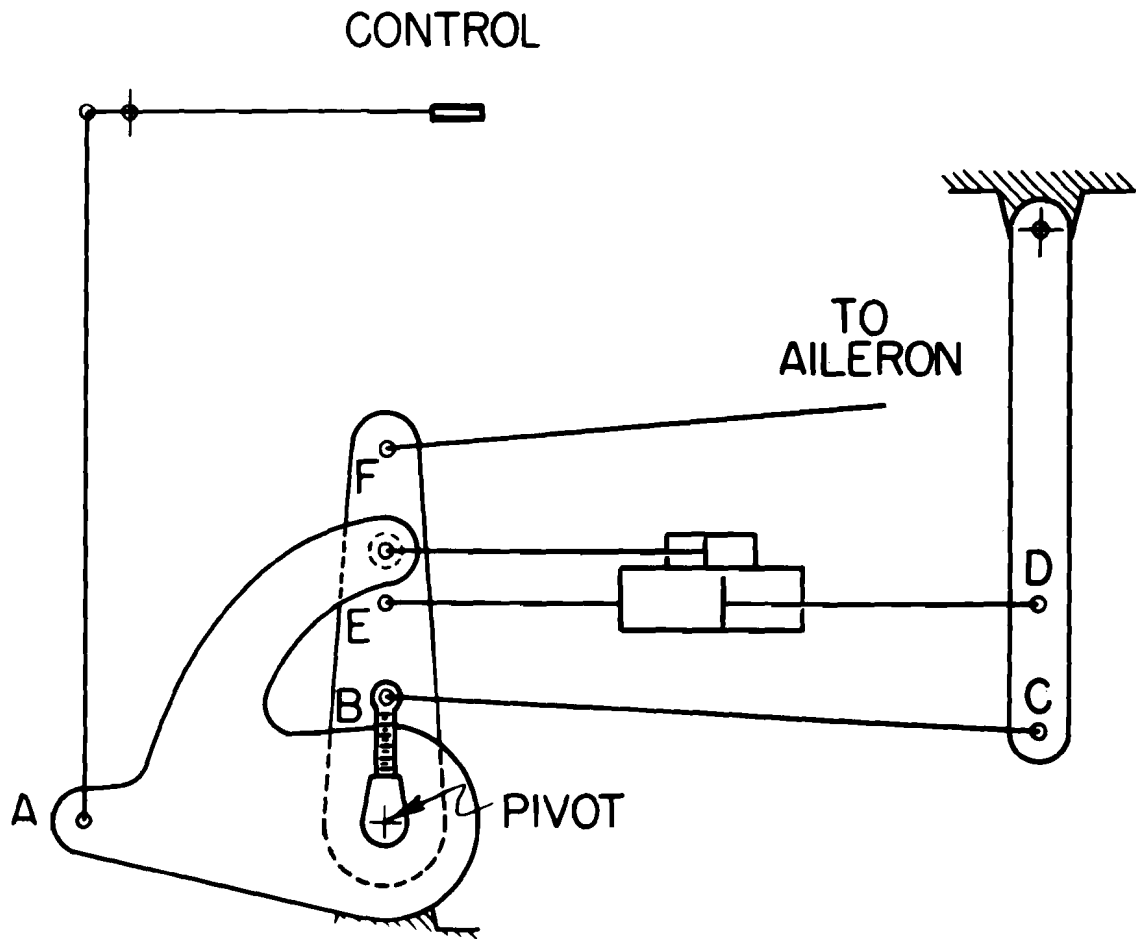


Fig. 3

joints were redesigned. The completed linkage was mounted on a test rig and checked for alignment and clearances. The new control valve and boost cylinder were checked thoroughly. Finally the parts were brought together and tested for operational characteristics. A description of the boost unit follows.

The linkage arrangement at the boost unit is shown in Figure 3. A force applied at the pilots control follows the path from A to B, C, D, E, F, and to the aileron when the boost is operating. It passes directly from A to F after the pin holding the control valve link has contacted the side of the oversized hole in the member E, F when the boost is not operating. Any motion of the pilot's control causes relative motion between the control valve plunger and the body which is rigidly attached to the

boost cylinder. The valve is constructed so that theoretically only .004" movement is required to start boost action. Any boost ratio between 4 and 10.8 can be selected by changing the position of B with respect to the pivot point. This is accomplished by an electrically driven screw. A boost disconnect is provided also. This releases the grip on the booster piston rod at D.

POWER BOOST HYDRAULIC ARRANGEMENT

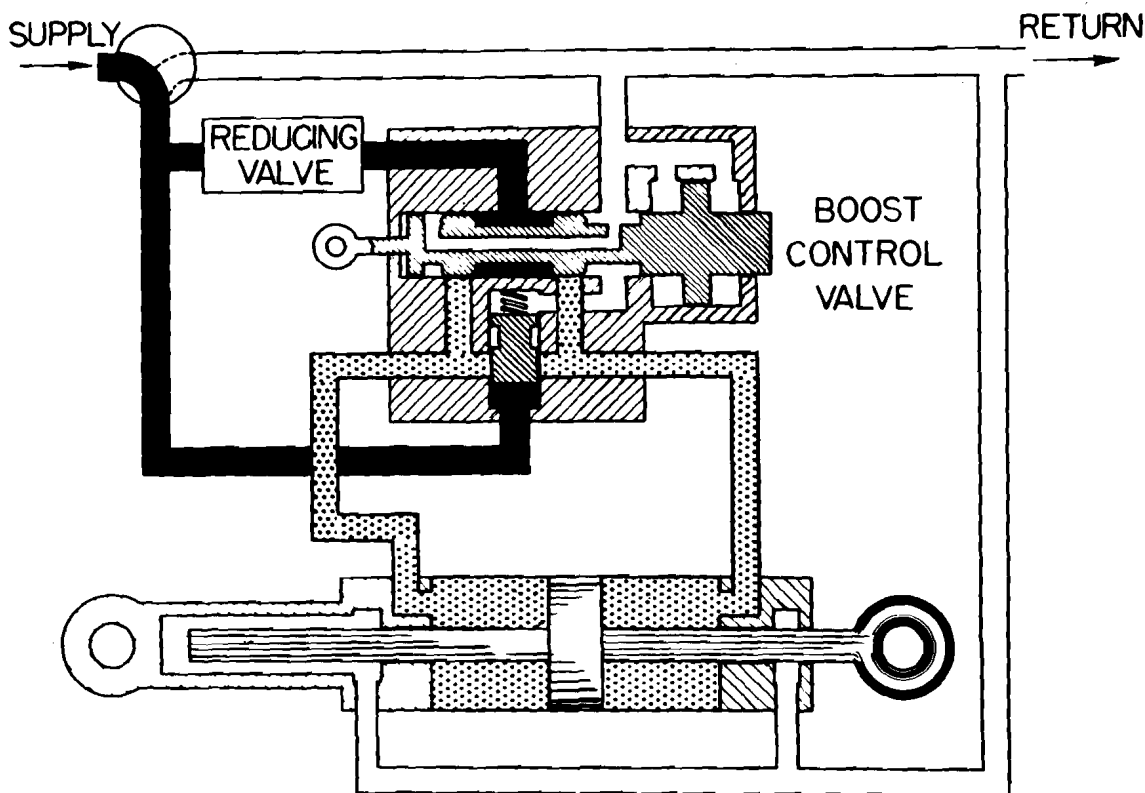


Fig. 4

The hydraulic system of the F-84 includes landing gear, wing flap, and dive brake actuators, as well as the aileron boost unit. The system is energized by a variable volume hydraulic pump operating at 1500 psi.

The hydraulic arrangement of the aileron boost unit is shown in Figure 4. An attempt has been made to show the three general pressure levels in the system. The darkest passages carry supply pressure and the lightest return pressure. The boost cylinder and connecting passages are at a pressure approximately half way between supply and return. The circle at the upper left represents the pilot's selector valve. Hydraulic fluid is supplied to the control valve at 1250 psi through a pressure reducing valve. The pressure reduction was incorporated as a precaution against the effect of pressure fluctuations in the hydraulic system. The control valve is shown in the neutral position. The change in pressure through the reducing valve has not

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been indicated on this figure. Extreme care is taken in the manufacture of the control valve plunger and body. The parts are held to close tolerances and lapped together during the final operation. The finished valve must meet rigid acceptance tests. On one hand the minimum clearances are controlled by requirement for a sliding friction under supply pressure not to exceed $1\frac{1}{4}$ pounds and on the other hand by limited leakage. At each port, the edge of the valve is ground off at four points 90° apart rather than chamfered around as it would appear from this diagram. This accomplishes a smoother change of pressure. The overlap at the valve, approximately $.004''$ as previously mentioned, permits a pressure in both ends of the piston.

When the pilot moves the control, he tends to open one side of the boost cylinder to system supply and the other to return until the required pressure differential is established. These features provide the smooth control aileron characteristic of the aileron system. The boost cylinder is designed with the same cross section area on each side of the piston to insure identical operation in either direction. The equalizer rod is mounted with some degree of axial freedom to avoid friction and jamming due to misalignment. The method of sealing at the piston and rods is somewhat unconventional but accounts for material reduction of friction. A bronze compressor ring with cast iron liner is used on the piston, while the rods incorporate special "U" cup packings beyond high pressure drop bronze bushings. A return passage is required at each end of the boost cylinder to drain the leakage and maintain low pressure at the packing. The same principle is used in the control valve. Two additional functions are performed in the control valve. The piston at the right end of the valve plunger has an area approximately $3\frac{1}{4}$ times as great as the valve area. By means of spring loaded orifices in the communicating passages this acts to damp any rapid motion of the valve, such as would occur in vibration of the aileron or chatter of the valve itself. This feature was added during the test period when it was found that a sudden application of force at either end would start a vibration capable of damaging the system. Several types of damper were investigated, but this proved to be the most satisfactory arrangement tested. No difficulty has been experienced with vibration since this damper was added. The second item is the provision of the bypass valve at the bottom. This is a simple spring loaded valve which drops down to provide a by-pass of minimum restriction from one side of the boost cylinder to the other when hydraulic pressure fails or when the pilot operates the selector valve.

The operational tests of the aileron system were conducted at several simulated speeds and various boost ratios. Air loads were duplicated by means of springs at the aileron surface. The results of these tests were gratifying. Response was smooth and rapid and centering was positive without hunting. Friction at the pilot's control without boost or aileron load was 3 pounds and with boost less than 1 pound. This factor and the good gradient of force with deflection made it unnecessary to use a centering device although we had anticipated the need for such a device during the tests of the original arrangement.

In service the record of the power boosted aileron control system has been good also. Elaborate field service records show relatively few "crabs" against it. The most serious charge is leakage. The arrangement of pressure lines was such that action of the booster applied a torque to the supply line which would loosen the fitting. After the line was rerouted relatively few cases of leakage were reported. As with any hydraulic system, care must be exercised to keep the system clear of foreign

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matter. Initial adjustments to locate the neutral position of the control are required. This is easily accomplished by a screw at the left end of the valve plunger. One of the major changes between the original boost unit and the present one is the location of the control valve. It was formerly inside the boost cylinder. Adjustment was extremely difficult and uncertain for the internal location. An accumulation of air in the damper can lead to malfunctioning of this unit and must be avoided.

In general pilots are favorably disposed towards the aileron control system of the F-84. Normally, they fly with the boost ratio set in the neighborhood of 6:1. This provides very good rolling performance with low forces. During recent months power boost has been tested in the F-84 elevator control system. This is the result of evolutionary changes in longitudinal stability characteristics combined with unpredicted maneuvering force characteristics. Although the tests have been discontinued, certain features of the installation and experiences with it may be of interest.

The basis for the use of power boost in the elevator control system is more involved than for the aileron system. To insure desirable maneuvering characteristics, the airplane had been designed with a center of gravity range of 4% m.a.c., a stick free static margin of 2% m.a.c. for the most aft center of gravity position, and a 30% chord internal balance on the elevator. The force gradients were estimated to be within the specified limits of 3 and 9#/g for all operating conditions. In practice the gradients were lower than estimated, but pilots found the maneuvering characteristics to their liking. The airplane was in service for two years when a series of accidents occurred which were eventually attributed to instability for a particular configuration. This was due in part to a 2% forward shift of the neutral point when wing tip tanks were added that had not been predicted by the wind tunnel data and a small rearward movement of center of gravity position with time. During extensive flight tests it was demonstrated that an 8 pound per g bobweight was required to maintain the minimum force gradient for the most adverse configuration at 30,000'. The gradient at the other extreme of operation became 14 pounds per g. Unfortunately the high gradients were associated with the combat phase of operation and many pilots who were accustomed to the light forces experienced a discomfort they referred to as "bobweight arm". We were anxious to correct this condition.

In the meantime, additional data at high speed were obtained showing that the force required to maintain a particular load factor in steady turning flight decreased at load factors higher than 4 or 5. This is shown in Figures 5 and 6, and was most severe with aft center of gravity positions and wing tip tanks on. This phenomena appears to be closely associated with the characteristic F84 nose up trim change in the vicinity of .8 Mach number in level flight. Various methods of improving the high as well as non-linear force gradients were considered. The approach which had been suggested at meetings following accidents was to reduce the force from the elevator to a fraction of its regular value and then to superimpose a bobweight force to provide a desirable variation. The various methods included a spring tab, a power boost unit, and a change in the mechanical advantage by means of an adjustable link. Estimates indicated that an equivalent boost ratio of about 2 would be required to barely meet the required force gradients; whereas very desirable characteristics would result with a ratio between 3 and 5. At this time the latest version of the airplane was being developed. The changes involved a considerable increase in the range of maneuvering force gradients as well as in take-off force. Assistance was now necessary and power

F-84-371
 COMPARISON OF STICK FORCE VS. "G" AT HIGH SPEEDS
 WITH AND WITHOUT TIPTANKS INSTALLED
 C. G. LOCATION = 27.5% M.A.C. ALTITUDE = 5000'
 173" B.W.
 NO TANK FINS

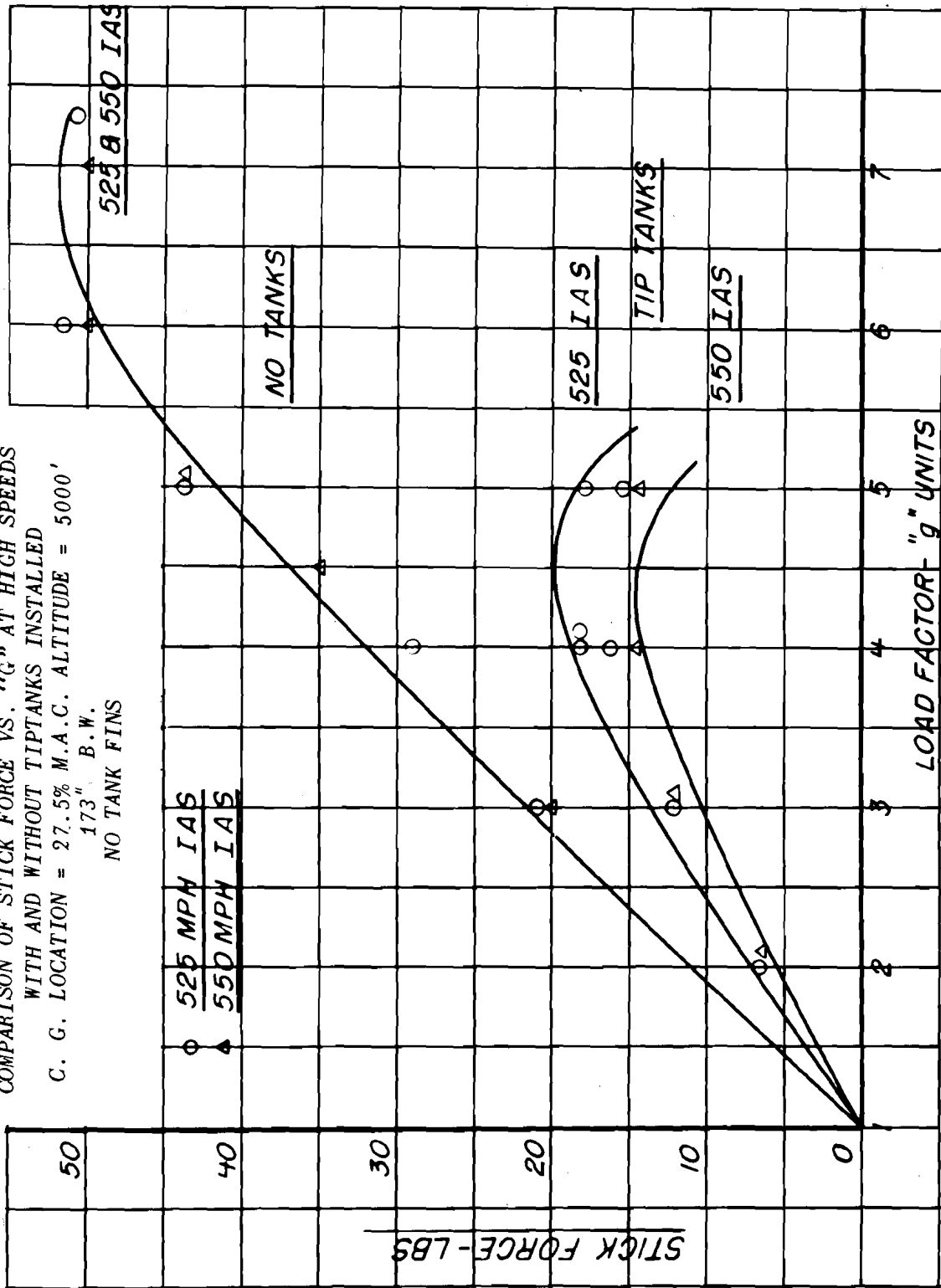


Fig. 5

F-84

STICK FORCE VS. G COMPARISON WITH
 FULL AND AMPY 185 GAL. WING TIPTANKS
 ALTITUDE - 5000 FT.
 C. G. POSITION - 27.5% M.A.C.
 NO TANK FINS

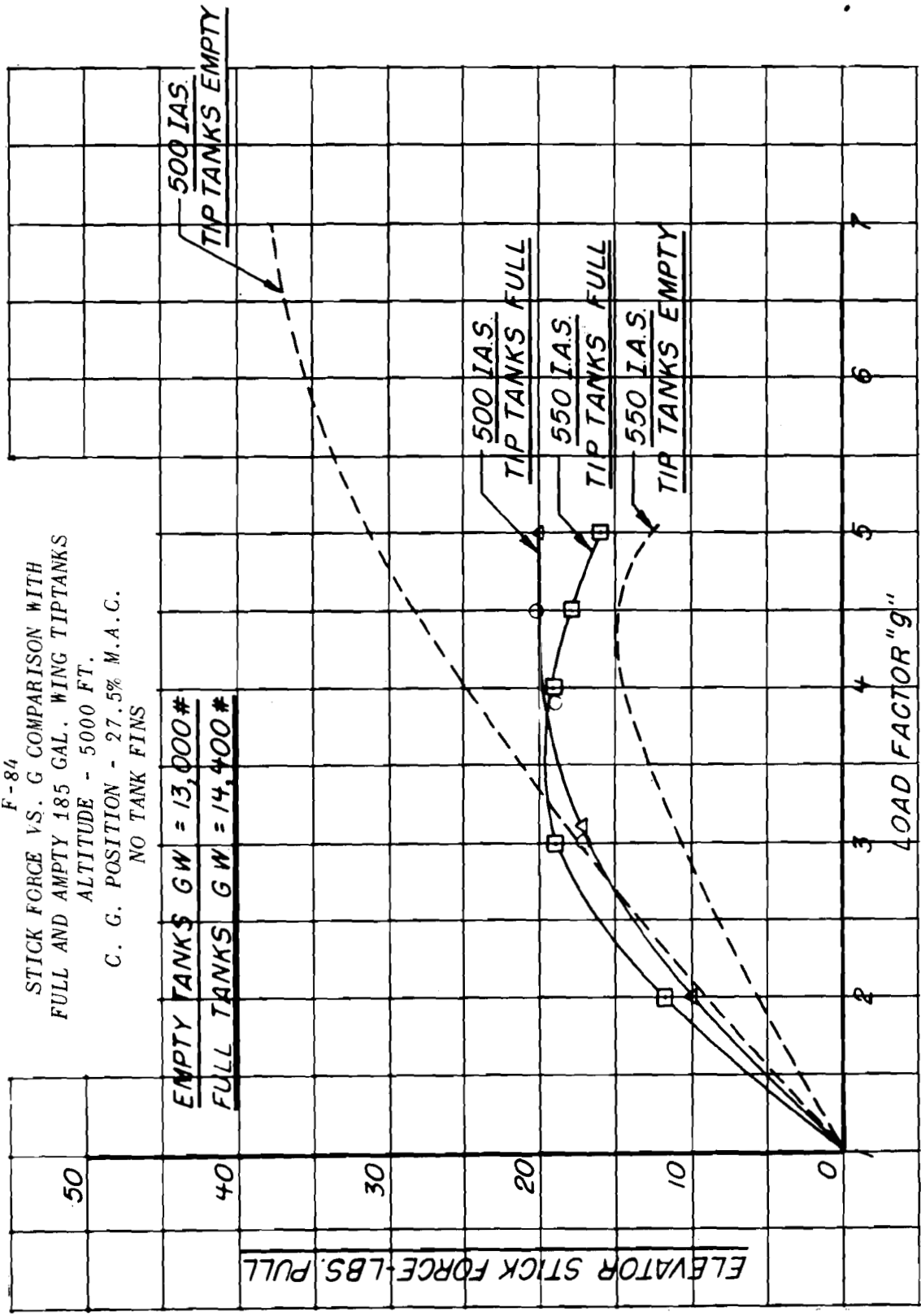


Fig. 6

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boost seemed the easiest way to meet all of the requirements.

The principle of power boost was examined by adapting the aileron boost unit to the elevator system. Since the elevator gave 1/3 of the aileron force at the same angular deflection and the elevator deflections were smaller in general, no question of boost size or capacity was involved. The arrangement of the elevator system without the boost unit is shown in Figure 7. Space is very limited in the forward part, making it necessary to locate the boost unit further away from the control than the aileron boost unit. Obviously, the bobweight would have to be between the pilot's control and the booster to retain its full effect on maneuvering forces. The other alternative is a larger bobweight by the factor of boost ratio. The boost unit was installed just aft of the wing where the rod system ends and the cable system begins. The only mechanical difference between the two systems is the bobweight. Excessive deflection of the trim tab to balance the bobweight through the boost unit was avoided by using a balancing spring at the bobweight. This provided static equilibrium with the elevator in neutral position and a slightly stable gradient of force with elevator deflection.

On the first flight with this arrangement the test pilot induced an undamped oscillation of the airplane by starting a mild pull-up and releasing the control. The oscillation was approximately 1 cycle per second in frequency and occurred at 350 mph indicated at 10,000', with fairly aft center of gravity position and boost ratio of 5:1. The oscillation was easily eliminated by steadying the stick or making a gradual turn or pull-up. There was no oscillation with the boost inoperative. Subsequent tests gave further information on the oscillation. The damping could be increased by higher indicated speeds, lower altitudes, and lower boost ratios. The center of gravity position had little if any effect on this phenomenon. The most pronounced effect was accomplished by reducing the size of the bobweight. Satisfactory damping over the range of operating conditions was obtained with a 3.7#/g bobweight and 5:1 boost ratio.

Figure 8 shows representative data from photo-recorder records. This was taken at 310 indicated at 10,000' with a forward center of gravity location, a 3.7#/g bobweight, and a boost ratio of 8:1. The motion is started on the right by a force of approximately 2 pounds. The response is indicated at the bottom of the plot in terms of normal acceleration. At this time the stick is released. The effect of normal acceleration on the bobweight to operate the elevator through the boost unit is clearly shown. The positive increment in load factor causes down elevator or restoring moment. The integrated effect of the bobweight acting on the control valve is greater than that of elevator deflection through the feel back rod with the result that sufficient elevator angle to cause negative increments in load factor is established. We felt little concern about this condition, since the maximum ratio anticipated was 5:1 where complete damping in one cycle was demonstrated. We were, however, concerned with the problem of sensitivity of the control in level flight, particularly at aft center of gravity position. Pilots found that trim could be established at boost ratios of 5:1 only by releasing the control and adjusting the tab. When he placed his hand on the control again it was difficult to avoid unsteady flight. Even at a boost ratio of 2:1 the trim characteristics were considered unsatisfactory. The balancing spring on the bobweight was removed to add to the stick free stability, but this proved to be hardly noticeable.

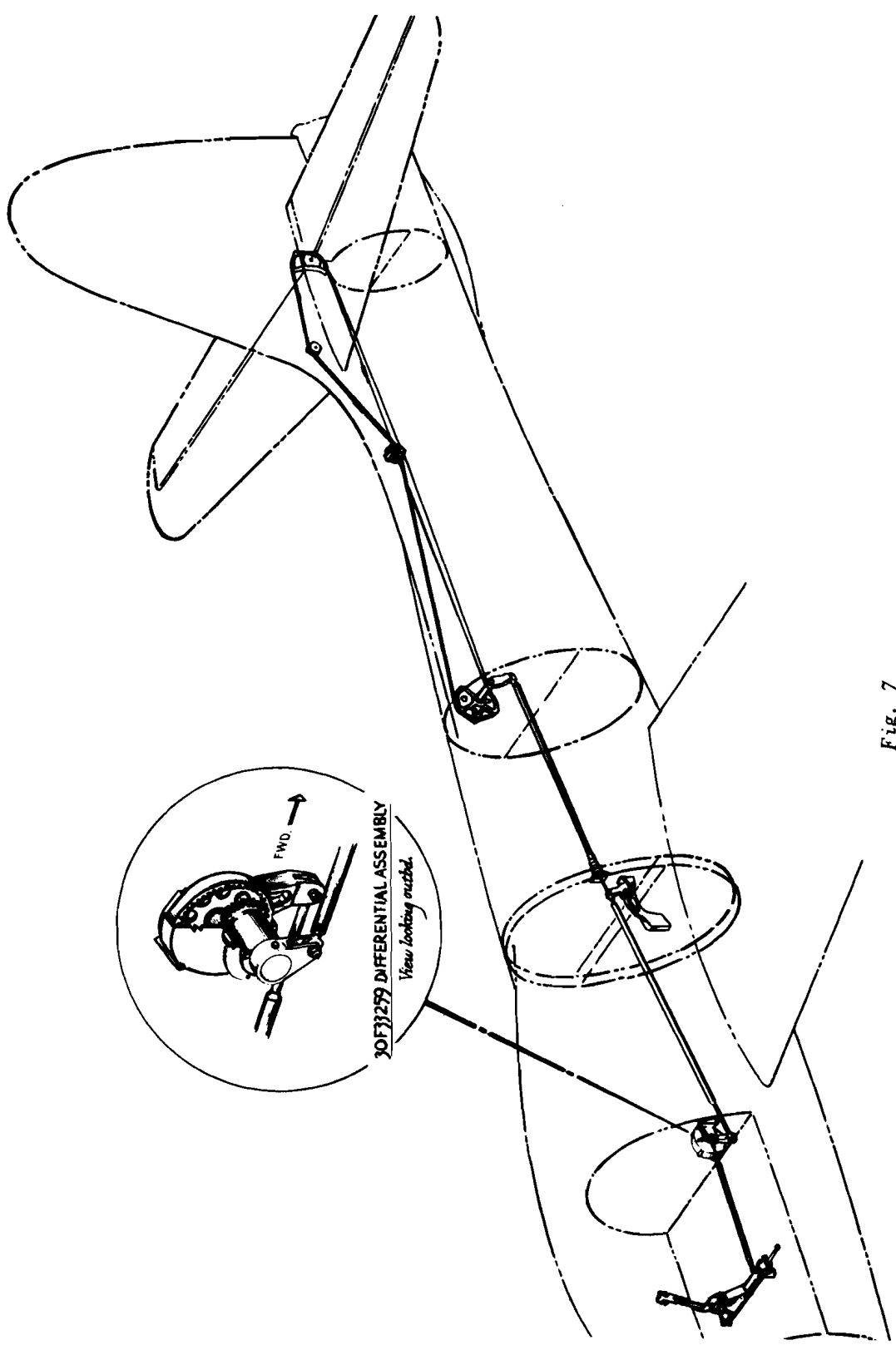


Fig. 7

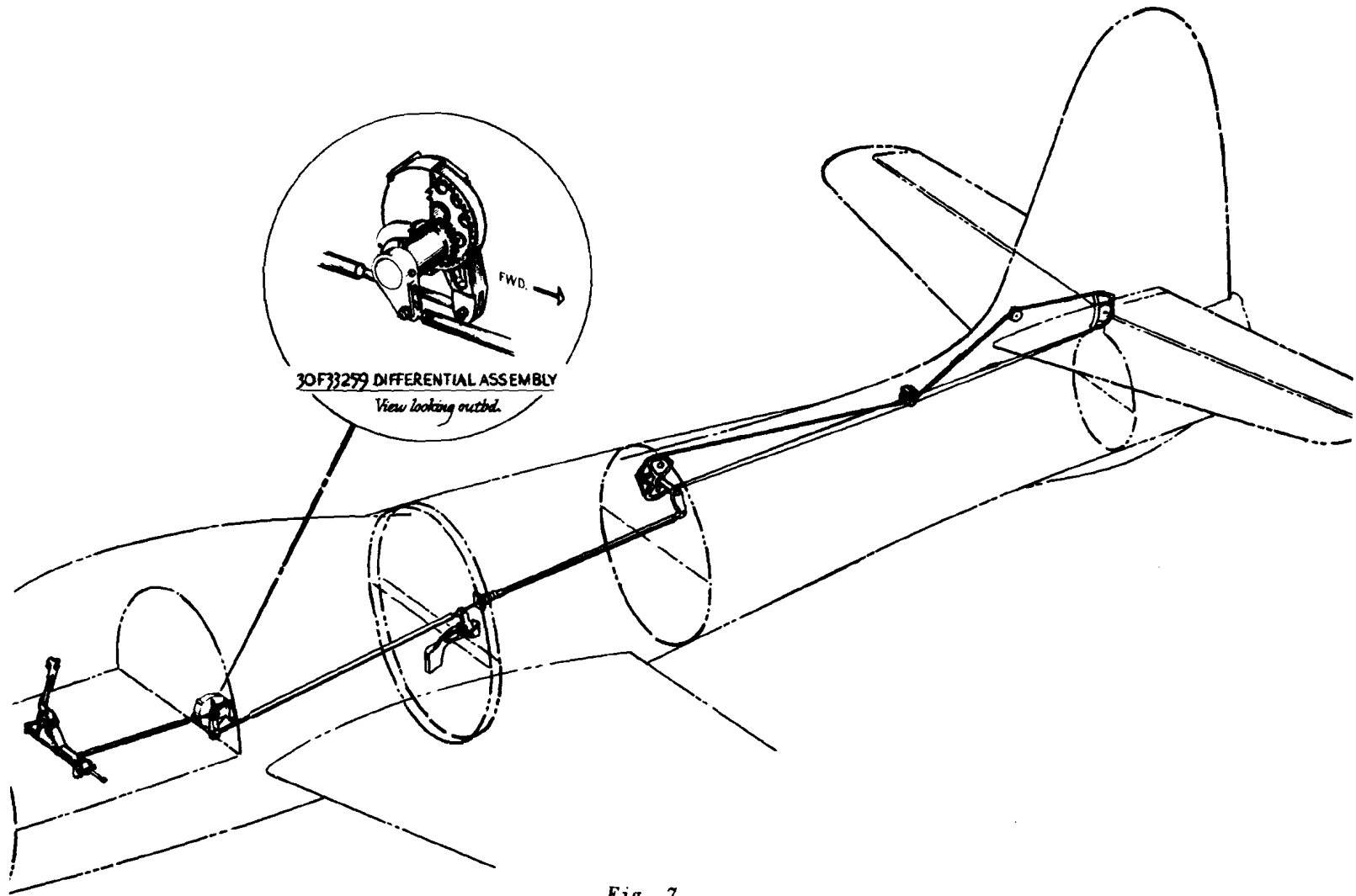


Fig. 7

TIME HISTORY OF OSCILLATION AT 310 MPH IND.

ALT. 10,000 FT.
C.G. 24.5%

BOOST RATIO 8:1
BOB WEIGHT 3.7*/G

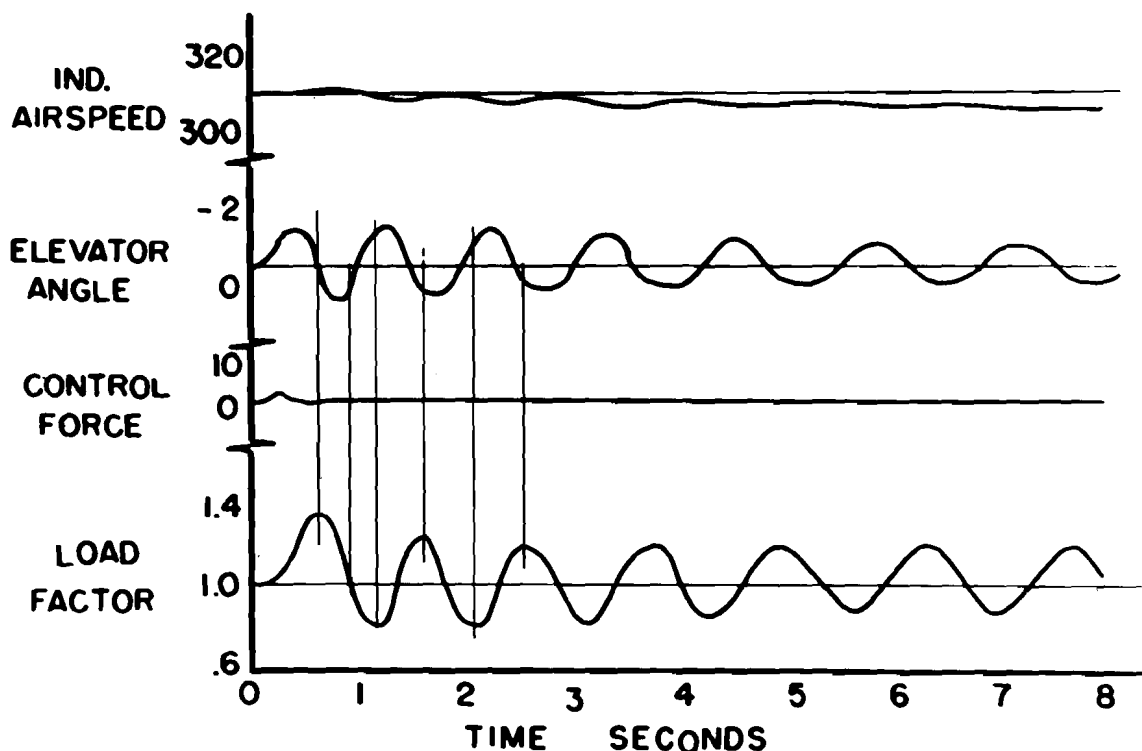


Fig. 8

Unlike the aileron control system, very small angular movement of the elevator was required to maneuver the airplane. While the friction in the system is low, that part ahead of the boost unit is effectively increased by the boost ratio factor in resisting return of the elevator to its trim position after a disturbance. We had the alternatives of trying a preload device in the boost action, that is a device to prevent boost action until a specified force is exceeded, or trying centering devices. It was felt that the types of preload device which were proposed were likely to produce jerky movement of the elevator, so these were eliminated. The centering device, while not the most desirable arrangement, had possibilities. Unfortunately the development program on the booster was discontinued at this point. Continued work on the tip tank problem had produced a fin mounted on the outer side and at the rear of each tip tank to provide a moment which compensated for the tank moment. This eliminated the tendency for reversal in the control force vs. load factor plot. Although the need for power assistance has not been eliminated, the solution appeared too

[REDACTED]

lengthy to be of value to the present airplane. At the present, two compromises are proposed. Neither of these satisfies the specification completely, but one at least comes fairly close. This is an electrically operated screw which changes the length of a link in the elevator system. By this method the mechanical advantage can be increased by a factor of 2. The associated loss of elevator angle can be tolerated for all conditions except take-off and possibly landing.

I would like to express my appreciation for the help given by co-workers in preparing this talk.

DISCUSSION

DR. CLAUSER, Douglas, El Segundo: *Can you vary the boost ratio in flight?*

WANNER: *Yes, we can vary the boost ratio in flight. This is accomplished by moving Point B on Figure 3 up or down by means of an electrically operated screw.*

MR. CHATTLER, Bureau of Aeronautics: *Is the variable boost ratio a permanent part of the installation, and how do the pilots handle the variable feature?*

WANNER: *Yes, it is a permanent part of the installation. In general, the pilots set it at about 6 to 1 and leave it there. If they are after maximum performance, they will move it up to 10 to 1. I suppose each pilot sets it according to his own particular desire, but in general, he doesn't move it around during flight. He is satisfied to leave it because he has many other things to take his attention.*

CHATTLER: *Are there any particular instructions for formation flying?*

WANNER: *Not that I know of.*

QUESTION: *Do the pilots think that the variable feature is a desirable arrangement?*

WANNER: *All the comments I have heard on it are favorable. You see, by having it variable, if they do want to have maximum performance at sea level, they need better than 6 to 1. In other words, with 6 to 1, maximum performance requires a total of over 60 pounds, which pilots are not too anxious to use on the aileron surface. On the other hand, if we gave him a constant ratio of 10 or 10.8 to 1, we think he would be likely to find that his forces would be rather low at high altitude for mild maneuvers.*

CLAUSER: *Did he have some kind of dial?*

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WANNER: Yes, he has a dial in the cockpit that he can see.

CHATTLER: Is the 10 to 1 system stable?

WANNER: Yes, we have had no indication of instability in the system at any boost ratio.

MR. RICHOLT, Lockheed: In regard to the disconnect at point D, I wonder if you might tell us a little more about how that is accomplished. At Lockheed we have experimented and built a lot of those and always come up with the decision that it is more dangerous than if we left it connected. I wonder how you accomplish that.

WANNER: I don't happen to have the details with me but what they have is a pair of claws, one on each side of the rod and the rod has, I guess what you would call detents in it. These claws are operated by a lever in the cockpit and we have fairly heavy spring action behind them and they grip the piston rod. Well, until the pilot moves his lever-- I don't know whether it is a lever; I guess it is a handle with a linkage attached to it--when he moves this linkage, it takes these claws out of the catch position in the piston rod. This particular arrangement is new on the present airplane, on the E model of the 84. Previously the disconnect was something that could be used once. You could disconnect it once and couldn't reconnect it in flight. With the present arrangement, it can be reconnected in flight if the pilot so desires.

MR. GRANT, Hughes Aircraft: I would like to review that change you made where you had the valve built into the piston and then changed to the external valve. Would you go into the reasons for that again? I didn't quite get them.

WANNER: I think perhaps Mr. Bergh could give you better reasons than I could.

MR. BERGH, Republic Aviation: I think the first and most important reason was friction. You see, when the valve plunger has to be passed through the outside working at the fairly high level of pressure, the friction of the packing within the boost cylinder affects the friction on the piston and we found that that was point number one as far as the valve is concerned. Point number two was that it was physically impossible with our arrangement to completely balance out the return line back pressure which you never get completely away from. After all, you have the valve plunger rod coming out of the cylinder and regardless of what means you provide for balance of the other end of that, the control valve within the cylinder itself is still subjected to a thrust pressure in one direction over others which is affected by the return line pressure. If you didn't have any return line pressure at all, you could balance it, but obviously the return line back pressure is a function of the amount of fluid that is going to flow through the boost control unit so you find the more you open the control valve, the greater the circulation, the more this unbalanced force, and it is always in a direction to push the plunger of the control valve out of the unit. In other words, in one direction of moving the control when you open the valve wide by rapid motion of the stick, your system will run away in that direction, whereas in the other it will not, so in effect, you have a variable, you might say,

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feel back load or variable response depending on which way the system is working and the rate of speed at which you move it when you move the valve out of the cylinder.

Point number three is purely, I think, a mechanical problem of production machining. You have a rather expensive device in the boost valve anyhow and when you incorporate inside it another unit, if anything goes wrong, you have to replace the whole unit. It is also much easier to machine when it is a separate part.

Probably still another point, number four, is the bypass effect, that is, when you want to shut the hydraulic part of the booster off and leave it mechanically connected in order to operate the bypass within the cylinder, it is extremely difficult. If you will notice on the slide that shows the schematic of the internal construction of the valve in the boost cylinder, we had a very large passage connecting the two ends of the cylinder together without going through the four passages of the main valve. If the bypass plunger is sufficiently large to produce an unrestricted area equal to the fluid line of the system, the frictional forces, or we'll say, hydraulic forces do not build up appreciably with the rate at which you move the control. If you incorporate that bypass feature within the cylinder itself, you find it extremely difficult to get sufficiently large passages from one side of the piston to the other and also you have a problem that the pressure applied to the bypass servo piston is difficult to keep at a sufficiently high level to make sure that that valve will not cut in and out in an erratic manner. In addition, the pressure which operates the bypass valve comes through a pressure reducing valve so that regardless of what happens to the demand on the system the valve will never open or shut. We found that was very important. At one time we hooked the bypass to the other side of the reducer and we could never start the system operating.

CLAUSER: In that connection, do you have an over-supply of fluid from the pump?

BERGH: Oh yes, because our hydraulic fluid supply is predicated upon the operation of the landing gear and we purposely reduce the pressure to the boost system for the design requirements at maximum speeds so that we'll never have an oscillating pressure at the intake of the control valve.

CLAUSER: You use a common supply system for the rest of the airplane and the boost.

BERGH: Yes, a common supply.

CLAUSER: Is that adequate and reliable?

BERGH: It works very satisfactorily. You see, at low speed--I will say speeds at which you would operate landing gear or wing flaps-- the amount of aileron hinge moment you have to be able to apply through the booster is greatly reduced. You might even need a differential pressure of 100 pounds per square inch in order to give you maximum aileron motion.

CLAUSER: But the rate of motion may be greater than at high speeds even.

BERGH: No, we haven't found that to be true.

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CLAUSER: *Isn't it true you have to throw further for the same rolling amount?*

BERGH: *Oh, yes.*

CLAUSER: *So that the velocity I might desire to have is greater at low speeds.*

BERGH: *For the same hinge moment, but you don't require the same hinge moment.*

CLAUSER: *The hinge moments are down but the pump output is limited regardless of pressure.*

BERGH: *We have never had that experience.*

CLAUSER: *When you are lowering the landing gear or some other operation?*

BERGH: *No. One of the things we were questioned about and one which flight test evidence showed there was no difficulty.*

QUESTION: *You have an accumulator check-off?*

BERGH: *No, we use a variable pump.*

DR. GOOD, John Hopkins University: *Do you recall the oscillation frequency you encounter before the damper is added to the transfer valve?*

BERGH: *Let me put it this way--it was in the order of 5 cycles per second and it was very destructive. I might say at this point it was so violent that it was like using a pneumatic drill to bore a hole in a concrete floor, I think most of us here have had that experience. It was so violent in the period of a half minute or less that our original test rig, which was extremely rigid, destroyed all the ball bearings in the system. It didn't seem to vary with either boost ratio or whether the forced oscillation was initiated by either tapping the stick or tapping the aileron. The result was the same. Of course, as soon as the pilot would take hold of stick, natural damping, and pilot's arm would stop the thing. It is only a stick-free condition that would give that trouble. The damper we built into the unit was made extremely powerful, and as Mr. Wanner has explained, with the check valves that were actually located in the two outlet connections of the damper cylinder. Actually those two restrictor check valves are incorporated in those lines in such a manner that we could use reasonable size holes in the orifices and could vary them over rather wide limits, so in the lab tests we varied the size of those holes, those restrictors that are built into the little disc check valves, within wide limits. We then struck a compromise half-way with those which gave excessive frictional forces or delay in motion of the control and those at which we got the first signs of instability, and as a result it was not a delicate job to machine these little restrictors. I think the hole size is equivalent to about a number 32 drill or something of that order, so it is a relatively good size hole and enabled us if we use the same control valve which we planned to do, to use identical valves by merely shaping the size of those holes.*

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GOOD: One other question. Do you remember the amount of leakage that the valve has in its center position compared with the maximum rate?

BERGH: Yes, I think so. It is a rather difficult thing to define. I'll be glad to show you on a drawing but I don't know how many other fellows would be interested. You have a control leakage not only between the pressure source and each cylinder connection but also each connection back to the return line, and although we test the valve with 1250 pounds per square inch on it and we'll say zero pressure on the connections, your pressure will leak through the system. The leakage pressure we require the manufacturers to meet are determined purely by experimentation with the actual assembly. In other words, we find we would have to have certain clearances between the valve plunger and the valve cylinder or bushing and the minimum clearances are predicated on what are the requirements of maximum friction, whereas the maximum clearances are established by what we considered would be the maximum permissible leakage, predetermined from the installation of the valve which has that characteristic. We took that valve back and measured the leakage and then established the leakage test on the valve tested by itself. I don't think it is possible to say what the leakage should be on the valve by itself because the leakage is a function of how the cylinder leakage enters into the problem too.

GOOD: Do you recall roughly if this was one cubic inch per minute?

BERGH: No, it's considerably higher than that. As I say, there again it varies greatly with the pressure that is acting at the cylinder port. In the actual installation, the pressure when the valve is in neutral and the system is steady, is roughly half the working pressure or we'll say roughly 600 pounds per square inch acting on both sides of the boost cylinder when there are 1250 pounds upstream of the valve and essentially zero pressure downstream on the return line side. The first motion of the valve tends to increase the pressure on one side and decrease the pressure on the other. To measure the total leakage as installed with the system doing no work, I do not have an accurate figure that I could give you here today, but I could tell you if you were to test the valve by itself in neutral, you would get roughly at room temperature, I think, three or four hundred cc per minute with the pressure of 1250 pounds per square inch on one side and zero pressure on the other. As I say, that is not a true leakage or anything like that.

MR. FOLSE, Bureau of Aeronautics: Do I understand correctly that in designing this system you did not find it advantageous to use servo theory?

WANNER: Actually I wasn't in on the design at the beginning. It wasn't advantageous to us. As in Mr. Bergh would know more about that. Do you know whether they used servo theory in designing this?

BERGH: No.

FOLSE: Supposing with the use of the theory you had been able to design it sufficiently well to fly off the drafting board with no testing. Have you an estimate of the flight hours required to put this system into operating condition as contrasting with no flight hours, assuming you had a perfect theory?

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WANNER: *Actually in our case the number of flight hours is small, but we do have more in terms of lab testing time. In other words, when they discovered that the system would not operate satisfactorily, they went into the lab to determine the causes and troubles.*

FOLSE: *That is to say they first tried it out in flight, discovered a fault, and then corrected it in the lab.*

WANNER: *That is correct.*

FOLSE: *How long a process was involved in that in flight hours, manhours or manweeks?*

WANNER: *I don't know in terms of manhours but in terms of weeks I think that the test program ran over a period of two or three months, during which time they were testing and, of course, a lot of time was eaten up in manufacturing new parts. It wasn't all testing time, but that period of time elapsed between the time that we were sure that the trouble was there and the time we had corrected it.*

FOLSE: *How many weeks?*

WANNER: *I would say two or three months.*

BERGH: *I would say something of that order.*

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DESIGN OF THE HYDRAULIC POWER
OPERATED CONTROL AND ARTIFICIAL FEEL SYSTEM
FOR THE XF-92A (MODEL 7002) AIRPLANE

By

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As many of you know, the XF-92A was designed as a flying mockup of the XF-92 airplane. The configuration is shown in Figure 1. It uses a 60° triangle for a wing and vertical tail, no longitudinal stabilizer, and is powered by a J-33-A23 engine. The basic aero-dynamic configuration is intended for transonic and supersonic speeds and all components, other than the power plant, were selected with such speeds as a consideration. The elevons and rudder are full span, constant chord, approximately 23 percent exposed area, radius nose surfaces. They are hydraulic power operated. An artificial feel system is provided.

Although some 20 hours of flight time have been accumulated on this airplane, it is still too early to fully evaluate the hydraulic and feel system characteristics. This paper is then a description of the system design and of the changes made as a result of flight test experiences.

1. Selection

The selection of an irreversible power-boost system for the airplane resulted from consideration of the hinge-moment characteristics and the flutter potentialities of the control surfaces used.

Very early in the airplane design it was realized that control deflection angles in excess of 20 degrees would be required for high altitude, supersonic Mach number maneuvering. This meant that adequate aerodynamic balance, when achieved with overhang, would unport the surfaces with unknown, and feared, results. The low airfoil thickness used (6.5%) prohibited the achievement of the desired result with internal balance. The use of spring tabs, or similar aerodynamic balancing device, was rejected because of the low effectiveness of a small chord surface at transonic speeds. This left us with straight-sided, radius nose surfaces on which the predicted hinge moments were very high. A design limit value of 28,000 foot-pounds has been used for structural design of the elevons. This moment would give a pilot force in the order of magnitude of 10,000 pounds with a conventional system. Even the landing forces would have been in the order of 500 pounds. Such magnitudes make direct pilot control virtually impossible. In addition, the predictions indicated that the surfaces selected on the basis of control effectiveness would be overbalanced in the subsonic speed range. This results from the relatively small surface deflection required to trim in this speed range coupled with an unusually large effect of angle of attack on hinge moments. These facts, added to the uncertainty of the predictions in the transonic range, pointed to the selection of a powered system in which the pilots forces were independent of the control-surface forces.

The radius-nose configuration of the controls and the low airfoil thickness employed made it difficult to provide even static mass balance for the control surfaces.

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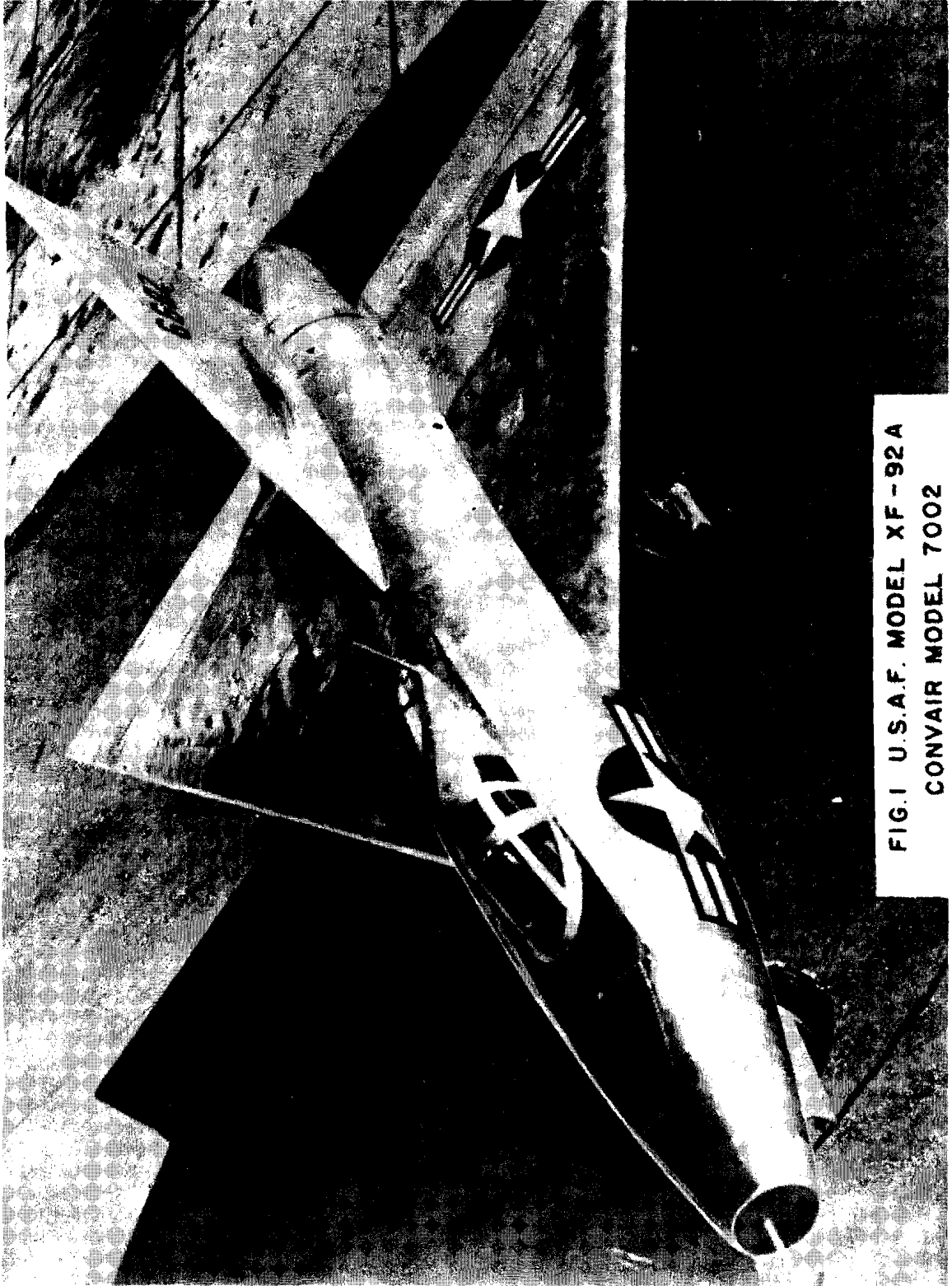


FIG. 1 U.S.A.F. MODEL XF - 92A
CONVAIR MODEL 7002

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Analytical investigations of the configuration indicated that without mass balance a very high degree of stiffness would be required in the surface controls to prevent flutter. Hence, the irreversibility feature was added to the requirements.

2. Requirements

Having determined that an irreversible power system was to be provided, it was then necessary to determine the power, duty cycle, precision and emergency requirements, so that the type of system and its component parts might be selected.

The power requirements consist of two parts; the maximum hinge moment that must be overcome, and the rate of surface rotation against that hinge moment.

In determining the first of these items, it was necessary to consider the response of the airplane to various sequences of applied pilot control motion. The approach used was similar to a maneuvering-load study for a conventional aircraft. The only features that might be considered unusual were first, the inclusion, as the design advanced, of the non-linearities introduced by hydraulic system and aerolastic effects; and second, the recognition that since the natural periods of the airplane were approaching pilot-response time, strength and power should be provided to permit at least one cycle of mis-coordinated pilot control motion in such a phase with the airplane response that maximum loads and hinge moments would result.

While these studies gave some indication of the surface rates required, additional studies were made of the rates required to recover from a 100-degree-per-second gust-induced roll during landing and of the requirements for a typical combat maneuver (taken from NACA Report RB-L5F27). To make these studies as realistic as possible, a pilots response lag of 0.1 second was assumed in the landing study. The combat data were used by assuming the airplane produced the same time history of "g", rolling velocities, and yawing accelerations as presented in the referenced data. These maneuvers were applied to the speed-altitude range of the airplane to find the most severe rate requirement. Horsepower requirements for this condition were not critical. These studies indicated that surface rates to 117 degrees per second might be required for this airplane. Actual rates finally used on the airplane were much reduced.

There is considerable question as to the degree to which the maneuvering sequence selected is representative of combat operating conditions for even present day fighter airplanes. However, the general principle of choosing a series of repeated maneuvers typical of those to be encountered in service as the basis for determining the system rates and duty cycle is considered valid.

The high horsepower requirements resulting from the high hinge moments and rate requirements led to the selection of a hydraulic system equipped with accumulators. The duty cycles were based upon the results of the foregoing landing and combat studies. In addition, a one-degree-per-second continuous motion of all controls was assumed for both normal and emergency system operation. This was to simulate cruise in rough air.

The selection of cylinder size was based on 2600 psi which is the cut-in pressure of the regulator. An arbitrary factor of 75 percent was used to allow for pressure drops etc. It is now felt that actual pressure drops should be estimated. This permitted the use of 10-inch diameter accumulators and 3.75 gallons per minute pumps.

The precision of a boost system might be expressed as the accuracy with which the surface follows the pilots control. Some inaccuracy is inherent in a hydraulic system since a valve must move a finite distance before fluid flow and, hence surface

motion, begins. Similar lag occurs when the surface stops moving. Any lost motion between the stick and the valve or the cylinder and the control surface adds directly to these inherent difficulties. Since it was assumed that the highest practical degree of precision was desirable, it was specified that the pilot controls should be mechanically linked to the surface, except for the motion in the valve itself. All tolerances were to be held to a minimum.

The friction in a boost control system is important from two main considerations. If the trimming is done through the feel system, as in the XF-92A, friction prevents accurate setting of trim. Secondly, excessive friction in the valves causes the stick to follow the surface until friction is overcome. In order to assure low valve operating loads, hydraulically balanced valves were specified, with operating loads not to exceed 2.5 pounds at the valve stem. Actually, the value obtained was less than 2 pounds per valve.

Standby system.

It was felt that adequate safety for emergency conditions could only be provided with a completely independent standby control system. Since even the landing loads were beyond the pilots strength, the standby system was also specified as a full boost system. In order to minimize the danger of a control system failure, it was considered necessary to specify that the standby system be automatically activated with zero time lag in the event of any malfunctioning in the main control system.

The power and duty cycle requirements of the emergency system were considered as those required to recover from a power-on dive, maintain one degree per second motion on all controls during slowdown, descent, and approach, recover from a gust-induced roll during a landing, and complete the landing. The gust recovery was considered to establish the minimum acceptable surface rates.

The emergency system is electrically driven and uses batteries for standby power in case of generator or engine failure. The battery life was based upon a maximum L/D descent from service ceiling driving all controls at 1 degree per second, and recovery from the gust-induced roll during the landing. In addition to the above requirements sufficient battery capacity was provided to attempt a restart of the engine.

3. Requirements of the Feel System

The foregoing requirements were considered to define adequately the hydraulic portion of the control system, but did not describe the type of control to be given the pilot.

Several types of pilots controls could have been incorporated into the airplane. A small "formation" type stick would require either electrical or hydraulic follow-up system to reduce friction loads to acceptable values and to provide a surface follow-up. Means of preventing the pilot from imposing excessive loads on the airplane must be incorporated.

At least two arrangements were feasible for use with a standard control stick. In one, the ratio of stick motion to surface motion would be altered as a function of indicated airspeed and Mach number, such that full stick motion would always permit trim to limit loads. This would give constant stick position effectiveness throughout the speed range. In the other arrangement the stick forces would be altered so that a constant stick force per "g" would result.

This latter system was selected on the basis of safety and conventionality. It was believed that pilots are more nearly aware of the stick forces than of the stick

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position in a conventional system. This should make the controls feel like those of existing aircraft. Moreover, in the event of a failure in the automatic device that could not be overcome by a manual override, the variable ratio system might leave insufficient control available for landing, while the force system could be designed such that a high-stick force landing would always be feasible.

The selected system is fairly heavy, and requires careful attention to detail in both design and maintenance. Friction and looseness must be held to a minimum, since they appear to the pilot as discontinuities in the control effectiveness. Location of the feel mechanism within the control system must be carefully considered.

Having determined that a force system was to be used, it was logical to meet, insofar as practicable, the customer's existing control force requirements.

This resulted in 5 pounds per "g" for elevator motion. In conformity with usual design practice, the force-intelligence curve was based upon the elevator deflection required to trim, rather than upon any accelerated condition. This leaves it to the pilot's technique to prevent excessive loadings. In spite of the relative low structural deflections associated with the delta wing design, it was found necessary to allow for the surface deflection in selecting the intelligence curves.

The specified value of 30 pounds stick force for required Pb/2V was used as the basic lateral force requirement. Here again, the steady state values, rudder fixed, were used.

The rudder requirements were more difficult to establish. There was no definite reason to provide for a great deal of rudder motion at other than low speeds, since the airplane is symmetrical in yaw, has no propeller, and the yaw due to aileron is favorable. A specification is needed for logically determining the high-speed rudder requirements. For this application, the structural requirements were paralleled, and the following criteria used:

- a. 180 pound pedal force at 1/2 rudder deflection at design high-speed.
- b. 180 pound pedal force at 1/5 rudder deflection and design terminal velocity.
- c. 100 pound pedal force at full rudder deflection for indicated speeds less than 100 mph.

In actual application, it became desirable to compromise these criteria, since the small difference in indicated speeds between design high-speed and terminal velocity would have necessitated a sharp break in the intelligence curve.

Since the control surfaces are irreversible, trim control in the conventional sense is not required. However, it is desirable to provide for zero control forces for a wide range of control positions. The trim system provided this feature. The design requirements needed are the rates, the range, and the permissible lag of operation.

No pertinent information is available on required rates of trim operation. A uniform rate of 0.3 degree surface deflection per second for all controls was finally chosen.

The operational trim range of the elevator control was selected to permit zero stick-force "1g" flight throughout the operating range of the airplane. The rudder

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and aileron ranges were arbitrarily selected as $\pm 2^\circ$ from neutral.

The fundamental operation of the trim system required it to move the anchoring point of the feel spring. Thus, in the case of hands-off operation, the hydraulic valve was actuated through the feel system springs. In either case, some lag was likely due to friction in the spring. A permissible lag of 0.5 seconds in system activation was arbitrarily selected.

4. Details of the System

Now that we have reviewed the basic criteria used for design, it will be of interest to consider the general arrangement of the resulting system as shown schematically in Figure 2. It can be noted that the actuating cylinder has been located close to the surface to provide added rigidity. The two-point drive not only minimizes the surface twist under air loads, but is very effective in reducing susceptibility to flutter. The feel system was located near the cockpit from space considerations, and and to reduce the deflection between the source of the feel and the cockpit controls.

The mechanical tie-in between the surface and the stick provides a rigid push-rod connection, except where it passes through the valve control. This feature has been considered as desirable since it eliminates all danger of the stick and surface getting out of phase. Both hydraulic systems are controlled through the tandem valve arrangement indicated.

The two hydraulic systems are completely independent except for the push-rod linkage from the end of the activating cylinder to the surface. The cylinder itself houses two separate equal area pistons mounted on the same shaft, each of the pistons is driven by one of the hydraulic systems. It was felt that this would result in the lightest and most straight forward-arrangement. It does, however, permit an ineffectual driving of one of the systems under rather special conditions. This phenomenon occurs when the surface loads are low, and the systems are provided with unequal pressures. No detrimental effects have been observed; in fact, the existence of this condition can be proven only by an examination of the fluid temperatures.

Some mention has been made of the two hydraulic systems involved, it may be well to describe the major feature of these systems. Both systems are normally in operation so that each system will immediately assume control in the event of malfunctioning of the other. The main system has been so designated only because it is supplied by the engine driven pump.

The hydraulic systems are shown schematically in Figure 3. The main system is driven by a constant-displacement pump geared to the airplane engine. The system is equipped with both high and low pressure filters, an accumulator-type reservoir to minimize altitude effects, two parallel accumulators, a pressure regulator to maintain system pressure between 2600 and 3000 psi, and a system to provide a low line-drop bypass in case of system malfunctioning. This same hydraulic source is used for normal gear and plenum chamber door operation.

The secondary system is quite similar in arrangement, but uses an electric driven pump and is electrically regulated to a pressure range from 1250 to 1550 psi. Under normal operating conditions the electric power is supplied from an engine driven generator. Two batteries (Type 6-GT-13) are used to provide standby power in the event of generator or engine failure. The life of these batteries is the critical item in

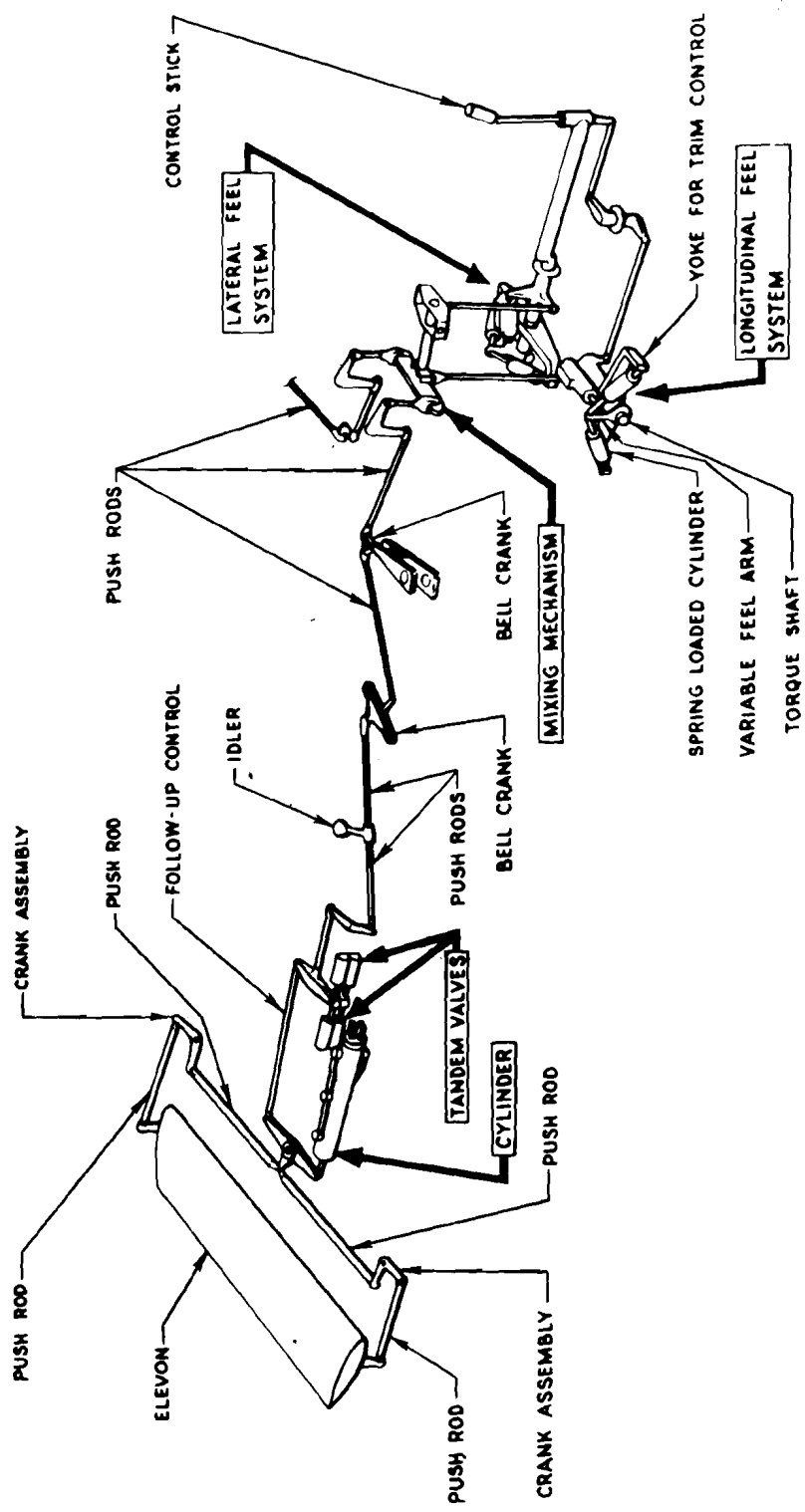


FIG.2 - SCHEMATIC ARRANGEMENT OF THE CONTROL SYSTEM FOR THE MODEL 7002 AIRPLANE

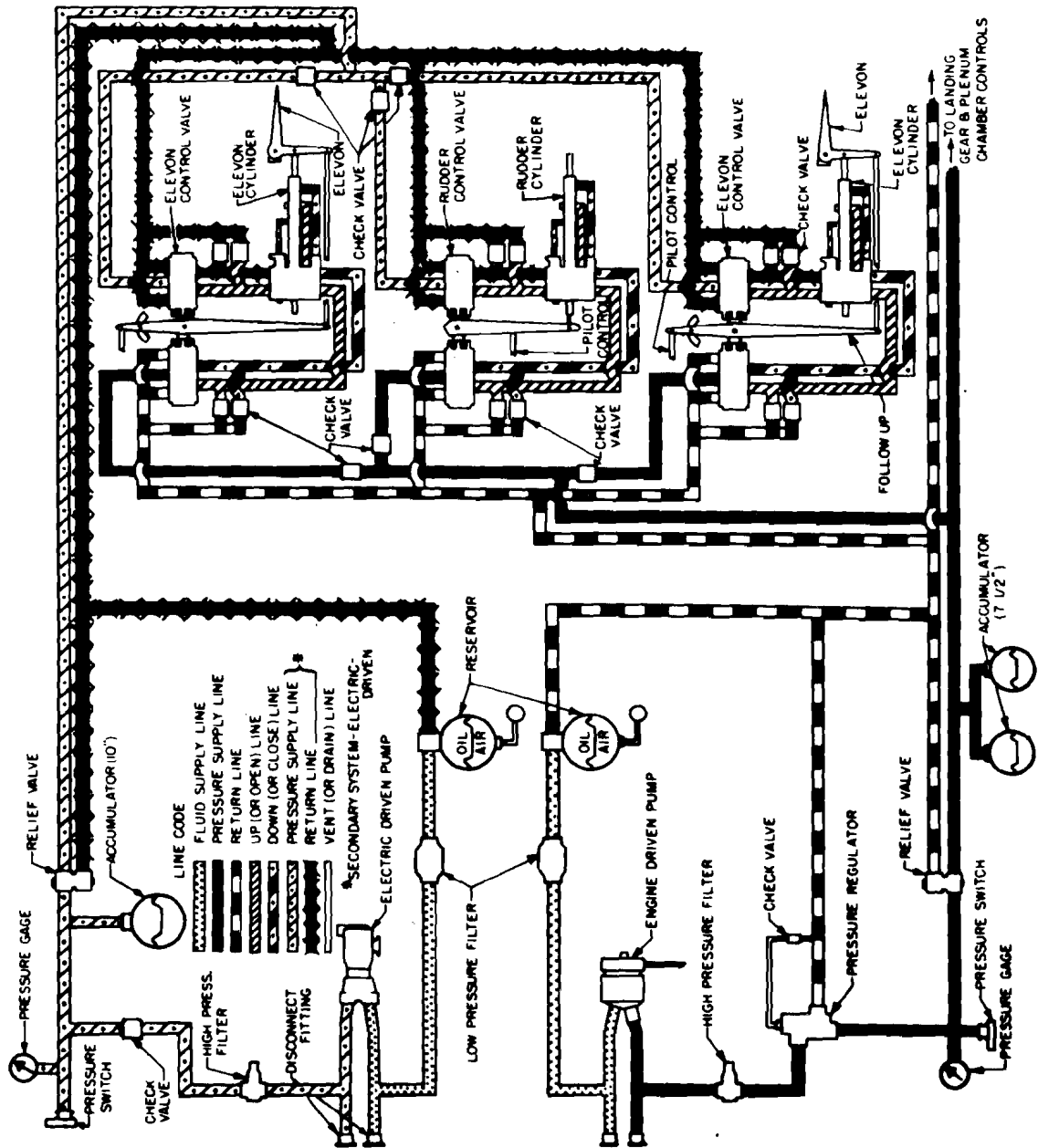


FIG. 3 - SCHEMATIC ARRANGEMENT OF THE HYDRAULIC-POWER SYSTEM FOR THE MODEL 7002 AIRPLANE

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selecting permissible valve leakage, continuous surface rates, and permissible dead-stick landing maneuvers.

The emergency electrical system operation is shown on Figure 4. Under normal conditions this secondary system is in continuous operation. However, in case of failure of the generator, means are provided to conserve a maximum of battery capacity. In case of failure of the main hydraulic system only, no change in the operation of the secondary system takes place except that a warning light goes on.

This duplication of systems, plus the standby feature of the electric system, offers excellent dependability and assures uninterrupted control at all times. With one system inoperative, the response of the airplane is unaffected except for the limited power available for extreme maneuver.

The cylinder and the valve are connected mechanically by the follow-up control. Their action is shown schematically in Figure 5.

The design of the valve itself is the most important single feature of the entire system. Here, it is necessary to compromise on nearly every detail. Some of the decisions made deserve comment.

In the initial design stages, it was believed that additional protection could be provided against jamming due to foreign matter in the hydraulic fluid by providing two spools per valve, actuated through springs. Subsequent tests have shown that this protection is unnecessary and may be actually dangerous. Therefore the springs were omitted and the resulting setup is shown on Figure 5.

The amount of overlap to be used provided another problem. Large overlap permits low leakage rates, but produce a large dead-spot in the controls. The amount of leakage that can be tolerated is primarily a function of the standby provisions of the emergency system. The amount of dead-spot induced is undesirable for smooth operation. The dual-spool design permitted setting the overlap to virtually zero.

The metering of the valve, defined in terms of flow rate vs. valve spool displacement, has undergone several changes since the initial conception of the design. A very rapid rise to the metering curve is desirable from the standpoint of high surface accelerations and rapid follow-up system action. Such a curve, however, tends to cause chatter in the system and seems to exaggerate the effects of dead-spot insofar as pilot's impression is concerned. The metering curves for the valve now installed on the airplane is shown on Figure 6. As shown, the metering starts from beyond center, so that slight leakage exists at the centered position. This was permitted to obtain the greatest possible smoothness of surface activation. It results in a system in which the lag between start of pilot's control motion and surface motion is very small. The lag between stop of pilot-control motion and surface motion is a function of previous surface rate. The surface rate will drop very rapidly to a very low value, but a small motion, less than 0.1 degree in magnitude, will continue for an appreciable length of time (in the order of 0.2 sec.) as the follow-up system closes the valve along the gradual curvature of the metering curve.

The major design problem in selecting the linkage between the valve and the pilot's controls is the determination of the optimum gear ratio. Small ratios reduce the tolerance and valve overlap problems, but exaggerate any valve friction that may exist. Large ratios exaggerate the tolerances in the joints and the dead-spot due to valve overlap. In this application, a ratio of approximately 20 to 1 has been selected to keep total friction at the stick to below 2 pounds.

Normal

With the jack plug inserted in the ground cutoff switch (3), the electric-pump (2) is held inoperative. Before flight or testing, the jack plug is withdrawn, closing (3), and the electric-driven pump operation becomes subject to the control circuit. As long as the generator (10) is putting out about 9 volts or more, relay (7) will be held in, and pump (2) will run as controlled by switch (13), which turns the electric-driven pump (2) on and off to maintain a hydraulic system pressure of 1250-1500 psi.

Generator Failure

In the event of generator failure, relays (17) and (18) will drop out, relay (9) will drop in. Relay (7) will stop the electric-driven pump (2), thus conserving battery power. Relay (8) will disconnect the test load. Relay (9) will light warning light (12) to warn of generator failure. Power is thus conserved for operating the fuel pumps. Engine Failure (or Simultaneous Failure of Generator and Engine-Driven Hydraulic System)

Relays (7) and (8) drop out; and relay (9) drops in, lighting generator failure warning light (12). Pressure switch (5) closes, as the engine-driven hydraulic pump system pressure becomes less than 2000 psi, causing relay (6) to remain closed, thus keeping pump (2) in operation. Switch (5) also allows relay (1) to drop out, turning on warning light (11). Override switch (4) allows pilot to turn on electric-driven pump (2) in emergency, overriding any operation, or lack of operation, of the automatic control circuit.

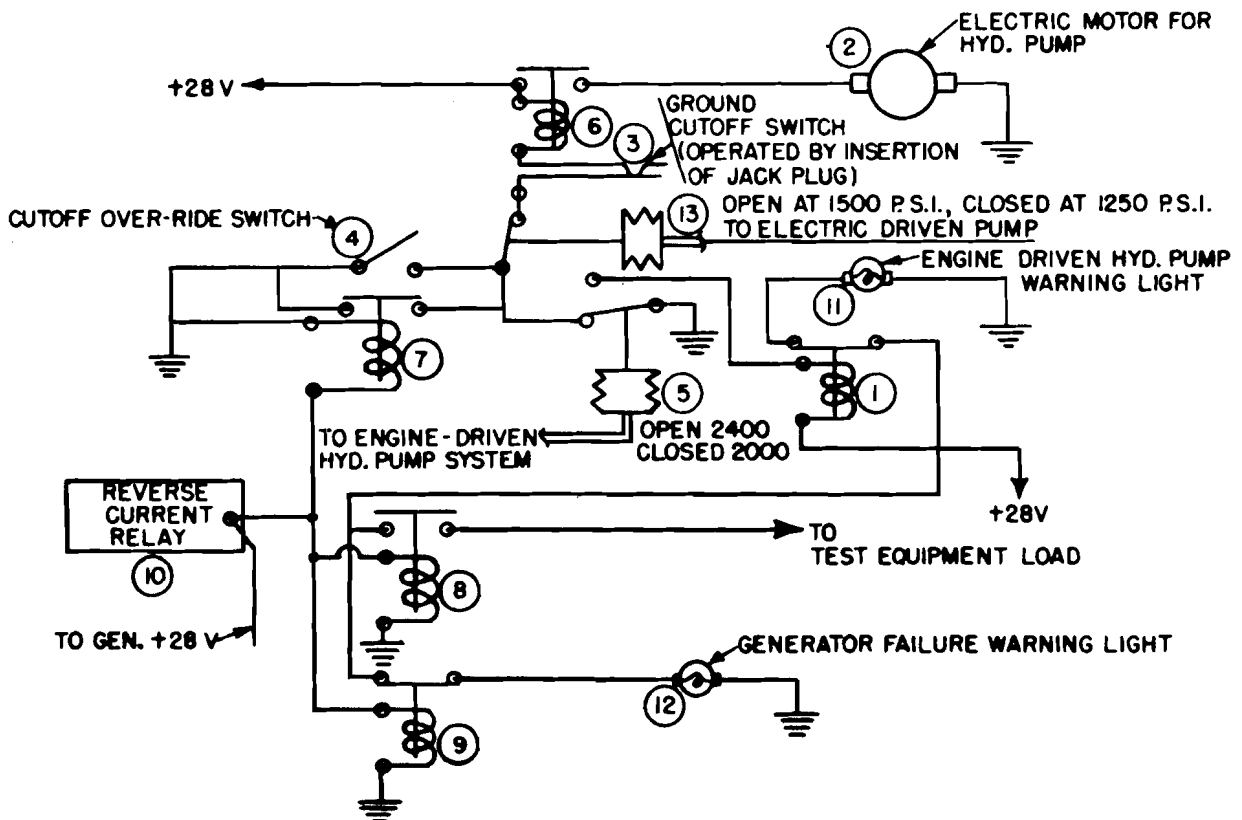


FIG. 4 - SCHEMATIC ARRANGEMENT OF THE EMERGENCY ELECTRICAL SYSTEM FOR THE MODEL 7002 AIRPLANE

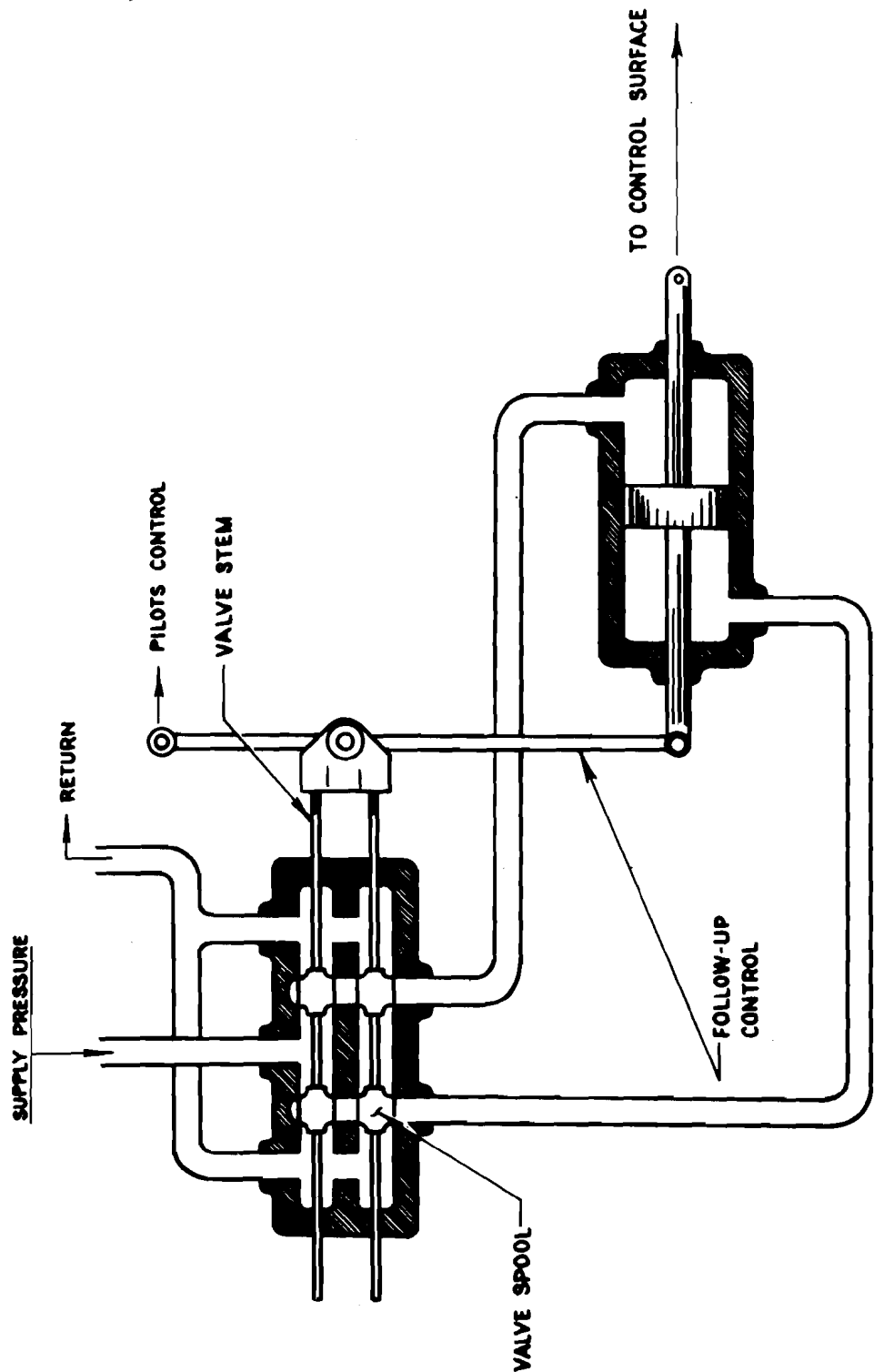


FIG. 5 - SCHEMATIC OPERATION OF THE VALVE AND FOLLOW-UP SYSTEM FOR THE MODEL 7002 AIRPLANE

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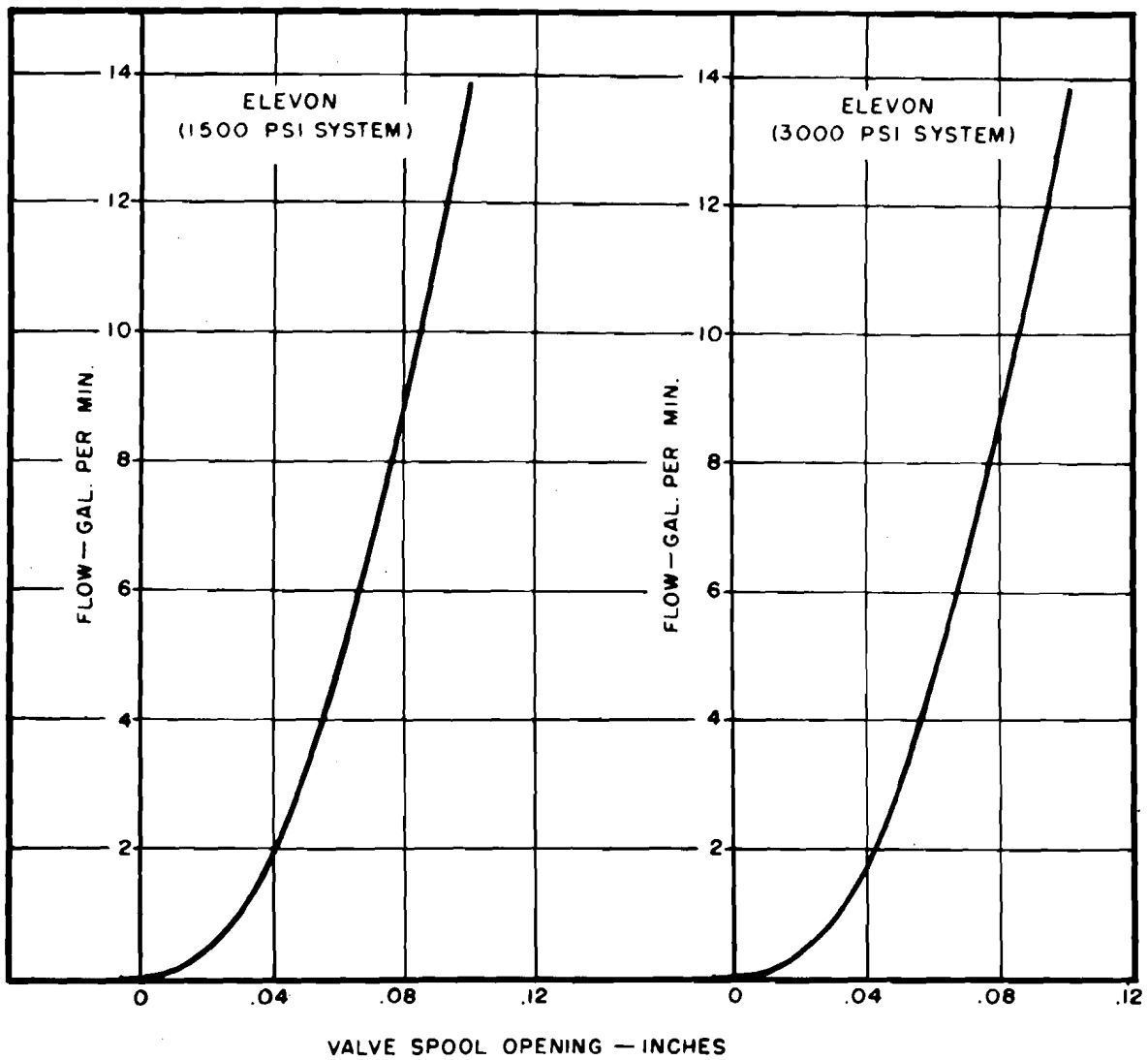


FIG. 6 - METERING CURVE FOR THE VALVES AS NOW INSTALLED IN THE MODEL 7002 AIRPLANE

Returning now to Figure 2 we can see that the control linkage passes through a mixing mechanism that combines side and longitudinal stick motions to a single signal to the elevon valves. The two elevons are completely separated aft of this point.

The basic details of the feel system are also shown schematically in Figure 2. The spring-loaded cylinders are designed to load the variable feel arm in either direction so that a linear force per degree of control deflection is provided. In such a design, great care in adjustment and maintenance is required to prevent roughness in operation.

The control-force gradient is altered by rotating the variable feel arm with respect to the axis of the supporting torque shaft, thus changing the effective moment arm of the spring force. As previously indicated, this motion may be produced by a servomechanism activated by indicated airspeed and altitude or Mach number as required by the speed range of the airplane. The variation is controlled by the shape of a wire-wound resistance, making alterations reasonably easy.

In actual flight, this automatic feature has not been used to date. The pilots have preferred to control the feel by means of the manual override provided. Most of the flying has been done at a constant feel-arm position, so that the feel system has acted as a simple centering spring. The one marked exception to this has been the rudder. The pilots have selected light pedal forces for take-off and landing, and high forces for normal flying. This selection may have arisen from the favorable aileron yaw present on this airplane.

Control-force trim is provided by rotating the yoke, to which the feel springs are attached, about the axis of the torque shaft. This rotation is electrically driven.

5. Testing Program

A comprehensive test program was initiated early in the system design. For this purpose a heavy test stand, shown on Figure 7, was built on which the complete full scale control system was constructed. This stand provided pneumatic means for loading the surfaces. All details of the design were checked on this equipment before incorporating them into the airplane. The testing program could well be the subject of a separate paper. Consequently, only a brief listing of the main subjects investigated will be attempted here.

- a. Bench tests of the various components.
- b. Cause and elimination of chatter.
- c. Temperature survey of the hydraulic fluid.
- d. Determining the effects of dirt in the system.
- e. Determining the effects of air and development of bleeding techniques.
- f. Effects of simulated flutter of the control surfaces.
- g. Investigation of stick-to-valve ratios.
- h. Determination of operating speeds under simulated air load.
- i. Cycling time during the combat problem.
- j. Calibration of the feel mechanism.
- k. Life cycle tests for 175 hours.
- l. Battery life under emergency conditions.



FIG.7 - THE TEST STAND FOR THE CONTROL SYSTEM
OF THE MODEL 7002 AIRPLANE

[REDACTED]

These tests were conducted over a period of approximately 10 months. As a result of this program, some of the components were changed, the causes of chatter were established and removed, bleeding and maintenance procedures were established, the freedom of difficulty from vibratory surface loads was demonstrated, and the adequacy of the system for the expected maneuver was proven for both the normal and the emergency conditions. Surface speeds from 130 to 55 degrees per second, depending upon surface load, were obtained for the normal system operations.

6. Flight Test

The flight tests to date cover some 20 hours of flight test. However, quantitative data on the boost system are very meager.

The initial testing of the airplane showed the control system to be very sensitive. This was believed to be at least partially due to the relatively low moment of inertia of the airplane coupled with exceedingly powerful aerodynamic control. Accordingly, the first step was to reduce the available control-surface travels, thus increasing the stick to surface ratio. This also increased the gearing between the valve and pilot's controls to approximately 20 to 1.

The pilot still complained of control difficulties because of the suddenness of the surface operation after passing through the deadspot. Accordingly, the valves were redesigned to eliminate the over-lap and to give the metering curve previously presented. This redesign not only changed the shape of the metering curve, but reduced the maximum rate available, so that the maximum surface rate was reduced to approximately one half of the test stand values. These changes left the controls still sensitive.

Any air that was permitted to accumulate in the system proved very annoying to the pilots. Careful and frequent attention to the bleeding procedure could eliminate this source of trouble.

As previously mentioned, the automatic feature of the feel system has not been flight tested. The manual control has been used to adjust the feel to suit the pilot.

An unexpected development in the directional control system is worthy of note. The pilot complained of a continuous change in directional trim. A check of the flight data indicated that the rudder angle required for trim remained constant throughout the flight range, but that the pedal position required was markedly altered. In attempting to correlate the pedal position required with flight conditions, no correlation with indicated speed was found, but fair correlation was found with outside air temperature. Further verification of this effect was found in rudder motion, with locked pedals, due to day to night temperature changes.

The data indicate that thermal deflection in the fuselage cause sufficient change in the linkage between the valve and the pilot's controls to necessitate a change in the pedal position required to hold the valve neutral.

In general, the power-control system as defined herein has proven to be a successful unit. Careful evaluation and separation of the hydraulic system characteristics may show the need for further improvements, but the system has demonstrated the feasibility of such units on even the most unconventional of aircraft.

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7. Recommendations

There is a need for design criteria to define a power-operated control system. Such criteria should be based upon the tactical and operational requirements of the particular aircraft. These criteria should result in specifying the power and duty cycle requirements, as well as the aerodynamic control requirements, and should consider the landing as well as the combat conditions. The existing criteria are particularly lacking in the definition of the high-speed requirements of the directional control.

A trim device for use with a full-boost system should provide positive action without depending upon the centering characteristics of a feel system. Such an arrangement is recommended to make the trim relatively independent of the system friction.

Looseness in the system should be minimized on at least two counts. Play between the cylinder and the surface reduces the stiffness and increases the flutter potentialities. Play between the cylinder and the stick appears to the pilot as lag in control effectiveness. This lost motion is particularly objectionable if it is accompanied by a stick force as happens when the feel mechanism is close to the stick.

Care should be taken in the design of a hydraulic-powered system to provide adequate bleeding facilities. Steps taken to prevent air entering the system will pay off in reduced servicing and maintenance troubles.

DISCUSSION

DR. WILSON, Goodyear Aircraft: *On this oil system--I'm not trying to teach you people any new tricks because you have been in the field much longer than I have--but I'm wondering if you have used evaporation techniques.*

MR. BURSTEIN: *Not on this system; we have used some on missiles because we would like to avoid trouble in service. However, it is the last resort. If we can't do anything else, we'll use that, but it doesn't provide a practical solution to the problem.*

WILSON: *The stick feel problem was interesting to me. We have two schools of thought at Goodyear. Some of the men who have been pilots believe in stick feel as being fundamental, and the others who are not pilots, who are not competent to judge, think otherwise. In this problem, I was interested because your stick feel is not really stick feel in that you don't feel the actual force on the control, but it is simply proportional position. You are flying a fast airplane and still your pilots have a little trouble, and I think that is significant.*

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BURSTEIN: What they are trying to do is to give the pilot the same feel he would have had if he had had a normal airplane. The whole purpose of designing the boost system, and its success, will depend on the pilot not knowing he has one.

WILSON: As far as I can see, the system he is flying by stick position but you are giving him a different sense to tell him what position his stick is in. You are not feeding back the actual force on the control surface.

MR. CHATTLER, Bureau of Aeronautics: That isn't just a linear displacement system, is it?

BURSTEIN: It is. What you are shooting for is so many pounds per G. Say it is four pounds per G and the pilot happens to pull four G's. It would take him 12 additional pounds. What we are doing is just exactly that. We determine that in order to pull, say four G's, he would have to rotate the elevon to 3 degrees. That means so much motion of the stick. Therefore, to break the spring and adjust it so as to move that surface 3 degrees, he has to pull 12 pounds.

WILSON: You still don't have the pilot feeling the force on the controls. The pilot should.

BURSTEIN: It would drive him crazy.

WILSON: Perhaps it would in this airplane, but the point I am making is that while you are providing a method to control the number of G's he can pull by controlling the deflection, you are not guaranteeing it at all. He can easily be putting in the deflection say for 4 G's and get 6 G's. It is quite possible.

BURSTEIN: It is possible the same as in any conventional airplane. Republic had trouble with a boost system. We feel that it is easier, if you are only depending on the position of your surface, to determine more accurately degrees of aileron required per G than to work on hinge moment that would be right throughout the speed range going from subsonic to transonic to supersonic where your loads have to be increasing and suddenly you have to lighten up the stick by a factor of 2 or 3 and then start going up again. You try to feed anything like that back to the pilot. Well, if you could design a control system and a surface that would have proper hinge moments, fine, but we felt we weren't that good.

WILSON: There is a third method that hasn't been discussed by either paper; that is, to actually measure the number of G's you are pulling, the rate of roll you can stand, and control accordingly.

BURSTEIN: We considered that, and it was the first approach we made but when you have an airplane like this one, you have a pretty fast response and by the time the pilot finds out how many G's he's pulling, it's too late.

WILSON: Make it purely automatically, without telling the pilot.

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BURSTEIN: By the time you can measure the G's, he may have put on too much surface control. In other words, the first thing you do is deflect the surface, then it takes some time for the airplane to pitch and get the G's. If he had no force to deflect the surface, he wouldn't know how far to deflect, by the time the G's hit, he might have set the surface for 10 G's.

WILSON: That is a problem in stability the same as any. If you had your rate, you can solve it.

BURSTEIN: You could go to a complete auto pilot but then I don't know. I mean, the thing that we felt was that is not an ideal system but we felt it was close enough to what normally the pilots feel. In other words, normally when they are flying an airplane with certain trim they have so much force. Now actually when they are executing a maneuver, they deflect the surface more than is necessary for the ultimate trim position. Then they have to back off but through training, the force that took them to deflect the surface to produce certain hinge moments is a measure that they can use and give them a chance to learn the airplane by having some reference. Maybe it is not an ideal reference but the simplest one, and not so much dependent on lag. If you say you take rate of G build-up, you could produce probably a feel system that would yield maybe even better indications but it would be considerably more complicated. As I mentioned in the report, this is a relatively simple system. The pilots wouldn't use it because they were afraid of it, and if they had some more gyros in it they would have been panic stricken.

WILSON: I agree with you. I am not criticizing your system. Your system is doing a good job. I think just as you say, if you start out on a new approach, you have to educate the pilots and train the pilots to use it, but such a system would be relieving the pilot of all responsibility for determining when he was exceeding the factors that he could on the airplane.

BURSTEIN: You would have to have rate. You might even have to have pitch.

MR. HARRIS, Chance Vought Aircraft: I have a question to ask about two statements you made. I think the answers are similar. In the early part of your talk you mentioned that near neutral the valve has a very slow rate of response. It comes very close to the proper position then takes some time to come up; towards the latter part of your talk you spoke about slop in the push rod system. The question I had is, what is your allowable motion for those in terms of G?

BURSTEIN: Well I don't know that I can express it in terms of G because, as I pointed out, you could only measure it on the ground. We have never been able to measure it in flight because the pilots have never moved the surface that fast so that 1/10 of a degree lag does not exist, except in very extreme maneuvers, which so far we have not executed, and when they are executing a very severe maneuver like that, or any other maneuver, it is very questionable that the pilot would ever in action come to a point and hold a stick fixed. Actually the pilot is moving the stick continuously and so that whether he would ever be aware of that lag is very questionable. Actually,

he might move the stick a little bit more the other way to eliminate that lag by opening the valve the other way and that would tend to bring the surface up quicker. I think that probably is what would happen. As far as the slop in the rest of the system is concerned, it is hard to say what it is. We make it as low as possible; it usually amounts to maybe 3/8 of an inch maximum at the stick in one direction. The maximum total slop including the valve motion is about that much and that is a little annoying. If we could move the feel further back so that you could move through that distance without having to exert any force, that would be better. Actually it may take—well, it depends again in what feel he is flying. If he is flying in very low feel, it may be half a pound or quarter of a pound that is necessary to go through the slop. If he is flying very high feel, it may be a pound or a pound and a half.

HARRIS: The reason I asked that question is that he can move at top of the stick but in your system the surface will move.

BURSTEIN: That is before the surface will move. He takes up the slop in all the push rods, bell cranks; from the stick to the valve plus moving the valve. The surface hasn't moved. The surface will not move if you take the stick and throw it away. The surface never moves by itself unless you open the valve.

CHATTLER: Do you feel the force before you get displacement of the valve?

BURSTEIN: Yes, that is what I say is a bad feature of it. You shouldn't feel the force before you get displacement. That should be avoided. If you can put the feel some place in the valves so that any of that motion will be load-free, then it wouldn't bother the pilot.

QUESTION: Have you got records of level flight where the pilot has been unable to hold, say constant G?

BURSTEIN: Some time you have trouble, if you tried to juggle the arm when he takes his hands off the stick, but it is just a sensitive airplane. In the records of flight, you couldn't pick up this dead spot because he had been moving the surface a very small amount in flight. Maximum deflection used so far is in the order of 1 degree of surface. So far they have been using fractions of a degree, so that shows the system is fairly smoothly operated because they can move the surface 1/100 of a degree if they want to, and for that kind of a motion, there is no difficulty.

MR. BERGH, Republic Aviation: How do you take care of accelerated flight loads?

BURSTEIN: I used for example, the aileron. If you use elevator, say it takes at low speeds (assuming linear characteristics) 2 degrees of elevon or quarter of a degree of aileron per G at high speeds. Well, then at low speeds it would be easy to move to go to larger angle, and high speeds you would have the opposite effect. It takes more effort to go to a number of degrees and does maintain the same G's. This again without correction for -

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BERGH: *That takes care of the condition of pilot control information acceleration but how about stick reaction from gust?*

BURSTEIN: *There isn't any because there is nothing fed back from the surface.*

MR. BALDWIN, McDonnell Aircraft: *I think the interesting thing there is that after you have provided the system, the pilots didn't use it. They didn't make use of any Q changes in either aileron or elevator. Then they must have had variations with stick force per G of speed if they set this one constant spring rate and let it sit there. Did they still find it satisfactory?*

BURSTEIN: *Maybe I didn't make it clear. They didn't want to depend on the the system. They would rather punch the switch themselves and change the feel as they felt like it. If it becomes too sensitive, they increase the feel. If the stick gets too heavy, they lighten up the feel. As I mentioned, the amount of flying on this airplane is very meager. They haven't gone through any sharp maneuvers except pull-outs from dives, so that they haven't had to simulate combat conditions when they won't have time to fiddle around with feel. In this way, there has been a gradual change in speed. Another thing is that since they have been moving controls such a small amount so far. The trouble with the feel is that with these very small deflections it hardly has a chance to start working because they are within the slop of the system, so it is not to good. That is why I said I would not try to sell the feel system to anybody.*

BALDWIN: *You tie down this system to elevator position. Did you find that the elevator position variation was reliable enough that you could do that over the speed range of this airplane?*

BURSTEIN: *Well, so far, the results of flight tests seem to indicate that our predictions were on the button, but in any case we felt that this was something that we would have a better chance of predicting correctly than hinge moments or something else. We felt that if there was anything we could predict, this surface position would be it.*

BALDWIN: *But you didn't have any reversals in position of the elevator with the new airplane.*

BURSTEIN: *There is no reversal of position. There would be a reversal in hinge moments. That is why I said even as a partial system, it wouldn't work at all because it is an unstable stick-free airplane. It couldn't feed back the hinge moments even if you wanted it to. It would be entirely the wrong feel, but stick fixed stability, which would be a result of the position of the surface, is stable and therefore you can use that, but you couldn't use hinge moments.*

MR. HILL, Glenn Martin Aircraft: *You mentioned the fact that you first threw out counter balance in the control surface which automatically threw out dynamic balance. The practice then was to put in a booster which was irreversible. It appears to be irreversible and it might need some definition. What is yours?*

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BURSTEIN: As I mentioned later, irreversibility is different for each airplane. You, from your flutter analysis, can establish the minimum natural frequency of the surface and then for stability will give you that frequency, then it is irreversible. If it gives you less than that, you'll have flutter so you'll have to design stiffness into your old aileron system including cylinders. Construct your aileron properly so that it gives high enough frequency to keep you out of this danger.

QUESTION: You don't do that. I can see where your stiffness would be quite different. The effect of your irreversibility would be changed from the test rig and what was on the airplane.

BURSTEIN: What the test set up furnishes are intangible things, such as deflections of lower O-rings inside the cylinder which you can't predict. You can compute it, but we don't know how much the O-rings actually give and how much the cylinder swells under loads. Knowing these then we can get the spring constant and then the final test, of course, was vibration of the complete aircraft.

MR. GRANT, Hughes Aircraft: Did you on that test stand attempt to simulate massiveness of the control surfaces?

BURSTEIN: No, because we applied a forced vibration throughout the frequency range that we were interested in. We just applied force.

MR. FOLSE, Bureau of Aeronautics: Did I understand the speaker to say that he used servo theory and it broke down?

BURSTEIN: I didn't say that. I didn't say it would break down, but my feeling was this. In order to get good of such analysis, including all the non-linearities which unfortunately exist, you have to have the components to get the basic data from and, of course, I wouldn't want to say that that is entirely right but I think other people will have more to say on the subject. Maybe if we had been in trouble, we would have used some method of analysis to understand our trouble better and be able to trace it and find out where it comes from. If we were in trouble and couldn't lick it quickly, we would have used such methods in order to pin down the source rather than going blindly and changing everything all over the place.

QUESTION: As I understand, we'll get more of servo theory in these lectures. The suggestion I am making is that possibly in the supersonic or perhaps transonic aircraft design, it may be useful to consider using the jet action if that becomes desirable or necessary to eliminate error in the aerodynamic coupling.

BURSTEIN: Well, I don't know. It is a pretty buried subject. The only thing I might mention is that when you get into actual supersonic flight, if you have an airplane that has been designed for subsonic flight, you have, if anything, a more sluggish airplane. I don't think you will because of the great increase of stability in going from subsonic to supersonic. You don't have quite the problem of extreme sensitivity of the control so I don't think it would be quite as serious.

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GRANT: You have the two spool valve and it looks like a good way to get rid of the dead spot but how about the friction from the valves?

BURSTEIN: It was two pounds per valve only in very extreme positions due to some imperfection in the manufacture. When one pulled the valve all the way over to one end, he got two pounds. In the middle, we didn't have any measurable friction.

GRANT: What was that modulation range? You said it was 20 to 1 for the stick. How about surface movement. Did you get from valve closed to valve open?

BURSTEIN: I believe we wound up with 16ths of an inch of something at the valve.

GRANT: For how many degrees surface?

BURSTEIN: The final rate was 25 degrees per second, surface rate.

POWERED CONTROLS DESIGN PRACTICE AT NORTHROP AIRCRAFT

By

T. A. Feeney

Northrop Aircraft, Inc., Hawthorne, California

The use of powered flight controls at Northrop began in 1943. These controls are of the closed center hydraulic system type and are fully powered rather than power boosted. In other words, all the energy required to operate the control surfaces is obtained from the hydraulic systems and none is furnished by the pilot. Since we had had no experience with such systems, we purchased a commercially manufactured servo valve and built a laboratory system around it. This system turned out to be unsatisfactory mainly because it was unstable. It was finally determined that the system was unstable on two counts. First, it was unstable about the neutral point of the valve and second, it was unstable about a particular input velocity. The first was finally solved by mounting the servo valve directly on the cylinder body, thus making the lags of the follow up system a minimum. The second was finally solved by eliminating a region of very high flow curve slope that existed in the original valve design. Application of additional damping to the input end was considered and tried, although it produced stability, this method was discarded because of its undesirable effect on control forces. None of the powered controls used at Northrop has ever made use of damping specifically added for the purpose of producing stability and none of the systems installed in airplanes have ever been unstable. This has been true in spite of the fact that the built in damping has been kept to a minimum for the purpose of producing desirable control forces and of keeping the efficiency of the powered portion as high as possible. Powered controls have been used on five different Northrop aircraft designs and in every case the performance of the systems in flight and from the maintenance standpoint has been entirely satisfactory.

The original application of powered controls at Northrop was to the XB-35 Flying Wing bomber. At the time, there were two basic reasons for the choice of powered controls:

1. To allow the pilot to operate control surfaces requiring exceedingly high hinge moments.
2. To keep somewhat undesirable hinge moment characteristics during the landing from being reflected in control force at the pilot's control column.

Since then, many other advantages of powered controls as compared with power boosted controls have come to light. Some of these are:

1. Flutter is eliminated without the use of balance weights. This is a result of the fact that the system is irreversible and has resulted in considerable weight saving. A very thorough weight analysis was made on the XF-89 in which powered controls were compared with manual controls and with power boosted controls. It was found that powered controls were 356 lbs. lighter than manual controls and 738 lbs. lighter than power boosted controls.

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2. Control forces can be made to vary in almost any desired manner and can be easily altered after the airplane has been built and flown. The control forces can be made a function of dynamic pressure, normal acceleration, change in air speed, Mach number, control position, or any combination of these factors. It has been Northrop practice to obtain control forces for rudder and aileron systems from mechanical springs only. This has been done in the belief that actual "feel", from the standpoint of safety of the aircraft, is necessary in the pitch axis only. In the elevator system, it has been our practice to use what might be called an aerodynamic spring in which the effective spring rate is a function of the dynamic pressure. This results in more or less conventional "feel" since control forces vary with the displacement of the surface and with the square of the indicated air speed. Figure 1 shows a system of this sort in diagrammatic form. Bob weights, down springs, etc., can be used in the same manner that they are used in conventional systems.

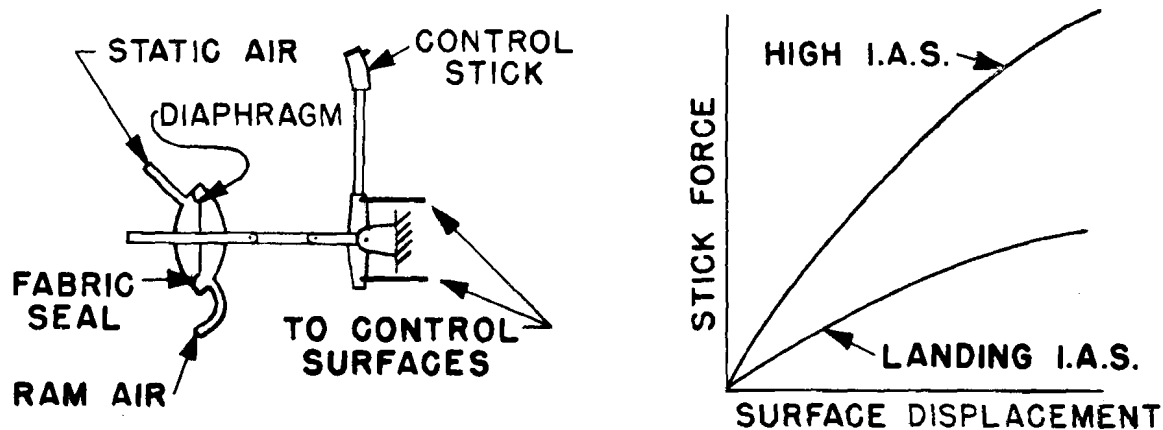


Fig. 1 - Aerodynamic stick force mechanism.

3. Control force trimming through full travel of the surface becomes possible and can be accomplished without the use of trim tabs which subtract from the moment effectiveness of the surface. Trimming is accomplished by inserting an actuator of the desired type into the system at a point between the point of application of control force mechanism to the system and the control surface. Since the only resistance offered by the surface end of the system to motion of the actuator is friction and since motion of the opposite end of the system is resisted by the loading mechanism, the surface will move whenever the trim actuator is operated. A diagrammatic example of such a trimming system is shown in Figure 2. Use of this type of trimming system renders emergency flight control locks unnecessary. The purpose of emergency flight control locks is to relieve the pilot of the necessity for maintaining high control forces for extended periods of time under certain battle damage conditions that the ordinary trim tab would not be capable of trimming out. Obviously such locks are not necessary if the trim system is capable of trimming to zero control force regardless of required surface position.

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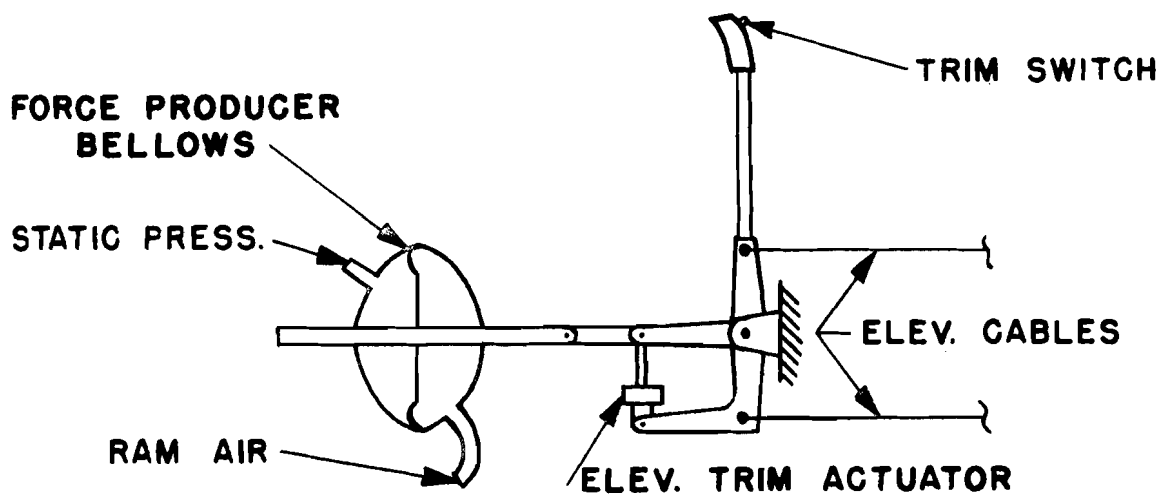


Fig. 2 - Elevator trim system.

4. It becomes unnecessary to provide gust locks. The potentially dangerous and relatively heavy gust locks are unnecessary when irreversible powered controls are used because, even when the power is shut off, the system provides such high damping to the surface that it is impossible for gusts to move the surfaces fast enough to cause damage to either the surface or the control system. It has been Northrop practice to provide check valves in the pressure lines for the purpose of reducing the speed, with which a gust might move the surface, to zero, for all practical purposes.

5. Since it is not possible for the air loads applied to the control surface to move the surface when the surface is operated by powered controls, it is not possible for "rudder snaking" to occur.

6. Makes possible the use of one control surface to accomplish a combination of control functions since erratic hinge moments occurring at the surface will not appear as erratic control forces in the cockpit. An example of this type of surface is the "deceleron" as used on the Northrop XF-89. This surface functions as a combination dive brake, aileron and split landing flap. Since the aileron stick forces are determined only by a mechanical spring, those forces are the same regardless of the configuration at the surface.

7. Since control cables are used basically to transmit signals rather than forces, the cables can be very small in diameter with resulting decrease in friction, weight, and sensitivity to temperature changes. Although it is still necessary to select a cable size which is structurally capable of carrying the maximum loads that can be applied by the pilot, the rigidity requirements, which normally determine the cable size, are much less severe than in either a pure manual system or in a power boosted system. For example, the rudders on the YB-49 Northrop Flying Wing jet bomber are controlled

very satisfactorily by 3/32 in. diameter cables in spite of the fact that over 230 feet of cable are used to control each rudder.

8. Since control forces can be made almost any desired magnitude, the use of a control stick rather than a column and wheel becomes possible even on large airplanes, thus improving instrument visibility, reducing weight and simplifying general cockpit design. Entrance and exit problems are simplified, particularly the problem of exit via an ejection seat since there would be no control wheel that would otherwise have to be cleared by the pilot's knees. The Northrop XF-89, a 33,000 lb. airplane, is stick controlled and a version of the Flying Wing Bomber, a 200,000 lb. airplane now under construction, will likewise be stick controlled.

9. Makes possible the use of such devices as "Little Herbert", an automatic airplane damping device which must be capable of moving the control surface without moving the cockpit control element. The application of this device to a powered rudder control system is shown diagrammatically in Figure 3.

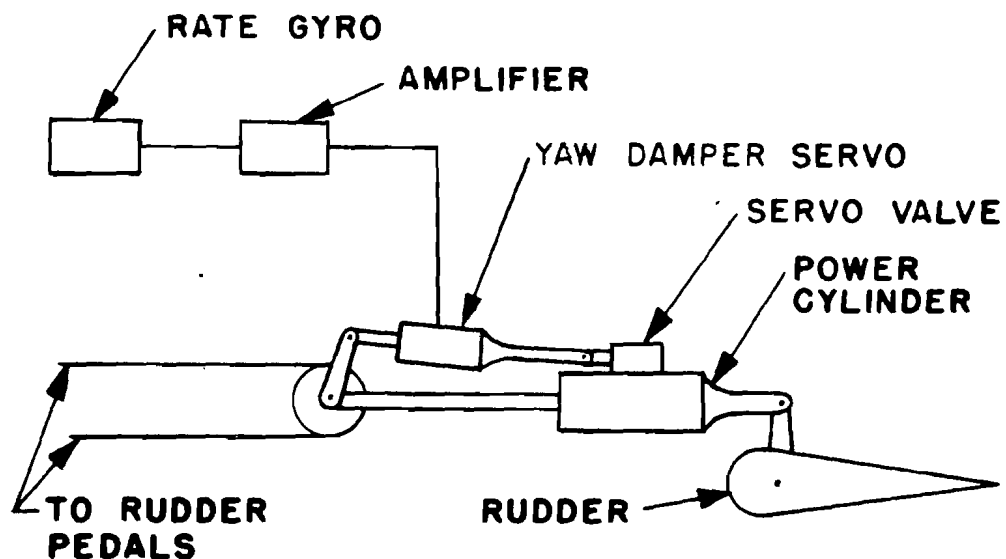


Fig. 3 - Yaw damper mechanism.

The rate gyro detects rate of yawing of the airplane and, through the amplifier, drives a servo motor to a position which is a function of the rate of yaw. The servo is connected in series with the rudder cables and movement of the servo causes a displacement of the rudder relative to the rudder pedals. The resulting rudder displacement produces a yawing moment which tends to damp out the yawing rate. In this manner, the desired amount of damping in yaw can be obtained without resorting to large vertical tail areas and the amount of damping can be varied through large ranges by the mere twist of a knob. This method of obtaining damping has been test flown very successfully on two different Northrop models to date. It is obvious that such a mechanism

could not function properly unless the system to which it is applied is irreversible.

There have been many problems involved in the design of our servo valves. Some of these have been:

1. Elimination of "flat spot" or effective backlash.
2. Elimination of incremental control.
3. Elimination of centering forces.
4. Reduction of friction forces.
5. Elimination of possibility of jamming.
6. Guaranteeing maximum cylinder - fluid rigidity.

The problems of elimination of flat spot, elimination of incremental control and of guaranteeing maximum cylinder-fluid rigidity have been solved in our valve designs by what we call "controlled leakage". The valve is constructed in such a manner that a small amount of fluid is allowed to flow from the pressure line to the return line through the valve ports when the valve is in the neutral position. This principle is shown in Figure 4:

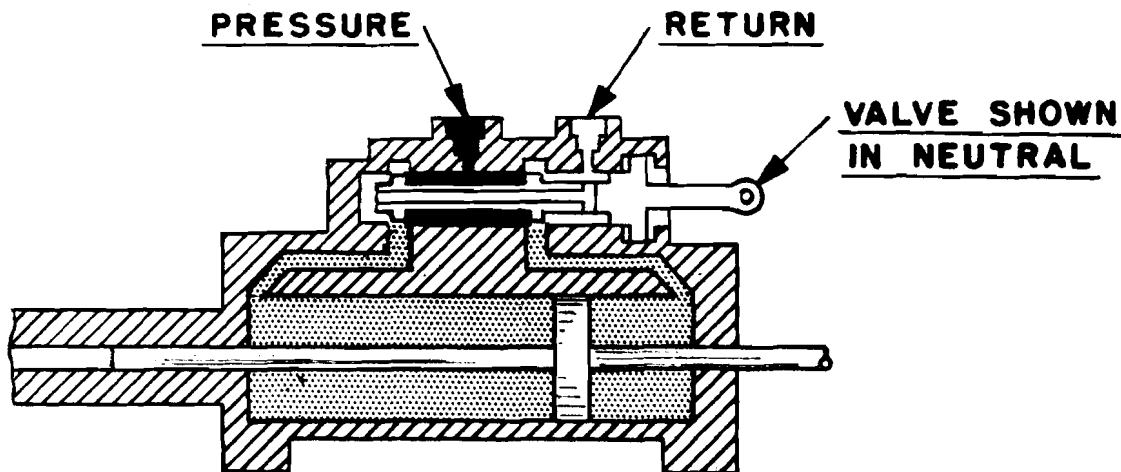


Fig. 4 - Valve design illustrating "controlled leakage".

With this arrangement, even when the cylinder is not carrying external loads, the pressure in the fluid on either side of the piston is very high (approximately one-half system pressure). Any air which might be mixed with the fluid is compressed to a minimum and the combination of cylinder and fluid becomes very rigid, thus helping to provide the high natural frequency required of the surface for flutter elimination and for system stability. The controlled leakage feature of the valve also means that over

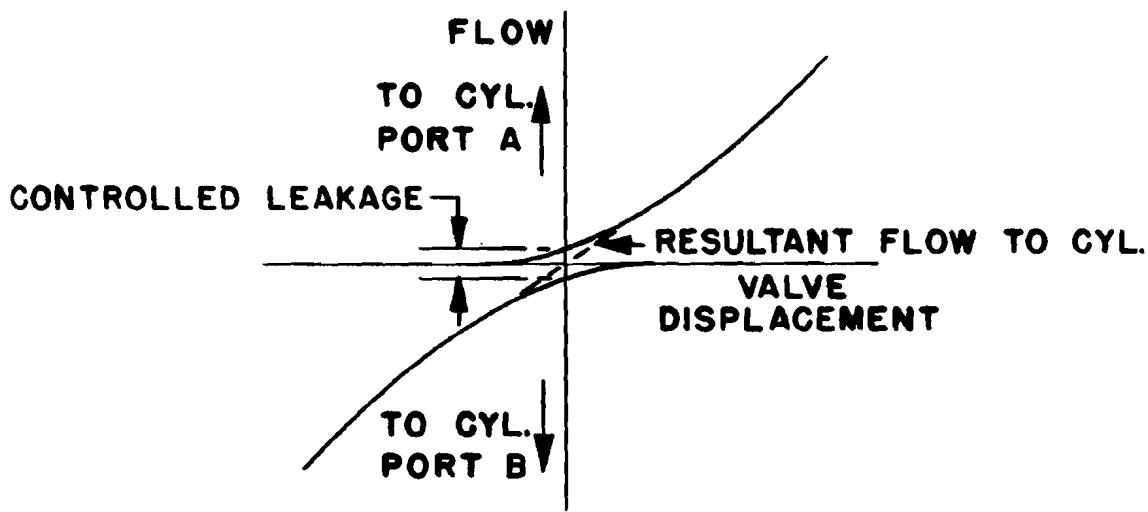
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a very small travel range, the valve behaves in manner similar to that of the so-called "open center" valve in that the pressure differential across the piston of the cylinder is a function of valve displacement. Thus, any movement of the valve will result in a pressure differential across the piston. In our actual valve designs, full system pressure differential is available to the cylinder when the valve has been displaced approximately 5% of its full travel. The complete system is designed in such a manner that full valve travel corresponds to two degrees or less at the control surface. Since a pressure differential on the order of 2% of system pressure is normally required to overcome cylinder friction, it can be seen that the "flat spot" due to the valve is about .002 degrees. It can also be seen that, since the incremental motion is less than the flat spot, the incremental motion, for all practical purposes, is zero. In actual practice, the incremental motion has defied accurate measurement either in the airplane or in the laboratory because of its small magnitude. Typical flow and pressure curves are shown in Figure 5.

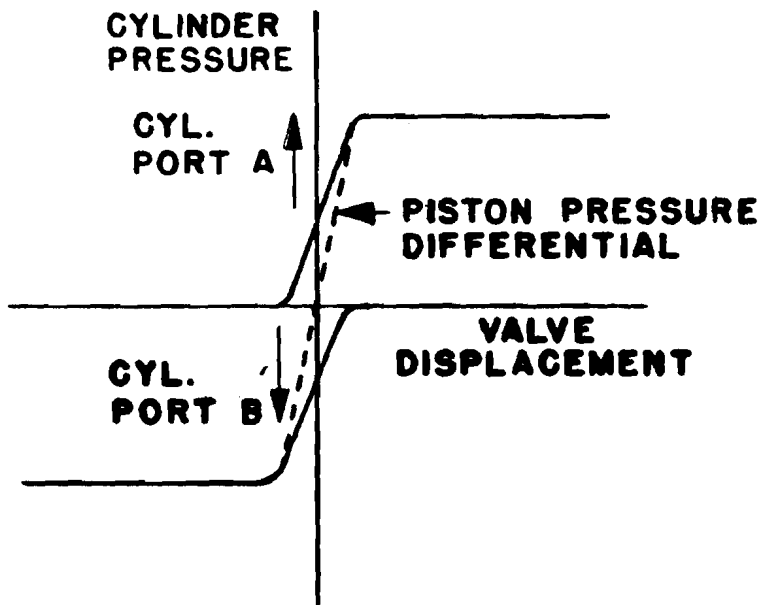
In certain valve designs, the flow of fluid through the valve results in pressure drops which cause forces to exist on the valve spool. These forces normally tend to return the valve to the off or center position. In some of our laboratory systems, we have found that these centering forces, coupling the powered portion of the system to the control portion, can cause instability. These forces have also been found objectionable to the pilot since they feel like viscous friction in the system. For these reasons, the valves have been designed in such a manner that the flow into and out of the valve is normal to the axis of the valve spool. The flow thru the valve has been broken into a series of flow patterns where at maximum displacement of the valve, the majority of flow is in an area where dynamic centering forces cannot be applied to the valve spool. With this type of design, the centering forces have been reduced to negligible values.

Valve friction, even if rather small in magnitude, is very objectionable. In an aileron system, for example, where a total of four valves are used, a valve friction force of 2 lbs. normally results in a corresponding stick force of about 1.25 lbs. Since the maximum allowable is 3 lbs. for the entire system, it can be seen that the valves have used up the lion's share. The character of the valve friction force can also be objectionable. Since it appears at the stick only when the rate of motion is being altered, it feels to the pilot as though the system has high inertia. The first valves we purchased for test purposes required 15 lbs. to move the valve stem. Since then, through a continuous process of redesign, reducing "O" ring squeeze, reducing diameters, etc. we have arrived at the point where our maximum acceptable friction is 2 lbs. and the normal production valves are running between .5 lbs. and 1.0 lbs.

The problem resulting from the possibility of foreign material such as filings and chips getting into the fluid and jamming the servo valve is a real one. It could result in a dangerous situation because a valve jammed in any position other than neutral will result in the surface being moved to the hard over position. Two major steps have been taken in our valve and hydraulic system design to preclude this possibility and we have never had any evidence of a jammed valve in any of our airplanes. The first step has been to provide a filter in the pressure line to each valve, located as close to the valve as possible. These filters are in addition to the main system filter and are intended to pick up particles which might enter the system between the main filter and the valve as a result of maintenance operations. The second step was to design the



(a) FLOW AT CONSTANT VALVE PRESSURE DROP



(b) CYL. PRESSURES AT ZERO CYL. FLOW

Fig. 5 - Servo valve characteristics.

valve so that, rather than providing one large-area, wedge shaped orifice which might be easily jammed by a particle, a series of small diameter drilled holes in the spool are uncovered in sequence by a sharp edge of the valve sleeve. The valve sleeve and spool are hardened to Rockwell C-55 to C-58. As a result, large particles cannot enter and those which can are small enough to be sheared off by forces developed on the spool by the pilot. The difference between the two principles is shown in Figure 6.

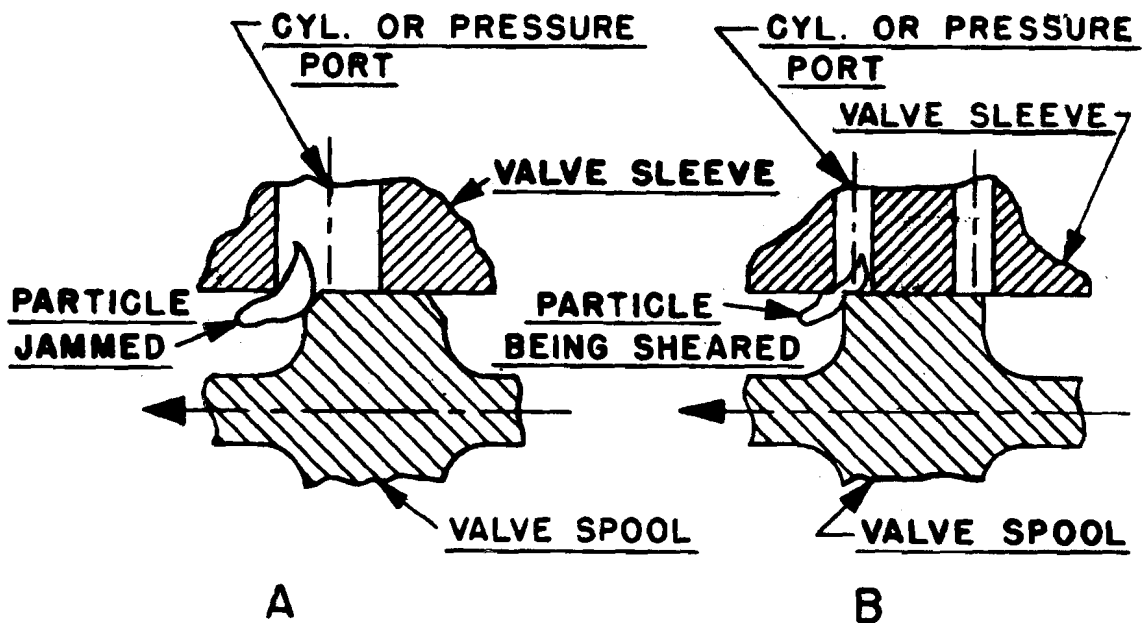


Fig. 6 - Valve design comparison.

Regarding the question of emergency operation of the controls, it is current Northrop practice on twin engine aircraft for example, to provide a hydraulic pump at each engine. Each pump feeds a system and the two systems are completely independent of each other. Each control surface is equipped with two cylinders and each cylinder is fed by one of the two hydraulic systems. With this arrangement, control of the airplane will be maintained in the event of failure of either power plant or of either hydraulic system. In addition, and in order to cover the possibility of complete power plant failure, an electrically driven stand-by hydraulic system is provided. This system is connected into one of the two basic systems and is capable of providing sufficient power to control the airplane during the period of time the airplane is capable of remaining airborne with all engines out. The airplane's battery is capable of supplying the power required during this period of time.

The use of full power flight controls in aircraft offers many new possibilities. Chief of these is probably to assist the aerodynamicist in solving the aerodynamic problems of the airplane. Others that may be mentioned are weight saving, automatic control of maximum airplane load factor, and of relieving the pilot of the fatiguing effort normally associated with flying for long periods of time.

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It is the writers opinion that the basic principles involved have been developed to the point where they are entirely satisfactory, and that now is the time to begin developing the full potentialities.

DISCUSSION

MR. BERGH, Republic Aircraft: *What experience have you had with Q diaphragm or plunger of the feel system jamming due to moisture and freezing?*

FEENEY: *We haven't had any trouble with moisture freezing. When we set it up at first, we were worried about the possibility of moisture collecting and forming ice, or birds jamming into the intake duct. At first we put in a drainage system so that moisture which does collect will go to the bottom and not get inside the bellows. It is actually a trap in the duct and we have attempted to locate the bellows in an area in the airplanes which should be warm enough so if moisture does get in, it won't freeze.*

BERGH: *You have made no provision for draining water out during flight?*

FEENEY: *Yes, the drain or trap is such a provision. It won't take a flow from a large rainstorm, but it has a large volume in the trap itself so it can collect a large amount.*

MR. BURSTEIN, Consolidated-Vultee: *Could you give us some rates of surface movement that you have designed?*

FEENEY: *Surface rates? Our procedure usually is to make a lot of calculations and come up with full travel in one second. We often wish the actual period of time represented by one second were a little longer--we would save a lot of power. I have never run into a really good analytical approach to the problem of how fast the surface could move. We have had good success with full throw in one second.*

BURSTEIN: *Is that in one direction from neutral?*

FEENEY: *Yes. In most cases that is from neutral to hard over in one direction. But it may represent 110 degrees per second or it may represent 15 degrees per second, but in all cases we attempt to obtain full control in one second.*

QUESTION: *Coming back to the bellows, was there any consideration given to the possibility that the bellows or some part of the system may fail when the pilot puts some heavy force on the stick? He may suddenly have no feel there and pull back and produce a big load on the surface.*

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FEENEY: *The gyro says no only on the basis of the rate, so if, for example, you had a large tail on the airplane, it would give you a similar effect and all the pilot does is throw in a little more rudder to get the amount of turning he wants. It is purely a damping system.*

CLAUSER: *But the pilot doesn't notice it at all. Doesn't it go the limits of its travel when he turns.*

FEENEY: *Well, it would of course, if he turns his maximum rate but the amount of rudder that Little Herbert subtracts from the pilot is the function of the actual rate of turning the airplane.*

CLAUSER: *The displacement of turning is proportional to rate of the airplane?*

QUESTION: *Isn't the total available rate of displacement small compared to Little Herbert?*

FEENEY: *Very limited amount of authority is given over to that mechanism. For example, the limit is .5 degrees maximum amount of rudder that Little Herbert can subtract from the pilot. It stops at that point.*

MR. GRANT, Hughes Aircraft: *You were talking about two control systems, two complete systems for one surface and I am wondering if you had any trouble with valve synchronization and also what happens in case you get a damaged cylinder?*

FEENEY: *We feel that to put in a method of disconnecting cylinder is adding a lot machinery which is more likely to give you trouble than you would have by taking your chance with gun fire. The synchronization problem--we worried very much about that. We set up one system in the lab and purposely rigged the cylinder with two valves out of synchronization and the thing that we were most worried about was that we would reduce the maximum available surface speed by getting out of synchronization, since one of the valves couldn't go full open, but we found that we had to get, as I recall it, somewhere around 3/10 of an inch out of synchronization from one to the other before it had any effect. The reason for that is that the two cylinders are not mounted in the same housing, but they are mounted separately so that there is a certain amount of flexibility between the two cylinders; thus, when you put it out of synchronization, it walks over and winds itself up.*

QUESTION: *Does it increase trimming? You mentioned that you had two high trim speeds at first, then reduced it. What did you reduce it to?*

FEENEY: *I recall the trimming rate was on the order of 3 degrees per second and actually we only cut it down to about 2 degrees per second which I didn't really hope was going to be low enough, but the pilots were happy and I don't know whether it was because of the change in trim speed or because we did something about their request.*

MR. CHATTLER, Bureau of Aeronautics: *When you have a failure in one system, do you bypass the fluid around that cylinder of that system?*

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FEENEY: On the B-35 for example, the bellows is connected to the stick by way of a quick disconnect. We weren't sure but what it might still jam up so we provided a quick disconnect so the pilot could flick it loose and after that he would be flying minus his control forces, but in all the flying that we have ever done on any of these airplanes, we have never had any sign of the bellows jamming or anything of that sort. so we are leaving that off on our new designs. There is no disconnect provided.

QUESTION: What I had in mind was, suppose with the force exerted by the pilot on the bellows it suddenly lost that force and he pulls back on the stick without any force.

FEENEY: Well, it is almost impossible, of course, to provide anything against that in the way of additional equipment or something of that sort, but what we have done is to take the bellows assembly and run it through a very complete life test cycling under load, pulsating loads, even reversing loads to be sure that we had a dependable piece of equipment before we had it included, and the results of the test convinced us that it was not likely to bolt. That is as far as we have gone.

MR. WANNER, Republic Aviation: Do you always have stable gradient of force with your airplanes that you designed in the past?

FEENEY: Yes.

WANNER: And in that trim device that you showed, do you merely trim out the off-standard position that the Q cylinder gives with the hydraulic cylinder?

FEENEY: Normal operation would be that the pilot has the stick displaced and the mechanism out of dead center and then operates the trim mechanism which will return it to dead center.

MR. FARKAS, Bureau of Aeronautics: Would you define this term "inter-motion"?

FEENEY: I had intended to do that. That is what we call the minimum increment of control. In other words, if you have breakaway friction (stiction) in the system, you have to operate it with something that has a spring rate to it. You have to build up enough force to overcome the stiction and then you have to drop down to running friction; you therefore have a certain increment of motion. We have never used an open center system as such but I would imagine if you had an open center system and some cylinder friction, by the time you have displaced the valve far enough to produce the pressure difference that is required to make that cylinder start to move, it will continue to move until the valve is returned to a position corresponding to the pressure that goes along with the running friction. Thus with an open center system the entire valve travel is used to control pressure, and I would think the increment of motion would be rather high. That was the thing we were trying to get rid of.

DR. CLAUSER, Douglas Aircraft: On your Little Herbert, how do you keep it from counteracting the efforts of the pilot because the minute he begins to turn the airplane, the gyro says no, and counteracts his efforts.

FEENEY: *Only through the servo valve.*

CHATTLER: *You mean the servo valve rides along, producing the proper sequencing for by-pass.*

FEENEY: *It always opens in the proper direction to allow the fluid to circulate.*

CHATTLER: *Does the pressure drop hurt you any?*

FEENEY: *No, we haven't had any pressure drop difficulty.*

DR. WILSON, Goodyear Aircraft: *What sort of failures do you anticipate in a system like that?*

FEENEY: *Hydraulic fitting faults, for example, engine failures, pump shearing, pump shaft failures, etc., those are the things that we have fought against. We actually have never had any of those things occur but there could be a day.*

MR. HILL, Martin: *Would the use of duplicate systems seem to have any effect on stability or chatter characteristics? In other words, would one system by itself tend to be unstable possibly, where two counteract one another to a certain extent?*

FEENEY: *No. That has been our experience anyway. On our XF-89 we do not have this dual hydraulic system. In the early days we thought it was necessary that the standby system be completely different from the normal system. Our only choice was pneumatic and electric other than hydraulic so we originally used the electric standby system, electric motor, screw jack and so on and at that time, of course, there was only one hydraulic system. Since then we have added a second system to the same airplane and it is still perfectly stable, so I would say it has, in our experience, had no effect on the system's stability.*

QUESTION: *Do you attribute your good fortune in stability to luck or skill?*

FEENEY: *A lot of luck. We have built so many of them that we have developed a lot of rules that we use in the next design which are based on experience that we gained from the others and as Mr. McRuer tomorrow will give us a talk on the frequency response analysis on the system as he puts it, we actually used servo theory except we didn't use that name.*

MR. HARRIS, Chance Vought Aircraft: *Go back to Little Herbert again. You put quite a bit of emphasis on the use of the irreversible system. Is it necessary to have an irreversible system?*

FEENEY: *I was very careful to say, if it is to operate in this manner. What I had in mind was surface moving or being controlled in series with the pilot. If it is controlled in parallel with the pilot, that is not the case, but it is very desirable that it be in series with the pilot so he won't know the thing is there and that is the way it turns out. The pilots say they just don't know he is on board.*

HARRIS: *If they did know, would they object?*

FEENEY: *You see, if it is a parallel connection instead of series, what it does then is simply build up the control force as a function of rate. That is a different principle.*

MR. BURSTEIN, Consolidated Vultee: *In connection with Little Herbert, supposing something happens to it; it puts in sort of a flexible link in your valve operating mechanism and something happened to that flexible link. I don't know how you operate it--hydraulically or electrically, or what manner you do that; is it a screw jack?*

FEENEY: *The actual application on the airplane is not a screw jack of that sort. I might show you on the board how it is actually installed. The cables from the cockpit come out this way and are on a pulley and then each of these turns in here and goes around the pulley and back around another and out to the rest of the rudder system. These pulleys here are mounted on a bell crank which pivots around this point. That has a quadrant cable attached to it and that goes to a rotary electric servo. So now you see anything can happen to this--it can die in its tracks and you would still have the complete system. Things have happened. Flights aren't all perfect. The system has gone out in flight but so far we have limited its application to yaw and there is nothing to worry about. If it goes out, that's that. You still have full control of the airplane. Right now we would be a little hesitant about applying it to pitch.*

QUESTION: *Have you flown it at cold temperatures?*

FEENEY: *Yes, sir.*

QUESTION: *Did you find any adverse effect?*

FEENEY: *The original installation was more complicated and much less efficient than the one on the board. We actually got into temperatures of minus 70 and it began to get pretty sluggish then. So far, since we have changed over to the more efficient system, we haven't noticed any temperature effects on the servo or the rest of the system.*

QUESTION: *I was thinking, it is in series with the boost or power control itself and usually the power control falls off in performance when the temperature gets colder.*

FEENEY: *That is another thing I would like to mention. The control leakage solves that problem too. Actually we have measured temperatures around minus 70 and the temperature of the hydraulic fluid stays up to the point where there has been no noticeable change whatever in the performance of the system.*

MR. RICHOLT, Lockheed Aircraft: *How much leakage do you have?*

FEENEY: *.05 per gallon per minute.*

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DESIGN AND OPERATION OF POWER BOOST CONTROLS AS USED IN LOCKHEED AIRCRAFT

By

Robert R. Richolt

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Introduction

After listening to some of the discussions given here I believe that possibly we have been concerned with power boosters longer than anyone else represented. Our experience dates back about ten years, and we have used the cut and try methods as well as some mathematical analyses. Most of our development, however, was by the cut and try method. The Constellation was the first airplane to use boost controls, and our experiences date from the beginning of that development.

The Problem Statement

The initial design studies for this airplane were undertaken in June of 1939. It was conceived as a long range, high speed, high altitude transport, with low operating cost as a basic requirement. The flight characteristics were to be a substantial improvement over those of existing aircraft, with maximum controllability for all emergency and normal flight conditions. New Civil Air Regulations required a low landing speed to permit the use of small emergency fields. The paramount requirement was safety in combination with speed and economy.

The safety and economy requirement indicated the use of four of the largest engines then available to obtain the lowest fuel consumption during cruise conditions. These large engines also permitted the best take-off performance but posed a serious problem in maintaining complete directional control during take-off should an engine fail. The turning moment caused by failure of one or two engines when developing maximum power was more than could be handled by the normal methods of rudder control used at that time. The low landing speed requirement indicated the use of a large Fowler flap to give the wing a high lift coefficient. By incorporating an extremely large flap in the design, the problems of ample elevator control during landing and satisfactory aileron control with two engines on one side inoperative were greatly increased. The basic design, therefore, was tentatively planned to incorporate power boosters on all of the flight control surfaces. It was estimated that the assistance to be supplied by these boosters, or the amplification of the forces applied to the controls by the pilot, would require ratios of 30:1 for the rudder control, 10:1 for the elevator and 8:1 for the ailerons. Control surface angular velocities should be at least 40° per second.

The decision to use boosters on this aircraft was based upon a number of practical and aerodynamic reasons beyond the scope of this discussion, but it can be said that one of the main reasons was the increased safety obtained by using boosters, since they permitted complete control down to the stalling speed of the airplane, where the effectiveness of all other types of control force reducing devices is seriously

paired. The decision to proceed on this premise was made at the inception of the design so that full advantage could be taken of all the benefits to be obtained without compromise.

The only problem was how to build such a device for each of the three controls which would meet the following requirements.

1. Give the type of stick force curve shown in Figure 1, where the effective ratio between input and output (the boost ratio) was relatively low near the neutral position to obtain good stick free stability of the airplane, would increase to the desired value for higher loads to be expected during maneuvers, and would decrease near the maximum allowable hinge moment value in order to discourage the pilot from over stressing the airplane.
2. There must be no "dead spots" or lost motion of the control, particularly through the neutral position.
3. The cockpit control must always be mechanically connected directly to the control surface. No other type of connection is considered reliable enough.
4. The booster system must not "motor". With improper design it is possible for any type of mechanical servo unit to act in reverse and drive the load without a directing signal from the input end. This can be likened to feedback in an audio amplifier.
5. The boosters should take their power from the main engine power plants.
6. Dual sources of power should be available automatically.
7. Rapid shut-off means should be provided.
8. It must be possible to fly the airplane after failure of the power sources. (This means higher air speeds are required for adequate control during landing.)
9. Relief valves should be incorporated to limit the maximum control surface loads to their design values.
10. Control surface trim tab effectiveness must not be lost due to booster friction.
11. The booster must be capable of operation at very low temperatures.

Mockup

From a preliminary examination of the problem it was obvious that development of such a complex hydraulic system and the related effects of various parts of the system on the power boosters would require too much delay if done on the airplane. It was decided to build a hydraulic mockup containing all the parts of the hydraulic system for development tests.

Figures 2 and 3 show the relative arrangement of the various components of the system in both the airplane and the mockup. The mockup was located on a platform above the laboratory floor to permit installation of the landing gear mechanisms in proper relationship to the rest of the hydraulic system. Flight station, control surface boosters and all other components were in the same relative position with regard to each other as they were to be in the airplane. All piping and flight control cables were duplicated exactly to scale. Space around this main mockup was relegated to individual test rigs and fixtures for development of various components of the system.

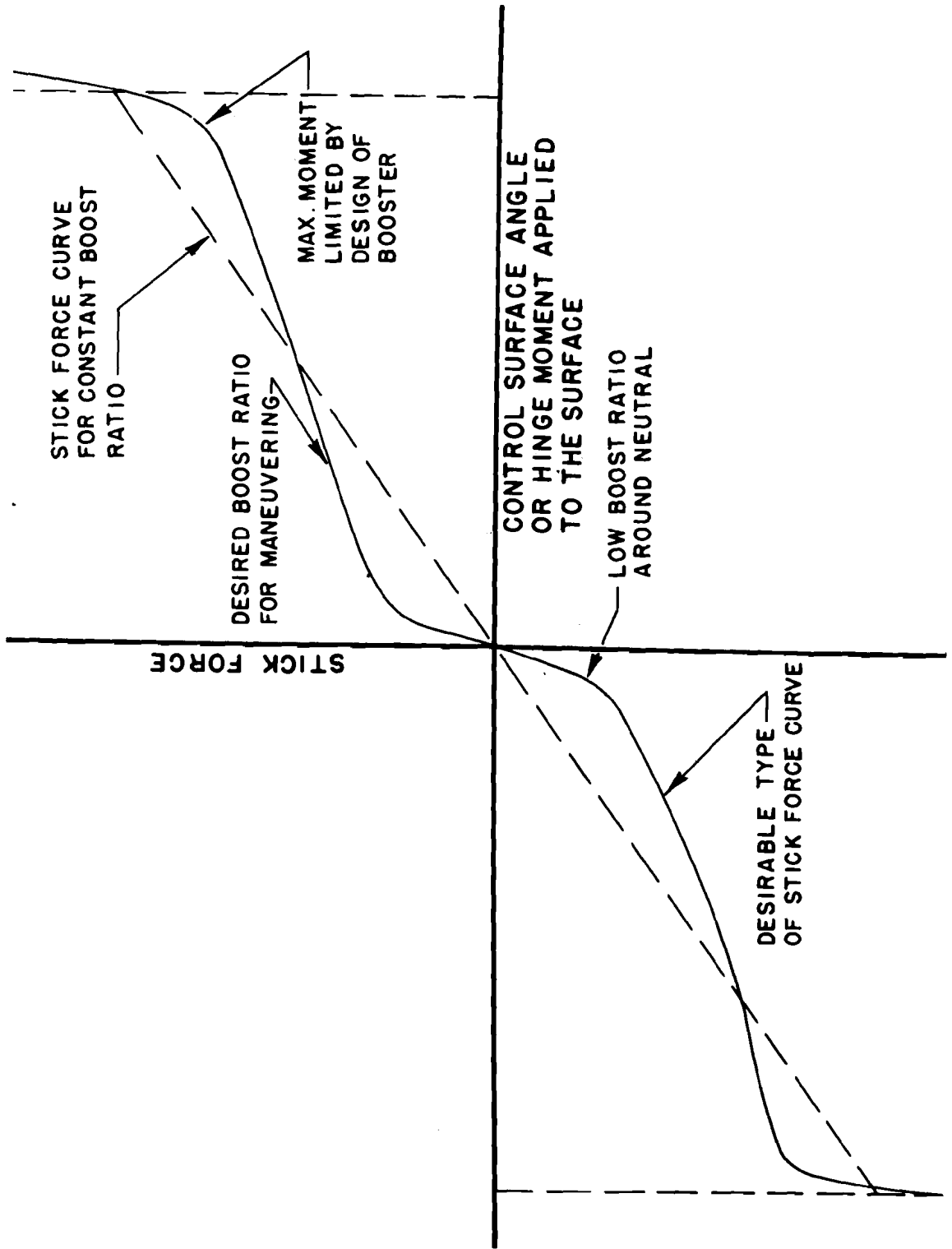


Fig. 1 - Curve showing desirable control forces versus hinge moment output of booster.

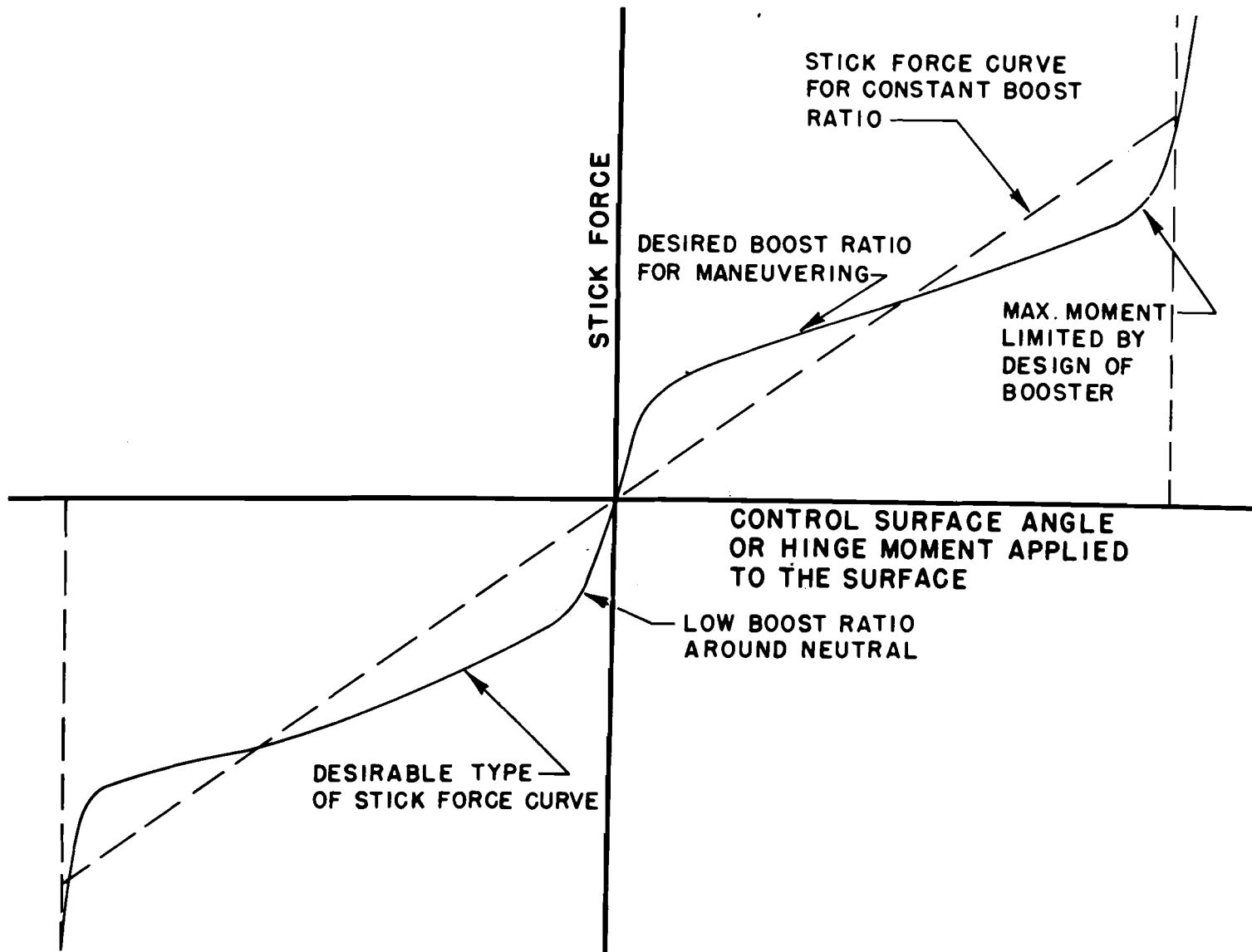


Fig. 1 - Curve showing desirable control forces versus hinge moment output of booster.

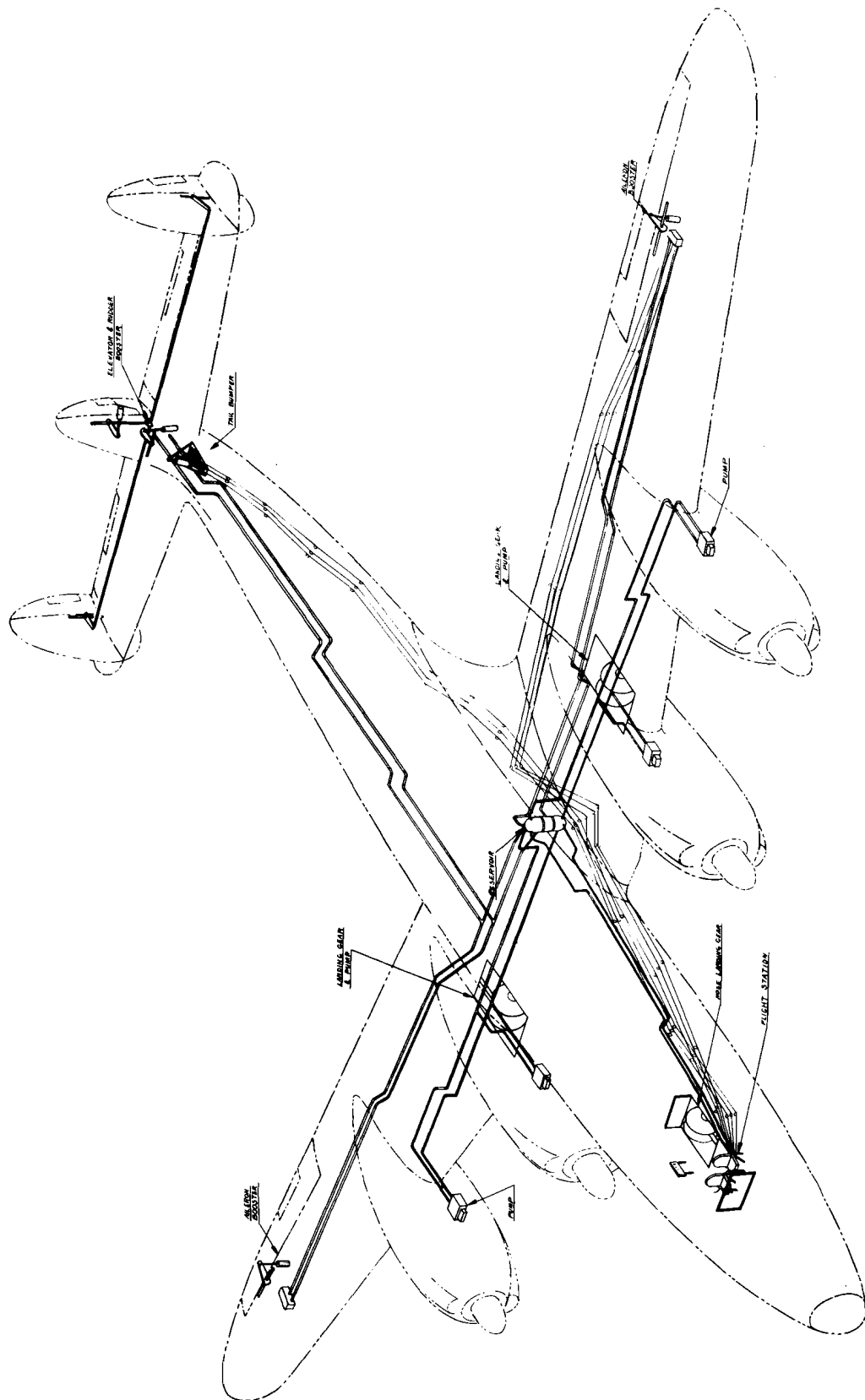


Fig. 2 - Isometric view of airplane showing location of major items of hydraulic and control equipment.

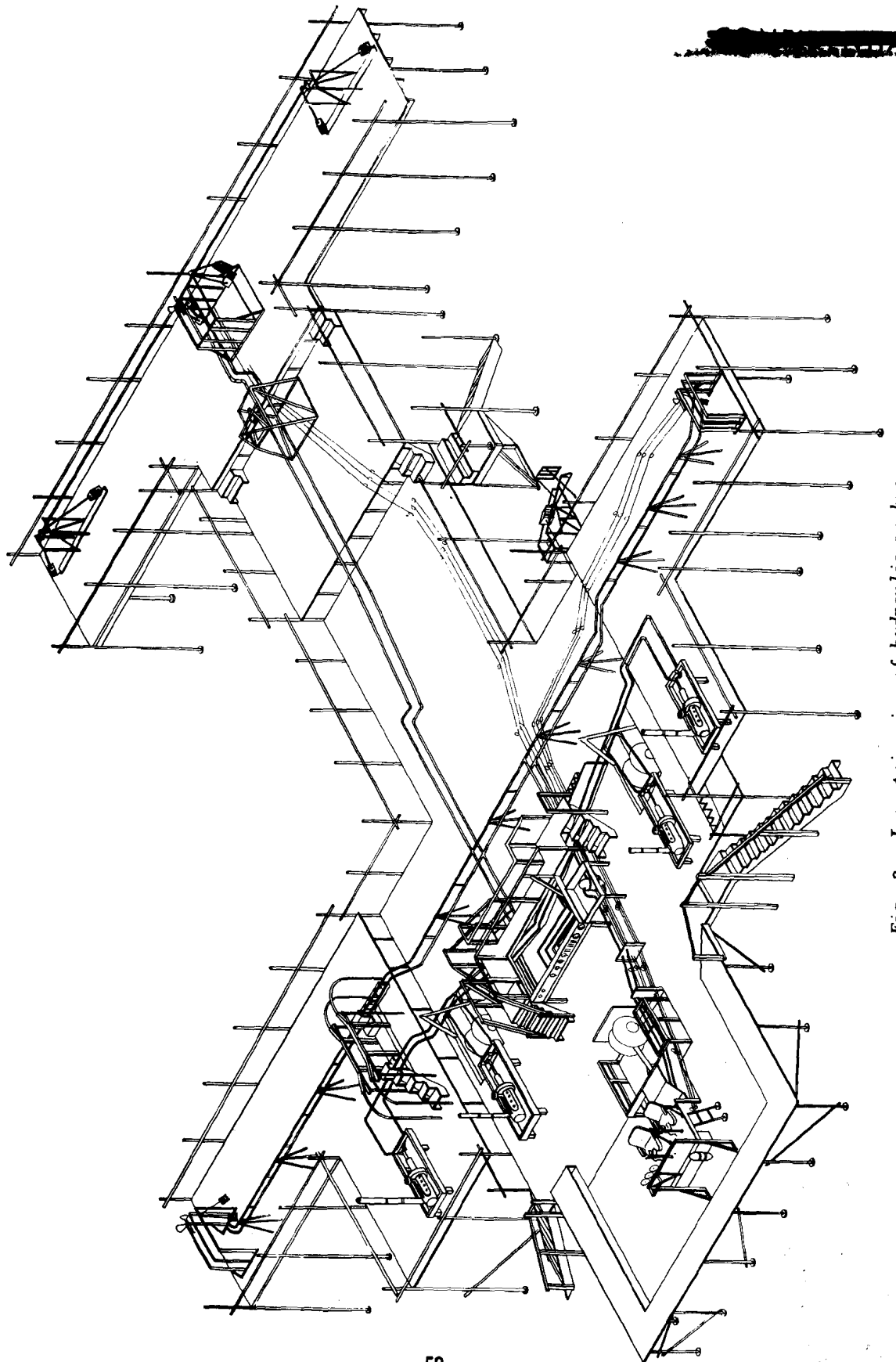


Fig. 3 - Isometric view of hydraulic mockup.

Development

The original plan was to install the parts and then test the complete mockup. However, the fallacy of this wishful thinking soon became apparent. Mechanisms just do not seem to work as well in practice as they do on paper in the layout stage. In fact, every part of the system was changed so much from the original conception that in many cases there is little similarity between the original and the final result. Considerable time and hard work were required before we had enough of the individual systems working properly to make a complete system test possible. Complete redesigns occurred in many cases either in the mockup stage or, in a few instances, after flight tests of the airplane. The striking differences between original and final design can be attributed mainly to an incomplete problem statement or knowledge of all the requirements at the start. Many of these requirements could only be learned through experience with the airplane in actual service. In order to describe these developments more logically, it is necessary to take each section of the system individually.

Boosters

Figures 4 and 5 show the original power booster for the rudder which was built for test in the laboratory. The control valve is mounted to fixed structure and controlled by a parallelogram linkage which provided follow-up and directional sensing. The actuating cylinder connections were made through swing joints located on the axis of the mounting trunnions for the cylinder. This permitted the elimination of flexible lines which were considered a hazard. The booster valve is balanced and opens the pressure and return ports simultaneously. Incorporated in each end of the valve is a "feel" cylinder connected directly to the actuating cylinder line. The area of this "feel" cylinder as compared to the area of the actuating cylinder determined the boost ratio or amount of "feel" received by the pilot from a load on the control surface.

The original booster configuration contained deficiencies which made it unsatisfactory for use on the airplane. In actual tests it "motored" or oscillated violently. Resiliency or deflection of the oil column between the piston of the actuating cylinder and the piston of the "feel" cylinder, aggravated by friction in the control valve, was the major cause of the oscillation. In addition, lead weights hung on the end of the beam shown in Figure 5, for the purpose of loading the mechanism, inadvertently provided the "flywheel" and the net result was a hydraulic engine. Reversibility of this type of booster is very poor due to the accumulative effects of friction in the actuating cylinder and control valve.

This type of booster mechanism has since been used on other aircraft but at lower boost ratios than that required by the Constellation.

Figure 6 shows the revisions necessary to obtain acceptable performance from the booster. It will be noted that the "feel" cylinders have been eliminated and replaced by a "feel" lever. The mechanical leverage system permitted accurate follow-up with minimum friction, since it was mounted on anti-friction bearings. Deflections equivalent to that encountered with the hydraulic leverage system were reduced to a minimum. In the revised booster it is not necessary to move the power cylinder piston rod before the valve is actuated, since the power cylinder piston will only move as directed by the booster valve. The "feel" lever actually pivots about the piston rod connection

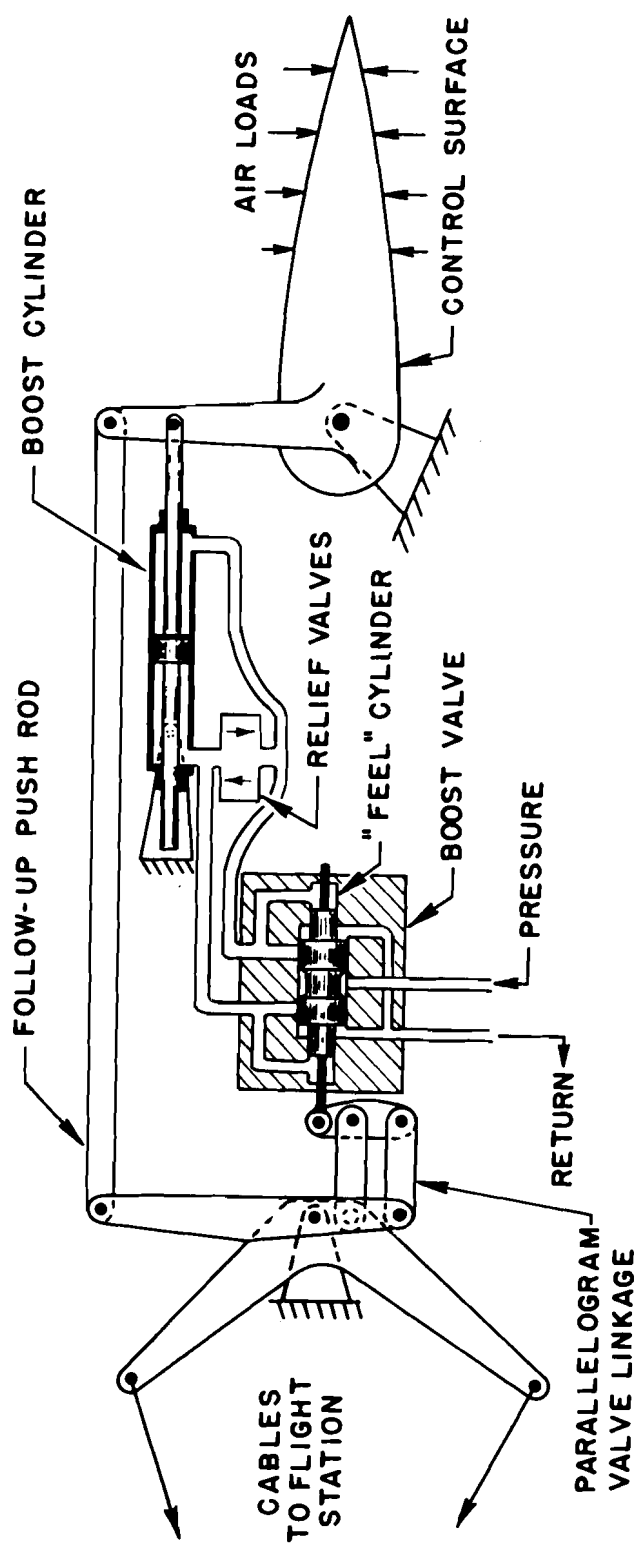


Fig. 4 - Diagram of original rudder booster.



Fig. 5 - Original rudder booster in laboratory test jig.

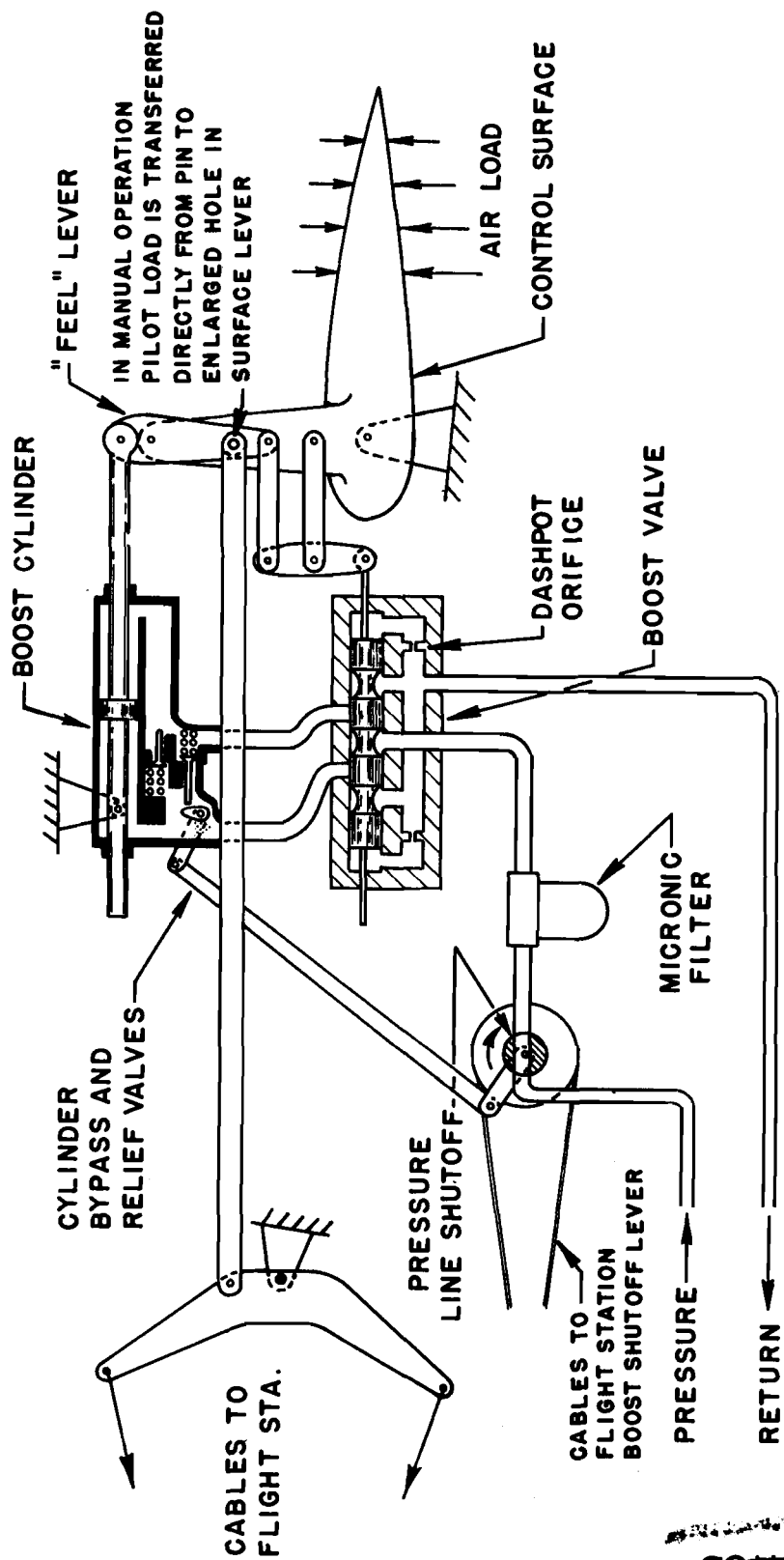


Fig. 6 - Diagram of rudder booster using "feel" lever.

until the boost valve has been actuated far enough to direct fluid to the cylinder and cause it to follow. The valve has been redesigned for minimum friction and incorporates dashpots in each end to limit the velocity of movement of the valve shaft.. The orifices in these dashpots are adjusted so as to limit the valve actuation speed to a point well below the natural "motoring" or oscillation frequency of the mechanism. With a hydraulic follow-up system such as used in the first booster, the amount of damping required is relatively large, but with the lever system used the natural frequency of the mechanism is high enough to require relatively little damping. The actual amount of damping required for stability in a booster of this type is a function of the boost ratio, the inertia on the output end of the mechanism (the surface), cylinder thrust, friction in the linkage and packings, spring rate of the control system between booster and flight station and spring rate of the system between booster and the control surface.

In case of hydraulic system failure, the shut-off valve in the pressure line is actuated simultaneously with operation of the by-pass on the cylinder to shut off the booster. The pilots' controls then are connected directly to the surface, with a small amount of lost motion due to the valve linkage.

This booster configuration produced what was thought to be satisfactory performance for incorporation in the mockup. Elevator and aileron boosters were constructed in a similar manner, using the same identical valves and many of the same parts as the rudder booster.

Complete functional tests were conducted at normal temperatures, in the cold room at -65° , and at $+160^{\circ}$. After the preliminary development, all boost units were mounted on the main hydraulic mockup and cycled in a life test. This test was run in conjunction with operation of the complete mockup and checked the effect on the boosters of operation of other components in the hydraulic system. Again, changes were found necessary. Life cycling disclosed weaknesses in linkage parts and piping details. After correcting these difficulties the mockup was put through a regular flight schedule simulating take-off, climb, cruise approach and landing for a period of 200 hours. During this endurance run the boosters were cycled, working against simulated air loads. The test conditions were much more drastic than could be expected in normal airplane operation. After passing these tests the equipment was considered satisfactory for flight tests.

The first flights were successful and, in fact, the airplane set a new record in making six flights the first day. Although the first flights were considered very satisfactory, it soon became evident that considerable improvement was still necessary to obtain good performance and reliability.

The first revision concerned the booster valve. It was determined from flight tests that metering characteristics of the valve needed improvement to obtain smooth operation. Better results were obtained by revision of the slide valve clearance to increase the leakage rate, and further reduction of friction in the valve itself. Further improvements were made in the cable control system to reduce friction. The minor changes improved the stability of the airplane, but were not enough to eliminate oscillation or directional hunting of the airplane in certain cruise conditions. We had exhausted most of the possibilities for improvement while still retaining the original hydraulic boost ratio, and it was evident that to obtain still further improvement, the boost ratio in the "hands off" or stick free condition must be reduced on both the

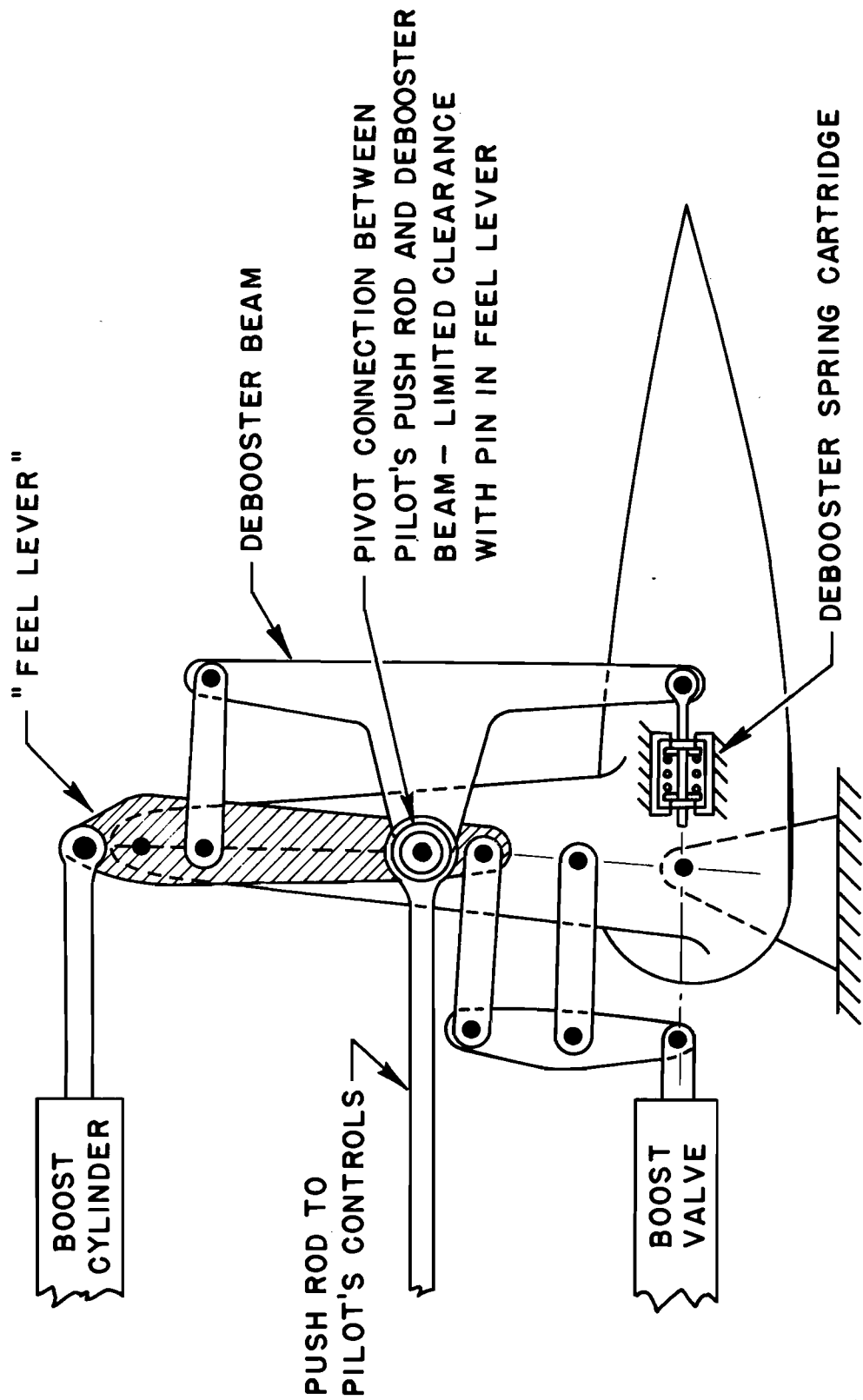


Fig. 7 - Diagram of rudder "debooster" linkage.

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rudder and elevator boosters. This was done by the "debooster" linkage shown in Figure 7. This linkage permitted the booster to work at a 2:1 boost ratio at low hinge moment or stick force conditions. After the pilot increased his load to a predetermined value the clearance between the pin on the "feel" lever and the hole in the pilot's push rod is taken up, and the boost ratio is effectively increased to the original high value. In the "hands off" cruise condition this permitted the control surface to adjust itself easily by overcoming the cable control system friction at a 2:1 (disadvantage) ratio instead of the 30:1. This revision corrected the hunting characteristics on the airplane and provided the steep slope around neutral indicated on the curve of Figure 1.

Further experience indicated that possibility of hazard existed in the booster valves should the orifices in the dashpots become plugged. In fact, one of these orifices became plugged with lint, in ground test operations. In order to eliminate this hazard, screens were located on either side of the orifices. Then it was discovered in laboratory testing that these screens could be stopped up at low temperatures should the hydraulic fluid contain over 5 per cent water. The water crystals froze and piled up on the screens, so relief valves were added. These relief valves were set to crack at a pressure low enough to permit the pilot to override a plugged orifice but high enough so as not to interfere with the damping action of the dashpots in the valve. Inadvertently, this produced another advantage. It permitted the pilot to move the control suddenly, if so desired, overriding the damping action in the boost valve.

Experience in oil line operation required revision to the cylinder packing design as well as changes in fits and clearances of the linkage. Although all boosters had gone through a 200,000 cycle life test before being considered satisfactory for airplane usage, 50 hours of operation in flight was enough to point up deficiencies in gland packing design. Revisions were made by incorporation of leather back-up rings behind the "O" rings, installation of felt wipers and revision to the gland bearing material. After these changes, cycling tests were run through one half million. Service experience indicates that this has produced a satisfactory design.

The final configuration of boost valve and cylinder is shown in Figure 8. The relief valves built into one end of the cylinder limit the pressure which can be built up across the piston, and in this way limit the hinge moment which can be applied to the surface. This produces the sharp upturn in the curve of Figure 1 near the extremes. Although simple in its principle of operation, the boost valve is complicated in construction due to the requirements of friction reduction. This is the reason for the ball universal joints to permit alignment and eliminate bind due to machining tolerances. These valves must operate with a maximum of one pound force on the shaft.

Elevator and aileron boost units are constructed similar in principle to the rudder booster and many of the same parts are used.

Concurrently with development of the booster units, the hydraulic system was being developed, and it was found that even with a primary and secondary system as mentioned above there still existed the possibility of failure of a common line supplying the rudder and elevator boost units in the tail of the ship. Should this failure occur during take-off or landing it could cause loss of boost at a time when it was most needed. In order to provide a safeguard against this contingency, it was decided to add a small auxiliary power system at the elevator and rudder boosters to be used only as a stand-by for these conditions. This consisted of an electric driven gear pump,

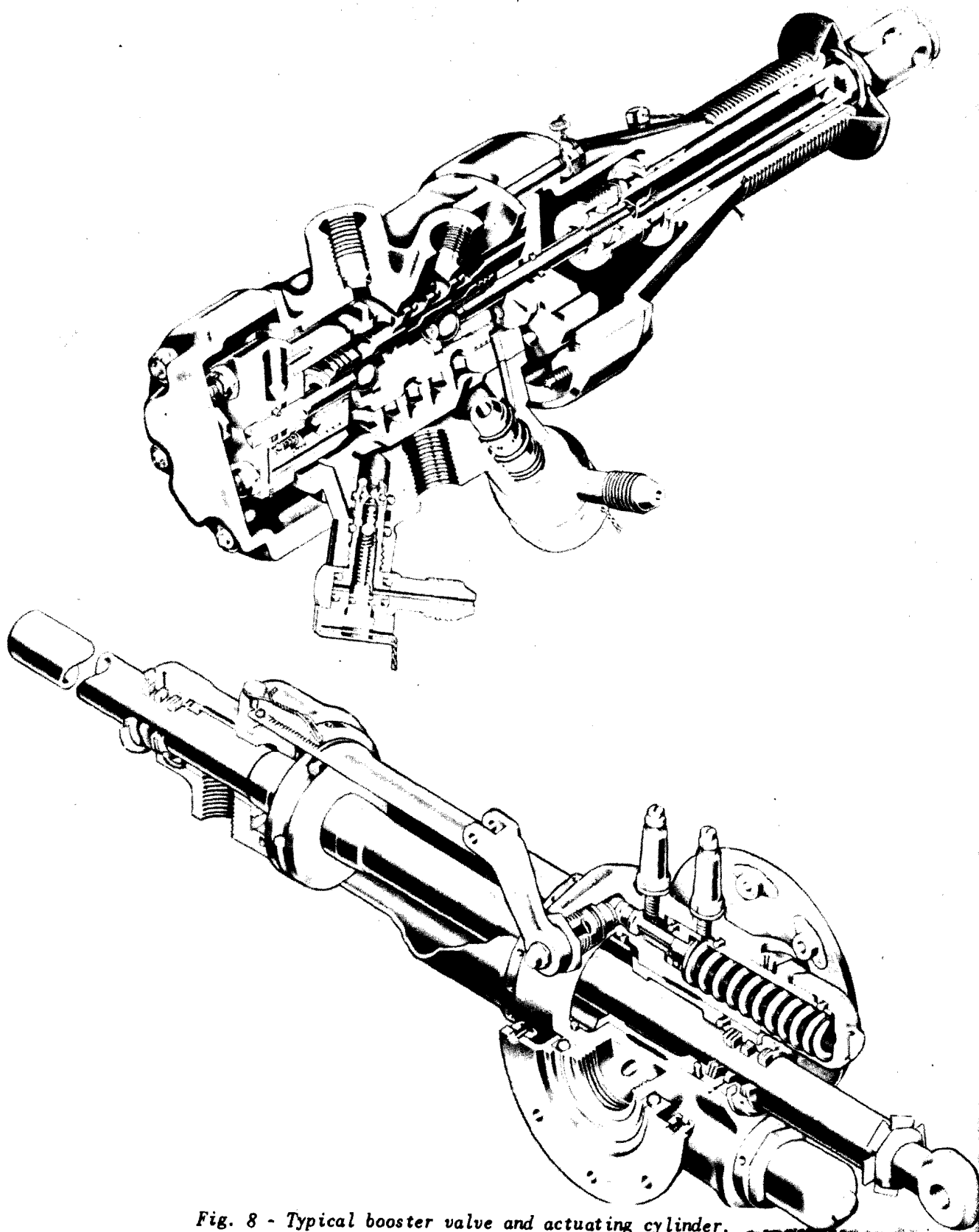


Fig. 8 - Typical booster valve and actuating cylinder.

accumulator, pressure regulator and a sump tank through which the main return flow passed, insuring that the auxiliary system was always charged with oil. Relatively little trouble developed with the auxiliary boost systems and both systems have remained essentially unchanged since the initial development.

Power System

Figure 9 shows the Constellation hydraulic system diagram. It will be noted that it is divided into primary and secondary systems, with the two left-hand pumps supplying the primary system for booster power only, while the two right-hand pumps supply power to the secondary system for landing gear, flaps, etc. The two systems are connected together at the crossover check valve which automatically switches the secondary system pressure to the boosters in case of primary pump or line failure in the left wing. This crossover check valve is so adjusted that the switch-over operation occurs as soon as the primary system drops to about 1150 psi, the normal operating pressure being between 1500 and 1700 psi. At the time this operation takes place, the crossover check valve also signals the two spring-loaded return by-pass valves which automatically switch the return flow to the secondary side of the reservoir. Priority for the boosters in this operation is maintained by the restriction control valve located downstream from the crossover check on the secondary pressure line. This valve is set to allow 11 gpm flow at 1300 psi minimum, and permits no more than 1.5 gpm flow should the pressure in the secondary system drop below 1150 psi.

This hydraulic system has given a good account of itself in service and shows one method of supplying alternate sources of power for the surface control boosters.

Figure 10 shows a schematic diagram of the elevator booster installation on the XR60-1 Constitution. Note that there are three separate boost units used, each being supplied by a separate source of hydraulic power. Each boost unit is mounted separately and connected to the elevator torque tube by means of a push rod. All three units are similar in design to the Constellation boosters in that the boost valve is mounted to fixed structure with solid lines in between the valve and cylinder. But in this case, additional hydraulic equipment is included in the boost valve housing to eliminate the complicated plumbing experienced with the Constellation. The Constitution has three hydraulic systems, one called the utility system which supplied pressure to one of the elevator boosters as well as the landing gear, flaps, and other hydraulic power devices. In addition to the utility system there are two separate systems used for booster operation only. The pumps of these various systems are so arranged that loss of any power plant never leaves any hydraulic boost unit without pressure.

Figure 11 shows a cross section of the Constitution boost valve. Note that in addition to the boost valve we have included the usual pressure line filter and the boost cylinder by-pass all in the same package. The by-pass on this valve is pressure operated, with a spring to move the valve to the by-passed position whenever pressure drops. In addition, the boost valve spool automatically disconnects from the operating shaft when pressure drops at the valve pressure port. Included in the valve operating shaft, on the outside of the valve housing, is a pre-loaded spring which will deflect, should the valve spool become jammed. This deflection operates a microswitch which in turn lights a warning light in the cockpit to indicate which boost unit is malfunctioning. This then permits the pilot to turn off this booster by operation of the motor operated shut-off valve located elsewhere in the pressure supply line. As soon as the pressure

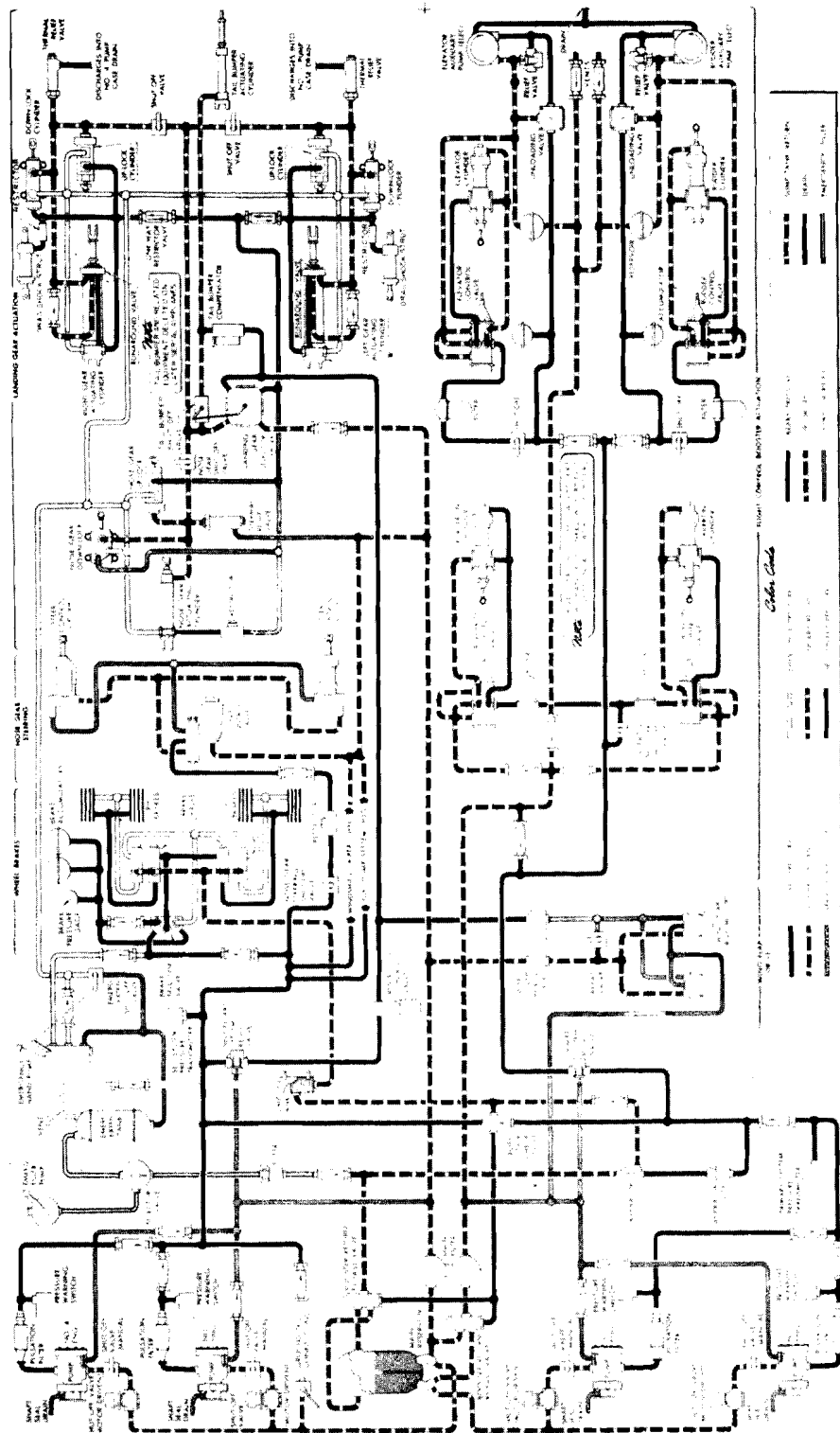


Fig. 9 - Diagram of hydraulic system used in latest Constellations.

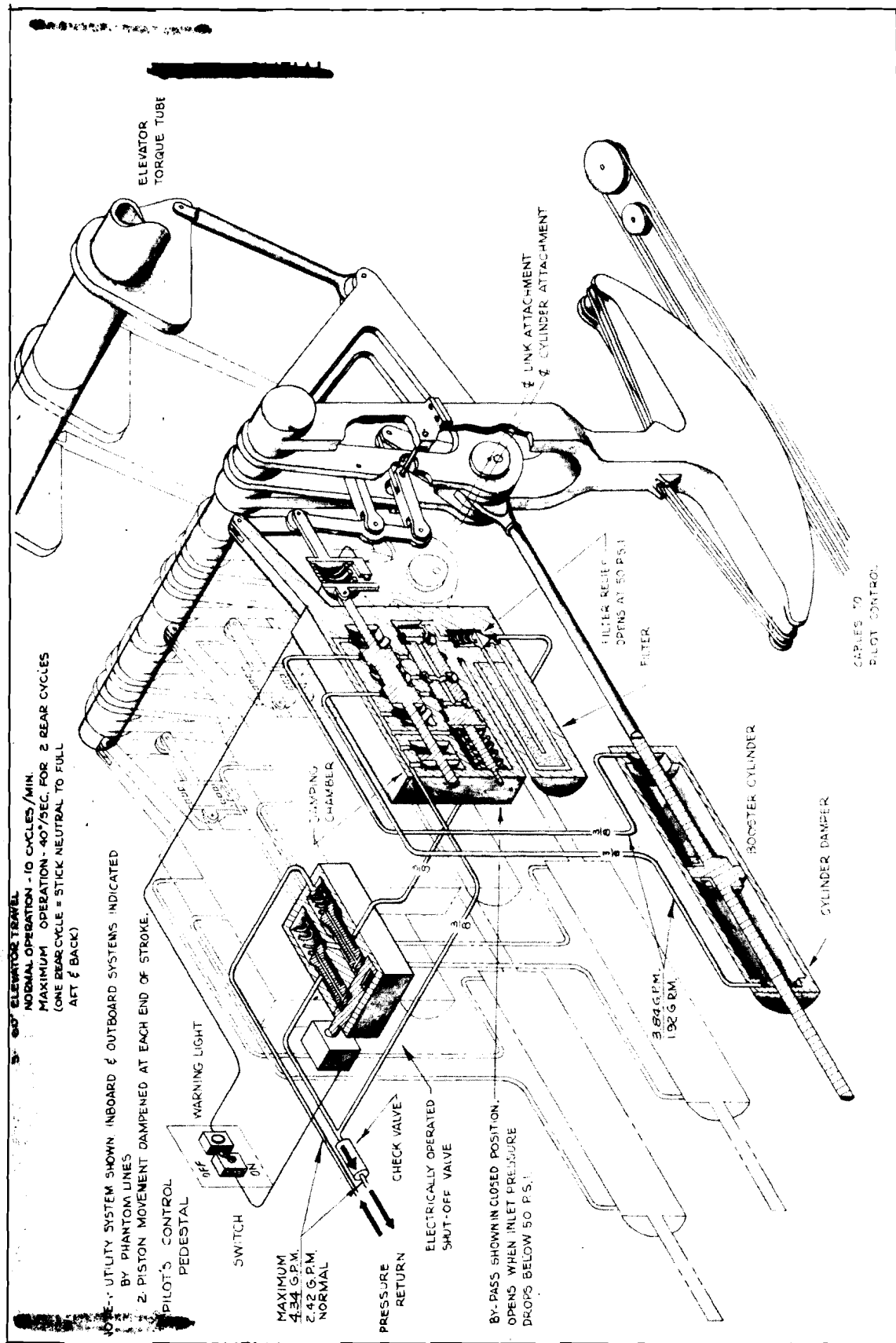


Fig. 10 - Schematic diagram of elevator boost installation on the Constitution.

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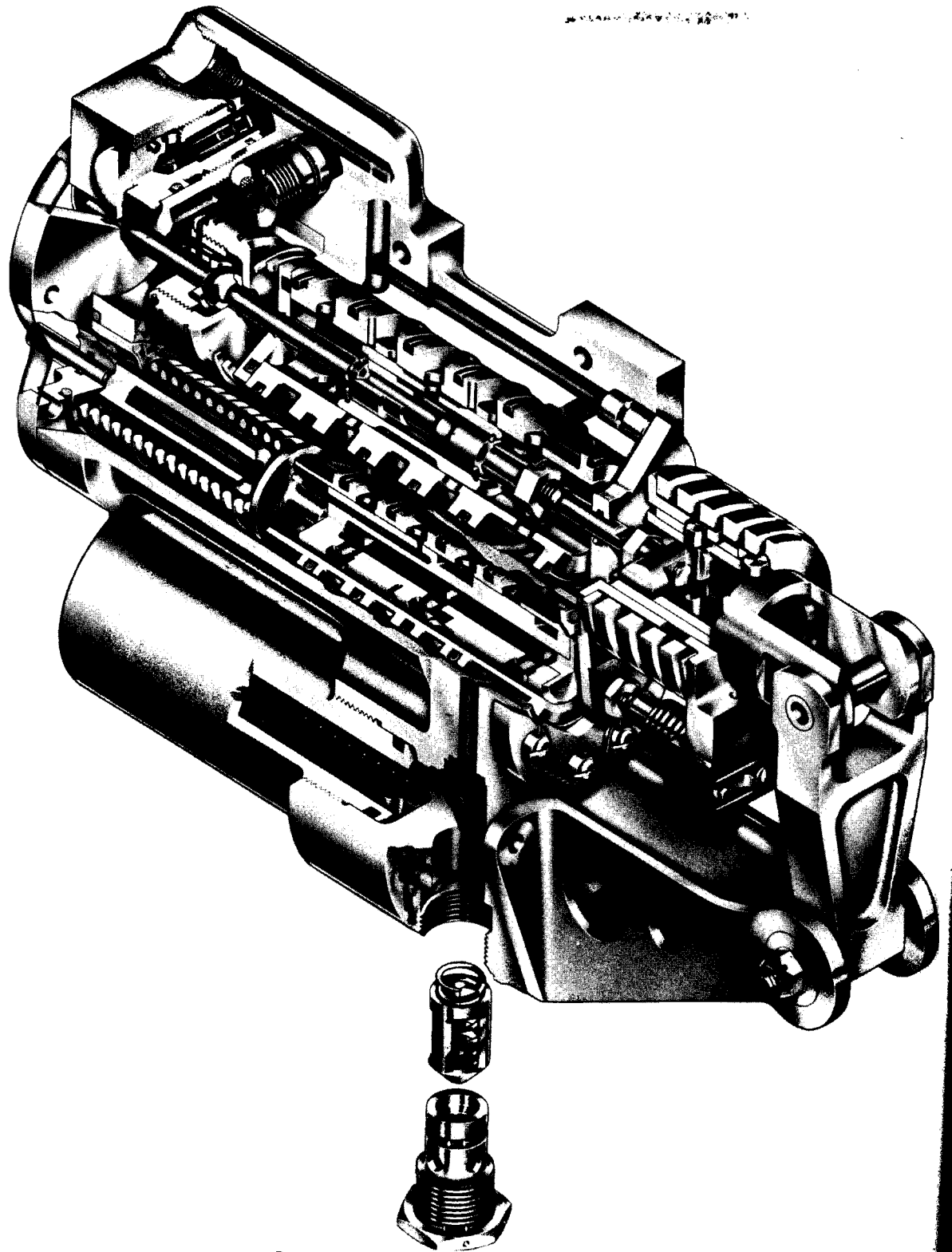


Fig.11- The Constitution boost valve.

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drops, the valve shaft becomes disconnected from the jammed spool as noted above and the cylinder is by-passed, which completes the operation of putting this particular boost unit out of operation.

Figure 12 is a photograph showing the installation of the elevator boost units in the airplane. It will be noted that none of the Constitution boosters utilize the deboost idea that was used on the Constellation. The reason for it is that the control cable system is much more efficient. At the time the Constitution was designed, the importance of control cable friction was recognized and every effort was made to reduce friction due to cable bends, etc. The installation shown in Figure 12 does, however, show one of the potential difficulties with multiple boost units. This concerns the method of coupling between the three units. It was discovered on tests that the mismatch in timing of the three units caused by play in the chain couplings used to transmit pilot load caused unsatisfactory operation, and these couplings had to be hand fitted to eliminate all lost motion before smooth operation was obtained. This particular problem did not occur on the rudder and aileron because of the type of construction used. We did experience chattering of the elevator boost and discovered that it was caused by the spring rate of the control system between the booster and the cockpit. However, the fix in this case was very simple. A limited deflection decoupling spring was inserted between the "feel" lever and the lever operated by the control system. This in effect changed the spring rate of the control system and smoothed out the operation.

Figure 13 shows a schematic of the rudder boost unit for the Constitution. Only two boosters are used and it will be noted that the boost valves are the same as those used on the elevator. Cylinders and valves are mounted in a rigid framework and it will be noted that a common "feel" lever is utilized. This eliminated any relative deflection between the two units and precluded the difficulty noted above with the elevator installation. This booster assembly is mounted underneath the horizontal stabilizer and connected by push rod to the rudder as shown in Figure 14.

Figure 15 shows a schematic diagram of the aileron boost assembly. Again, only two units are used. There is a notable difference between this boost installation and that used on the Constellation in that a separate booster was used at each aileron on the Constellation, while only one dual boost unit is used on the Constitution. This assembly is located on the centerline of the airplane on the rear wing beam. Connections to the ailerons are made through clad cables from the large quadrant. The difference in these two aileron boost installations produces one notable effect. Where separate units are used at each aileron, the ailerons are deflected upward by the air load when the booster is turned off. This takes all of the lost motion out of the pilot's control when flying boost off. However, when the boost is turned back on again, the ailerons are suddenly deflected back down to the normal position in order to bring the control valve back to the neutral position. Should the two booster by-pass valves be rigged differently, one aileron will be deflected down before the other, which results in a rolling moment on the airplane. On the other hand, with the type of installation shown on the Constitution, this action does not occur, but there will be some lost motion in the pilot's controls when the boosters are turned off. In the Constitution, of course, this is not considered since it is always intended to have power on one or the other boost units used on the aileron.

In order to go over some of our experiences, it might be well to comment on a few generalities concerning power boost installations that we have learned over the

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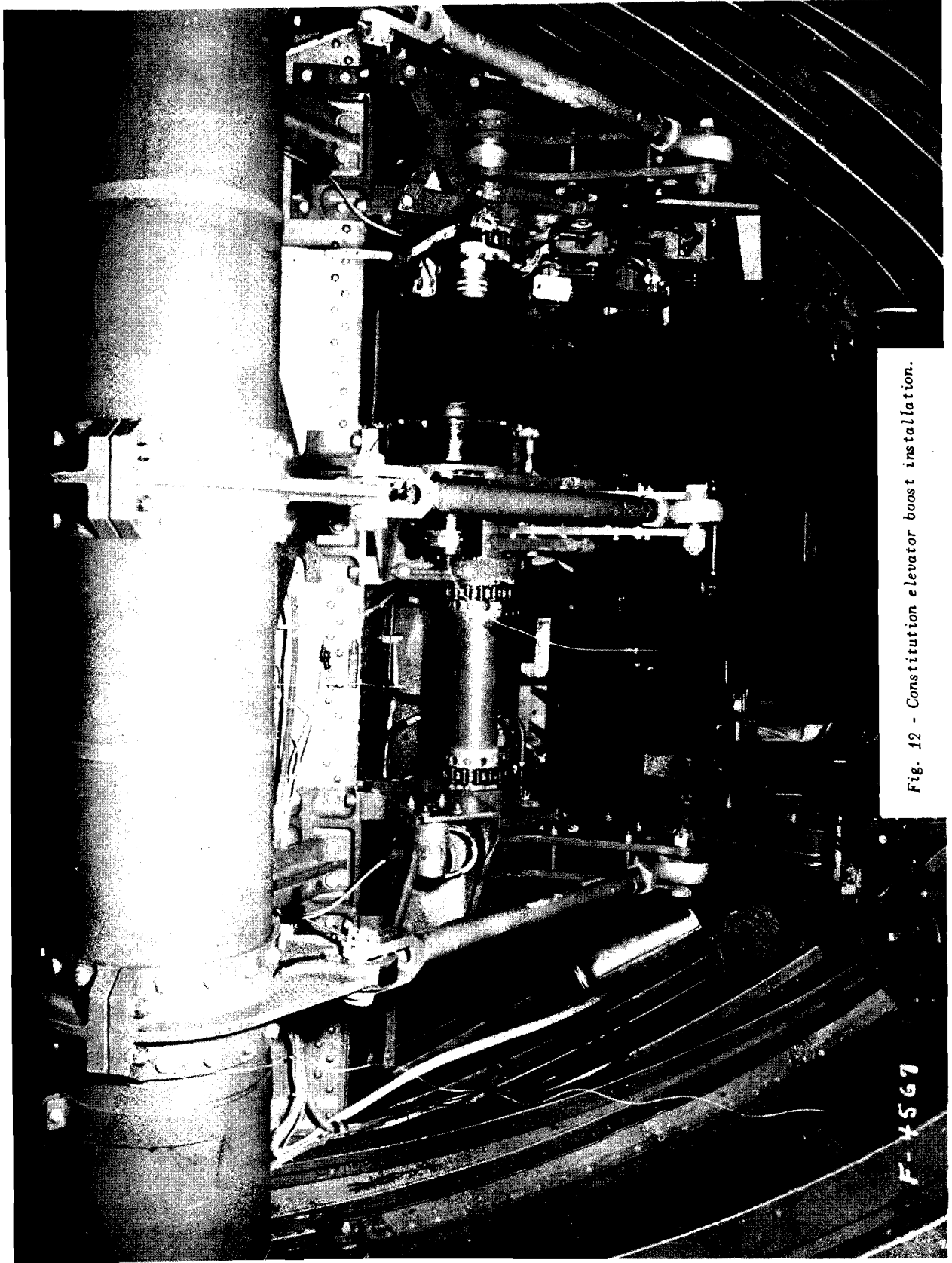
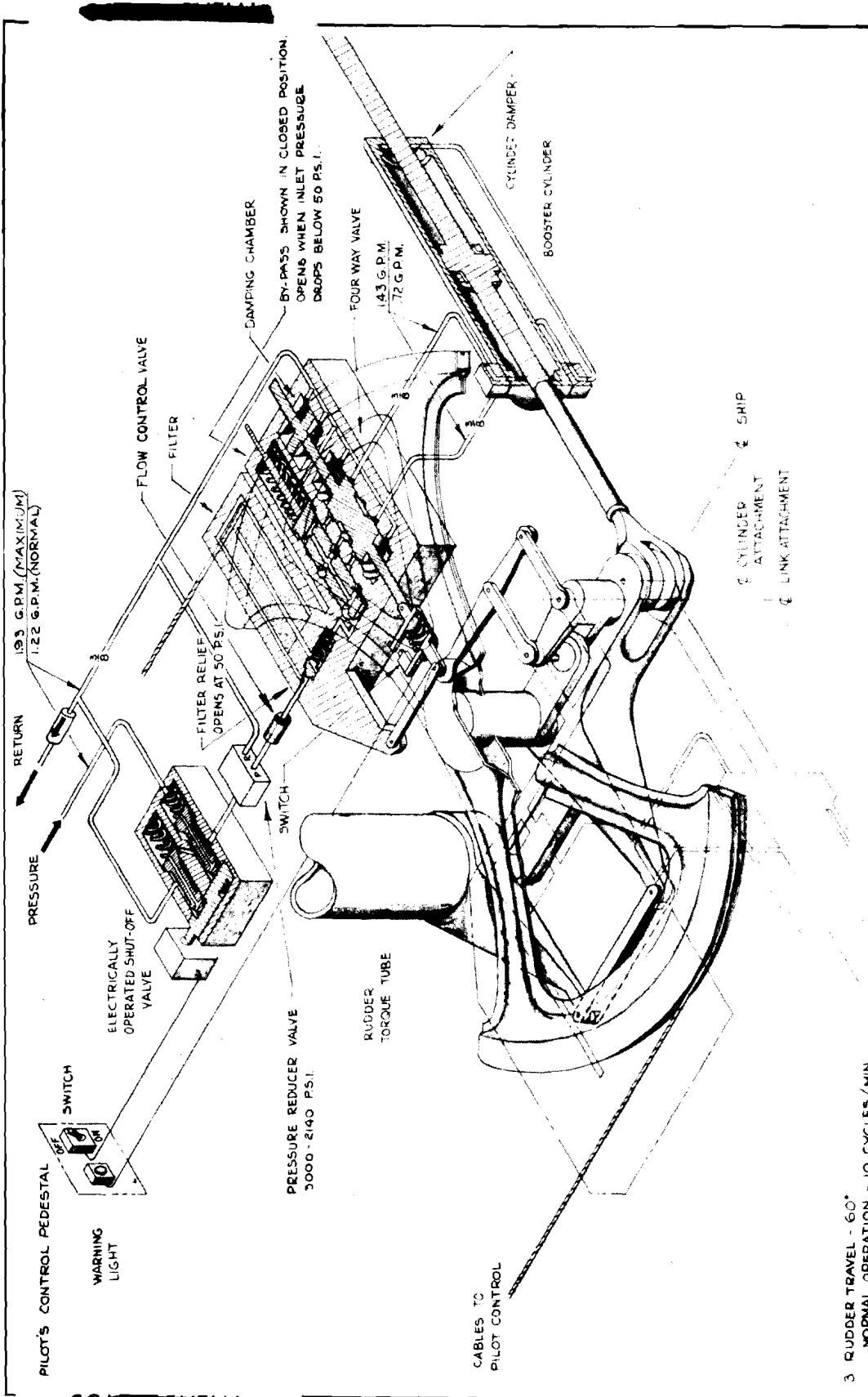


Fig. 12 - Constitution elevator boost installation.



- 3 RUDDER TRAVEL - 60°
- NORMAL OPERATION - 10 CYCLES/MIN
- MAXIMUM OPERATION - 40°/SEC FOR 1 FULL CYCLE
- 2 PISTON MOVEMENT DAMPENED AT EACH END OF STROKE
- 1 INBOARD SYSTEM SHOWN, UTILITY SYSTEM INDICATED BY PHANTOM LINES.

Fig. 13 - Diagram of Constitution rudder booster.

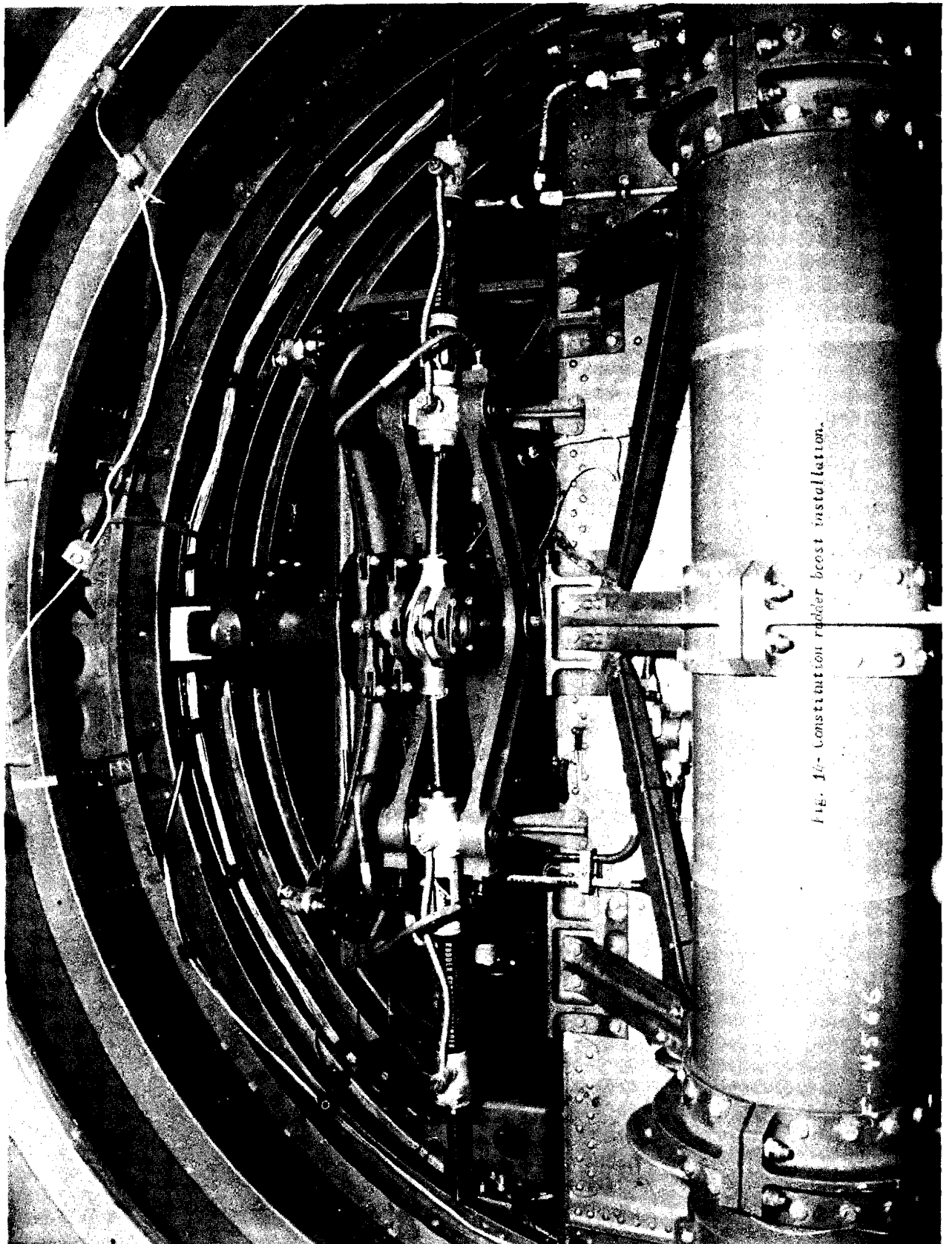


Fig. 16- Constitution rubber beest installation.

- NOTE -
1. PHANTOM LINES INDICATE SEPARATE HYDRAULIC SYSTEM.
 2. SLOTTED HOLE IN LINK REPRESENTS AN ECCENTRIC BEARING.
 3. PISTON MOVEMENT DAMPENED AT EACH END OF STROKE.
 4. AILERON TRAVEL - 85°
- MAXIMUM OPERATION - 407/SEC FOR ONE FULL CYCLE

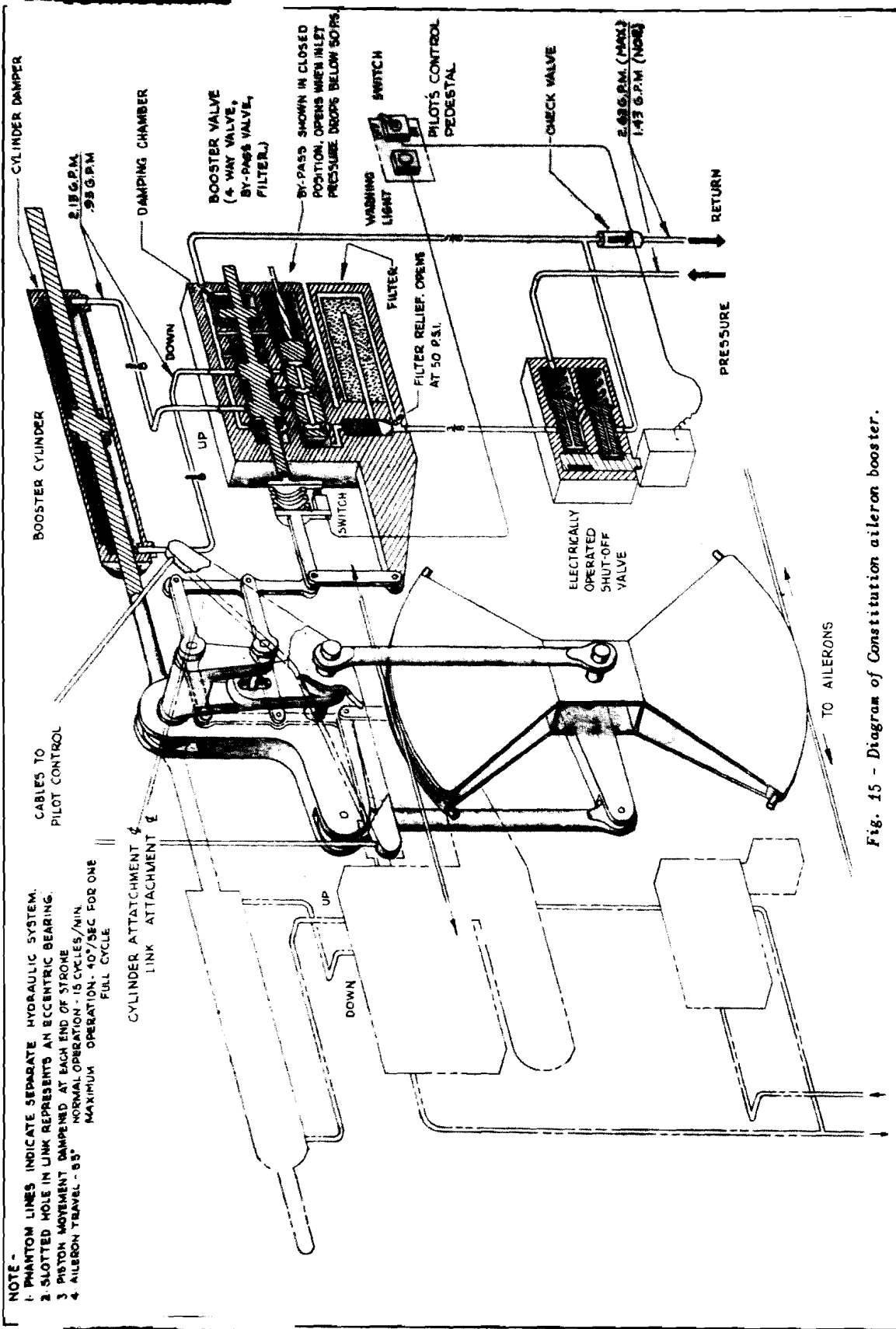


Fig. 15 - Diagram of Constitution aileron booster.

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last few years. We have built and tested a number of different booster valves, starting with the Constellation. As time went on we obtained a better understanding of the problem. Some of the requirements were learned as a result of considerable flight experience and service experience. We have come to the conclusion that it is better to include all of the various valves and, if possible, even the boost cylinder into one package, eliminating external plumbing connections entirely. This makes the unit more foolproof as far as servicing is concerned, and we have learned from our field service experience that anything of this nature which looks complicated gets either one of two treatments. It either gets left strictly alone and never serviced, or if someone does attempt to service it on the airplane he generally does not thoroughly understand the mechanism and may do more harm than good. For this reason, we believe it desirable to have the hydraulic units consolidated into one package which is easily removable, so that the malfunctioning unit can be serviced in the hydraulic shop by trained personnel. Our latest designs used on the F-90 incorporate these ideas. One package contains all hydraulic equipment with internally drilled porting and only two external hydraulic connections, one for the pressure and the other for the return line.

We have experimented with a number of ideas to reduce boost valve friction and learned that there is a better way of doing it than to use a linear type of seal for the operating shaft as illustrated. In our later designs we operate the boost valve spool by means of a submerged lever inside the valve housing and rotate this lever by means of a shaft coming out of the valve housing through a rotary seal. This eliminates the high breakaway friction experienced with the usual piston rod packing, since the rotary seal friction holds fairly constant.

A number of methods to accomplish the boost valve modulation characteristics have also been tried. The Constellation valve used the oldest method, that of chamfering the edge of the spool and allowing the spool to uncover one or two small holes in the sleeve before opening the larger port. Other valves have been made with a sharp edge on the spool and a larger number of small holes to get the progressively opening characteristic. However, this involves accurate location of a number of small holes in a hard steel sleeve which has its practical disadvantages. Our latest valve design incorporates a tapered thread on the end of each valve land. No small holes are used in the sleeve. In fact, an undercut port in the valve body makes the cleanest design. By varying the depth, pitch, and taper of the thread on the valve spool, any modulation characteristic desired can be accomplished. In effect, this produces a variable length choke tube and provides a simple solution to making a small diameter valve spool.

Booster cylinders have been built both with and without packings on the piston. We have a small boost unit at the present time which has a lapped piston with no packing except on the piston rod. This reduces the cylinder friction considerably and is advantageous where friction is an important consideration.

We have designed, built, and experimented with a number of disconnect devices for disconnecting the boost cylinder from the "feel" lever. None of them has ever flown, since it appeared that the complication involved added more hazard than would be involved if the piston rod were solidly connected to the linkage. This is especially true on commercial airplanes. On military aircraft the requirements are different, and we are convinced that the cylinder disconnect operation should be accomplished in

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another way, possibly by freeing the cylinder from the fixed structure rather than at the piston rod end.

One of our main sources of annoyances has been with the linkage parts, and especially with the "feel" lever bearings. In our designs, in order to obtain the desired reversibility of the mechanism at high boost ratios, we have found it necessary to use large ball bearings on the "feel" levers. However, these levers never rotate through a very large angle, although high loads are transmitted through these bearings. This action aggravates the false brinelling tendencies of the bearing, and after a period of time will gradually form some pockets or detents under each ball. The only known solution to this problem so far is to use bearings of much larger capacity than theoretically required, or rotate them far enough so that the brinelling action is prevented by lubricant in the bearing.

Boost installations at Lockheed have been made on a number of airplanes in addition to the Constellation and Constitution. This includes the aileron boost used on the P-38L, the F-80, F-94 Series, and the newer F-90. All of these installations have used a closed center hydraulic system operating at 1000, 1500, or 3000 psi. There seems to be little choice in the pressures used as far as operating characteristics are concerned. Some experimental work has been done on open center boost units, but we have never flown one on an airplane. There probably are a number of good reasons for using an open center type of unit on an airplane like the Constellation, while it seems more advantageous to use a closed center system on a small fighter airplane.

DISCUSSION

MR. FEENEY, Northrop Aircraft: *I didn't quite get what you meant by the threaded holes on the valve design.*

RICHOLT: *I'll have to draw you a picture, I guess. This is something we re-invented the other day. It isn't anything new. Supposing this is your housing for your boost valve and here's the valve spool which might be like that. Here's the port that you are going to uncover. You want to modulate that port and here's the other one. You want to control the leakage through here. We leave this corner sharp here. Then you just start grinding a thread in here, and you actually do this to it. That is enlarged. This thread actually does not come up and overlap this hole but by cutting a tapered thread on the edge of this spool and another one here, you can get very nice modulation characteristics.*

FEENEY: *It is sort of an effect.*

RICHOLT: *It is a variable length choke tube..*

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DR. WILSON, Goodyear Aircraft: *Would you tell me the difference between the closed and open center systems?*

RICHOLT: *The closed center system is where we maintain pressure all the time at the boost valve and do it with variable volume pumps; it has always been our method. The open center is where you have a flow through the valve and the valve actually is open at the neutral position and when you want to build up pressure in the cylinder, you move the valve over to throttle some of that pressure.*

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POWER BOOST EXPERIENCE AT GLENN L. MARTIN

By

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The Glenn L. Martin Company, Baltimore, Maryland

I. Introduction

This report is prepared in conformance with the agreement reached at the Power Boost Conference (Bureau of Aeronautics, Washington, October 6 & 7, 1949) in which each company represented is to submit a summary of its power boost experiences. The Martin Company experience to date has been quite varied and includes application to airplanes ranging in size from the AM-1, Mauler (21,000 pounds gross) to the JFM-1, Mars (145,000 pounds gross).

II. Summary and Conclusions

Applications of power boost at the Martin Company are listed in the following table. The XPB2M-1, "Mars" flying boat represents one of the first successful power boost applications to airplane flying controls. Outstanding power boost developments at Martin are the spoiler aileron, the demand assist bungee, and the automatic variable ratio booster. The mechanical feed-back type of fixed ratio boost has been found to be superior to the type using hydraulic feed-back. Open center hydraulic systems are most satisfactory for elevator and rudder boosters. The closed center hydraulic system works better for spoiler aileron operation. No applications have been made to date of artificial feel or dual boost systems.

III. Discussion of Power Boost Systems

In order to give an overall picture of Martin power boost applications the table of Part A has been prepared. Since the number of different airplanes to which power boost has been applied is quite large, the discussion has been limited to the basic types of boost systems used rather than to a detailed discussion of the controls of each airplane. The basic systems are discussed in parts B, C, and D. Special experiences from each model airplane are listed where pertinent.

A. Martin Boost Table. (See next page)

B. Fixed Ratio Power Boost Systems.

1. Description: An airplane fixed ratio power boosted control system is one in which the force to move a control surface is supplied jointly by the pilot and some power source, usually hydraulic. The proportion of the total operating force supplied by each is determined in the design of the system on the basis of maximum surface hinge moment. Since the pilot output is limited to approximately 2000 inch lb. the booster has to supply the rest. The ratio of the hinge moment

MARTIN BOOST TABLE

Airplane	Date	Gross Weight	Boosted Controls	Type of Boost	Approx. Boost Ratio (H. M. Boost) (H. M. Pilot)
XPB2M-1	1941	145,000	Elevator	Closed Center	4:1
			Rudder	Fixed Ratio	4:1
JRM-1	1945	145,000	Elevator	Open Center	4:1
			Rudder	Fixed Ratio	4:1
XB-48	1947	100,000	Elevator	Open Center	7:1
			Rudder	Fixed Ratio	
			Spoiler Aileron	Open Center Feel from Small Aileron	Power Control
AM-1	1948	21,000	Elevator	Closed Center "Demand Assist Bungee"	Variable
			Spoiler Aileron	Closed Center Feel from Normal Aileron	Power Control
PBM-5A	1948	60,000	Elevator	Closed Center "Demand Assist Bungee"	Variable
XP4M-1	1948	80,000	Spoiler Aileron	Closed Center Feel from Normal Aileron	Power Control
XP5M-1	1948	70,000	Elevator	Open Center	4:1
			Rudder	Fixed Ratio	4:1
P4M-1	1949	80,000	Spoiler Aileron	Closed Center Feel from Normal Aileron	Power Control
			Elevator	Open Center Variable Ratio	Variable 1.5:1 to 4:1
XB-51	1949	53,000	Spoiler Aileron	Closed Center Feel from Small Aileron	Power Control

supplied by the booster to that supplied by the pilot is known as the boost ratio. In the fixed ratio boost system the forces applied to the surface by the booster and the pilot are always in the same ratio for any hinge moment up to the maximum. There may be some variation in boost ratio in this type system due to changes in the mechanical advantages of the booster mechanism and the pilot mechanism as the control is operated through its total travel. The fixed ratio boost system has been most generally used to operate elevator and rudder controls on Martin airplanes to date. There are two arrangements of the fixed ratio boost system which have been used at the Martin Company. Their operation is described in the following paragraphs.

2. Operation.

a. Fixed Ratio Boost With Hydraulic Feed Back ^{JFM-1}(XPB2M-1). Refer to schematic control diagram, Figure 1.

- (1) The pilot moves the control column (1) which moves rod (7) and causes arm (8) to rotate about A.
- (2) Rotation of arm (8) moves the spool of the boost valve (3) and diverts fluid from the pressure line to the proper side of the boost cylinder (11). The boost cylinder moves the control surface (2) which keeps moving as long as the control column is moved and the boost valve (3) is kept open.
- (3) When the movement of the control column (1) is stopped point C becomes fixed and the motion of arm (9) which is driven by the followup rod (6) causes arm (8) to rotate about Point C and return the boost valve to neutral.
- (4) In the equilibrium position the same hydraulic pressure which is acting in the boost cylinder (11) also acts on the end of the spool of the boost valve (3). Creating a force which tends to move the valve spool in the opposite direction to that corresponding to the control movement. This force is transmitted through the linkage back to the control column (1) and must be reacted by the pilot in order to keep the control surface (2) in a deflected position. This force is the pilot's feel and may be easily varied by changing the area of the valve piston to give any boost ratio desired. The feel force is also reacted at point A by arm (8) and is transmitted through rod (6) to bellcrank (10) and through rod (4) to the control surface thus contributing to the hinge moment which reacts the air load.
- (5) Arm (9) carries a set of stops which permit only enough relative motion between it and arm (8) to operate the boost valve (3). In case of hydraulic system failure the pilot is connected directly to the control surface through the follow up linkage. In practice the points A, B, and C and their corresponding points on arm (9) would fall on a single line. They are separated here for clarification of the linkage operation.

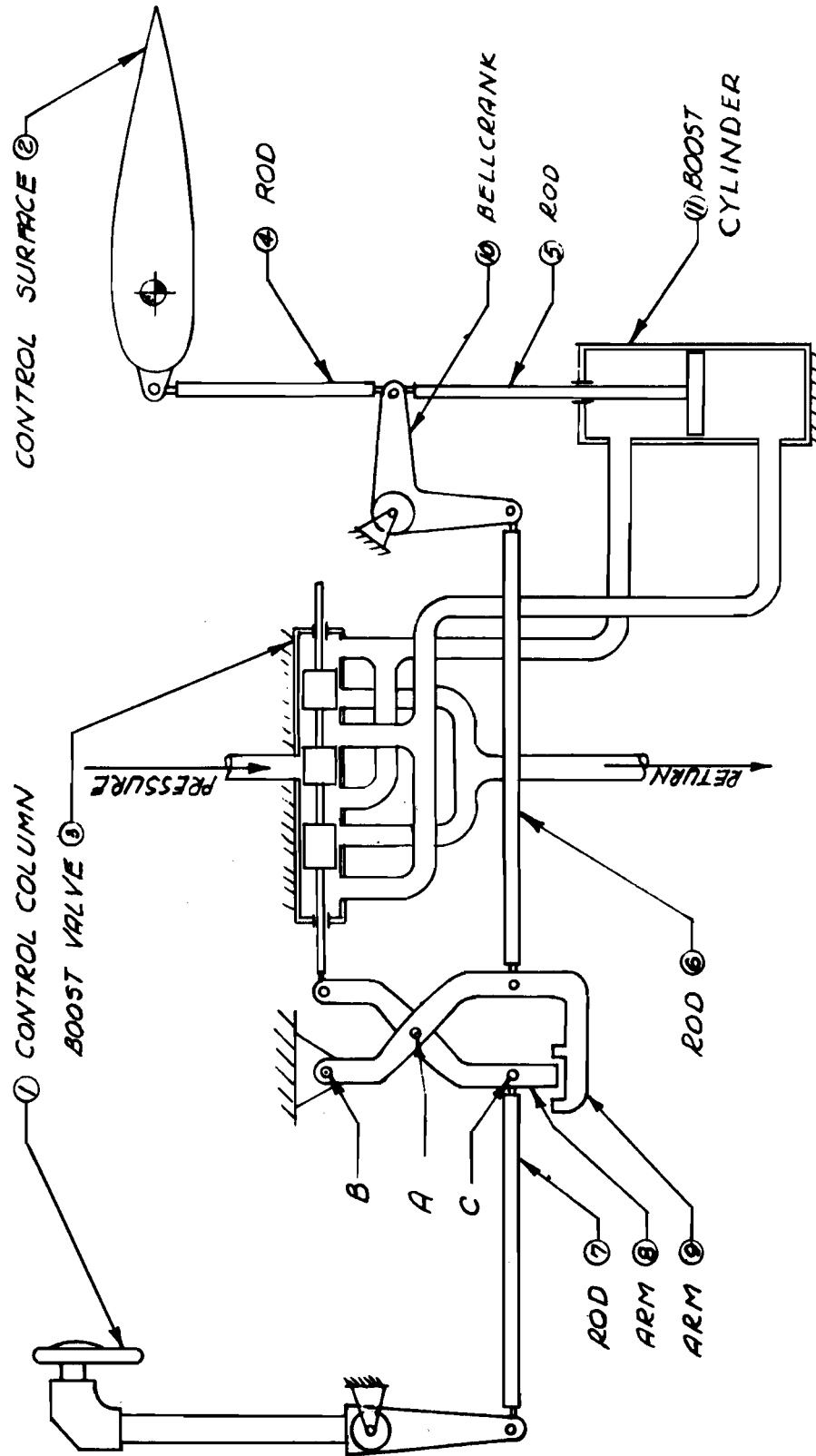


Fig. 1 - Schematic diagram - Fixed ratio boost system with hydraulic feed back.

b. Fixed Ratio Boost With Mechanical Feed Back. (XB-48, XP5M-1). See diagram, Figure 2.

- (1) The Pilot displaces the control column (1). This action operates the cable system (2) which in turn rotates mast (3) about its center.
- (2) As the mast (3) moves, the walking beam (4) is rotated about its pivot. This motion displaces the valve (7) and causes a differential pressure in the cylinder (8). The unbalanced cylinder pressure moves the elevator. As the elevator moves it operates the follow up rod (5) and tends to return the valve (7) to neutral. Equilibrium is reached when the pressure in the cylinder (8) is enough to balance the elevator hinge moment. The pilot feels a portion of the cylinder load in the ratio of the cylinder arm to the cable arm on the mast (3). The valve (7) in the equilibrium condition is displaced just enough to maintain proper cylinder pressure.
- (3) In case of hydraulic system failure the pilot operates the elevator directly through the follow up rod (5). The stops on the mast (3) permit only enough relative motion between it and the walking beam (4) to operate the boost valve (7).

3. Discussion.

- a. The fixed ratio boost system seems to be quite satisfactory for airplanes operating at comparatively low mach numbers. Under certain maximum speeds the hinge moment build-up is quite gradual as the airplane increases speed; consequently a system designed with a boost ratio which will give the pilot sufficient assistance at maximum hinge moment will also give him good feel characteristics with lower hinge moments. The surface loads on high speed airplanes very often build up gradually to a certain speed and then increase extremely fast to very high values. A fixed ratio boost system designed to take care of the maximum hinge moments would in this case result in extremely high boost ratios and poor feel characteristics with lower surface loads.
- b. The first installation of fixed ratio boost was made on the XPB2M-1, "Mars" flying boat. It consisted of a closed center type boost system, the mechanics of which are shown in Figure 1 and are explained in part 2-a. Boost cylinders, reservoir, and pumps were conveniently housed in the tail of the airplane. Two electric pumps were used, either one of which was capable of handling both rudder and elevator boosters. The system showed no tendency to be unstable and was in general considered a very successful installation
- c. An installation similar to that explained in part b. was designed for the JPM-1. Mock-up testing of this system showed violent chatter characteristics. Since the mock-up test stage was reached only a short time before flight test there was no time to make a detailed analysis of the vibration troubles. It was a very simple matter to convert the boost hydraulic system from a closed

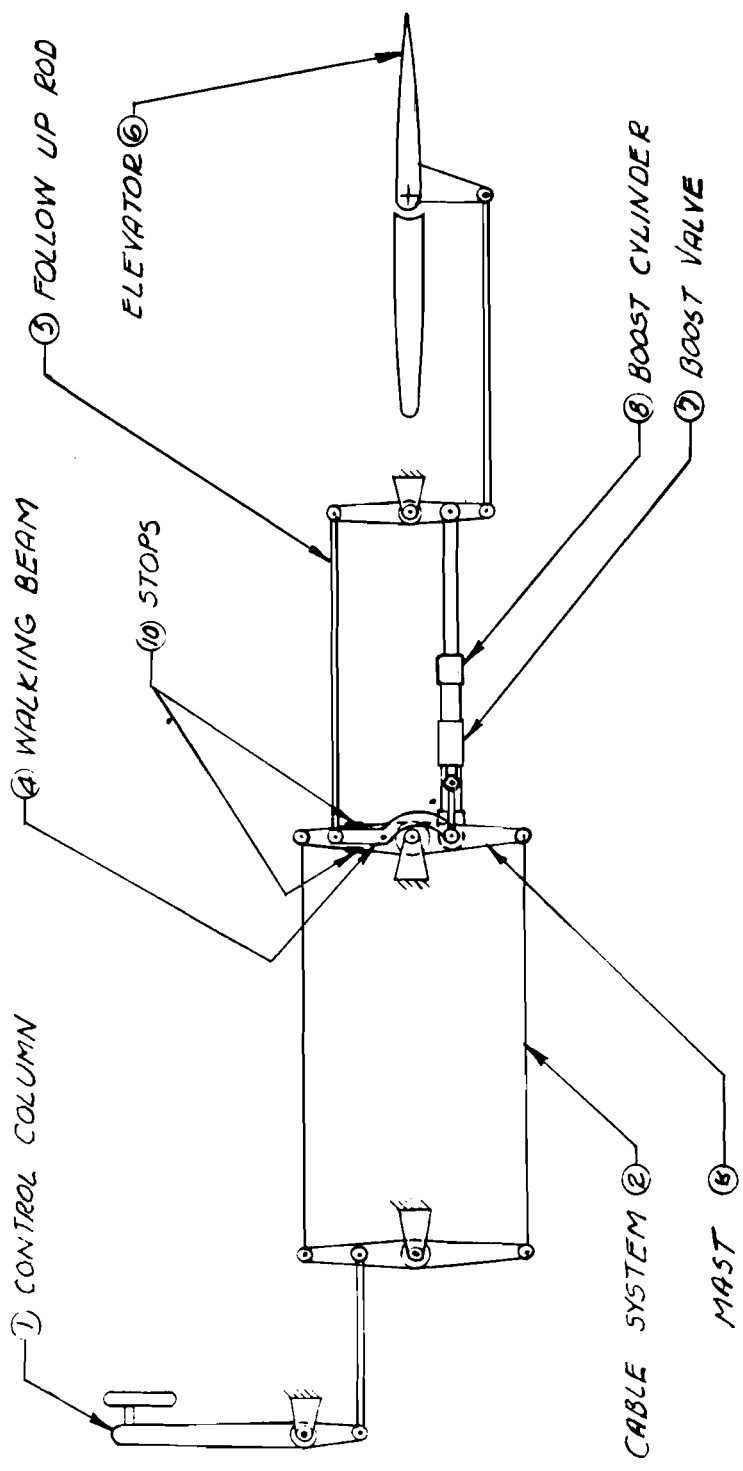


Fig. 2 - Schematic diagram - Fixed ratio boost system with mechanical feed back.

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center type to an open center type by making a minor change in the control valve spools. This change was made as an experiment and proved to be very successful. The open center boost system was stable and had the additional advantage of being self bleeding.

- d. The elevator and rudder boost systems of the XB-48 and the XP5M-1 were designed as fixed ratio boost systems with mechanical feed back and utilizing the open center hydraulic system. It was found that a certain amount of "chatter" could be induced in the control systems of both airplanes by disturbing the control while the surface was locked. Since the airplane is not flown with the control surfaces locked and the "chatter" is not apparent with the surface free it was not considered necessary to take corrective measures.
- e. It can be demonstrated that a smaller continuous power source is required for operation of a closed center system than for the operation of an open center system; however, the power requirements to date have been small enough to make this factor unimportant. The improved performance of the open center system makes it first choice for this type of control boost.
- f. The mechanical feed back system described in 2. b. is preferable to the hydraulic feed back type described in 2. a. for the following reasons:
 - (1) The boost cylinder and valve can be made up as an easily removable assembly thus making installation more simple.
 - (2) The valve friction and wear are much less since the valve spool does not carry any appreciable load.
 - (3) In trimmed level flight with the boost inoperative the pilot can automatically use a high mechanical advantage to overcome the high starting friction of the boost cylinder when he makes a small control correction. The mechanical advantage is equal to the boost ratio. It arises from the condition in which the pilot must actually move the boost cylinder (8) to displace the control valve. (See diagram, Figure 2) The high mechanical advantage occurs only within the limits of operation permitted by the stops (10).

C. Spoiler Ailerons (XB-48, AM-1, XP4M-1, P4M-1, XB-51)

- 1. Description: Spoiler ailerons are movable panels located in the top surface of the wing, usually between the rear spar and the flap in the vicinity of the conventional aileron. The spoiler panels are hinged along their forward edges and are raised hydraulically at a signal from the aileron as it moves up. Spoiler ailerons are very effective since they give the pilot powerful lateral control of the airplane with no additional wheel force.
- 2. Operation. See schematic diagram, Figure 3, and hydraulic diagrams, Figure 4.

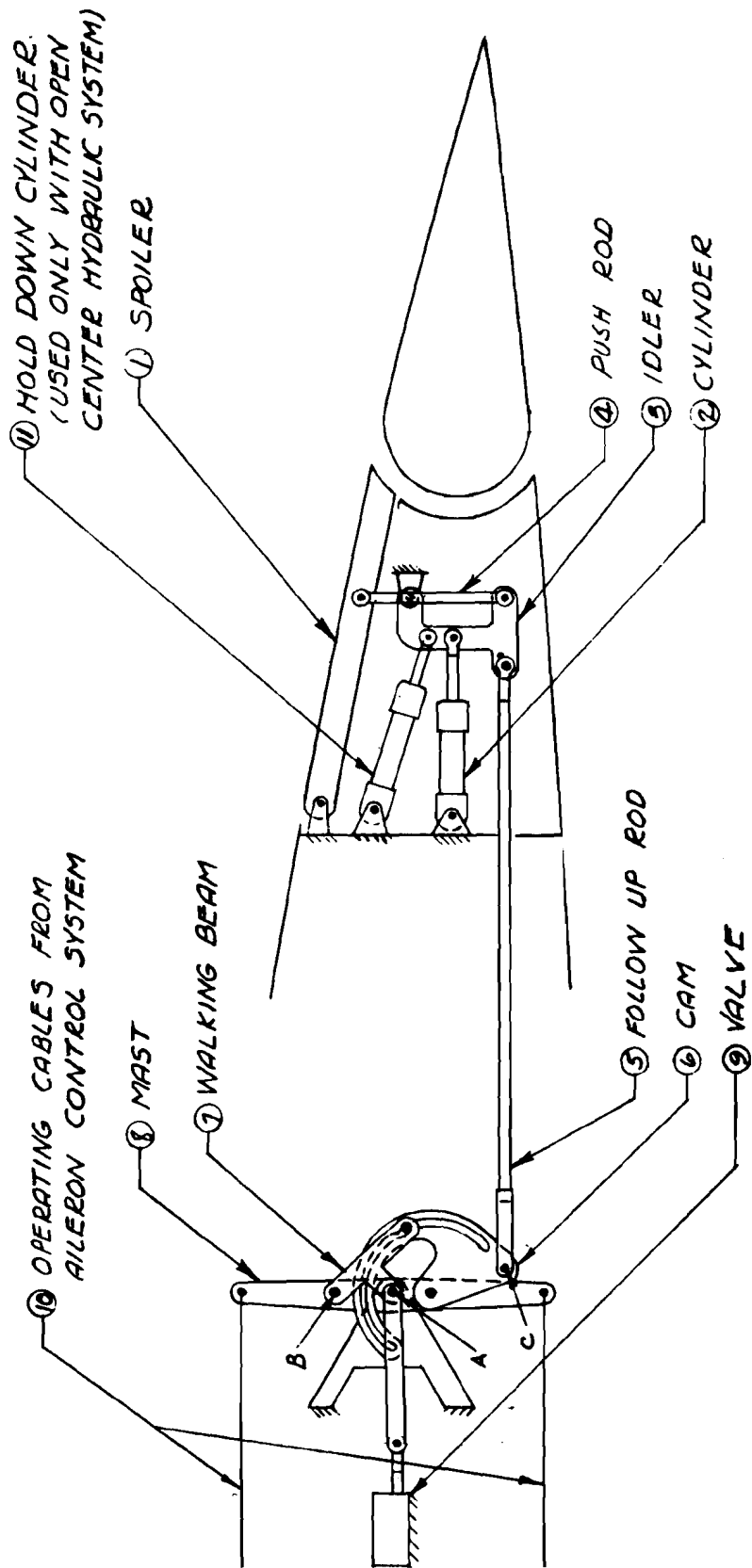
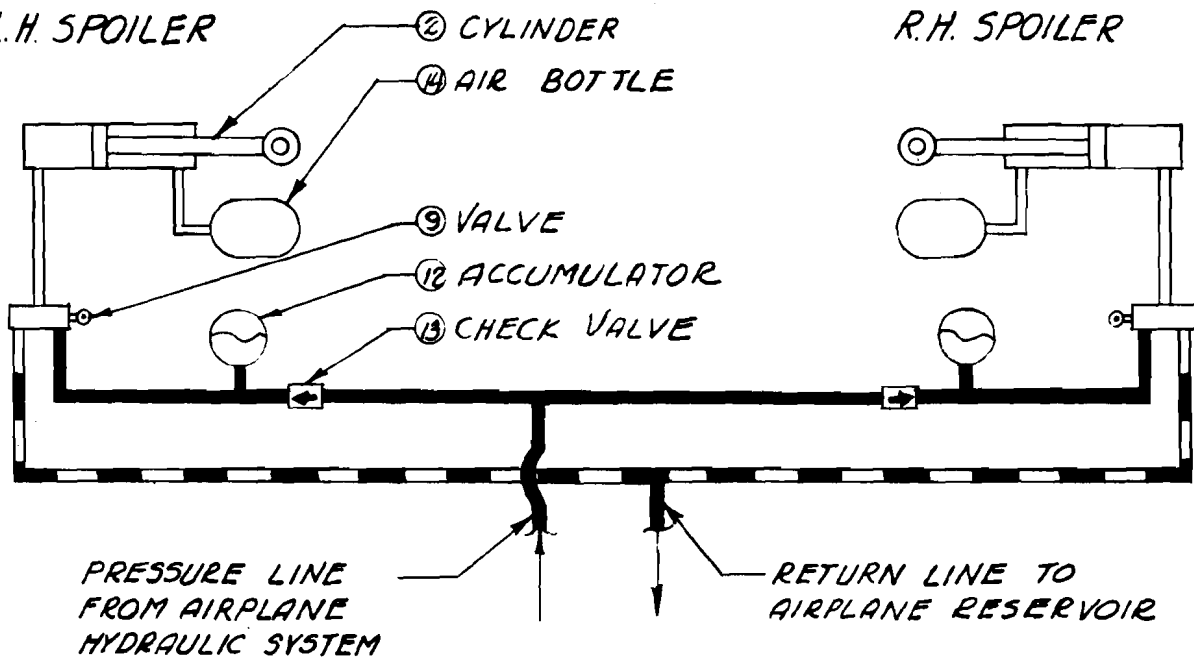


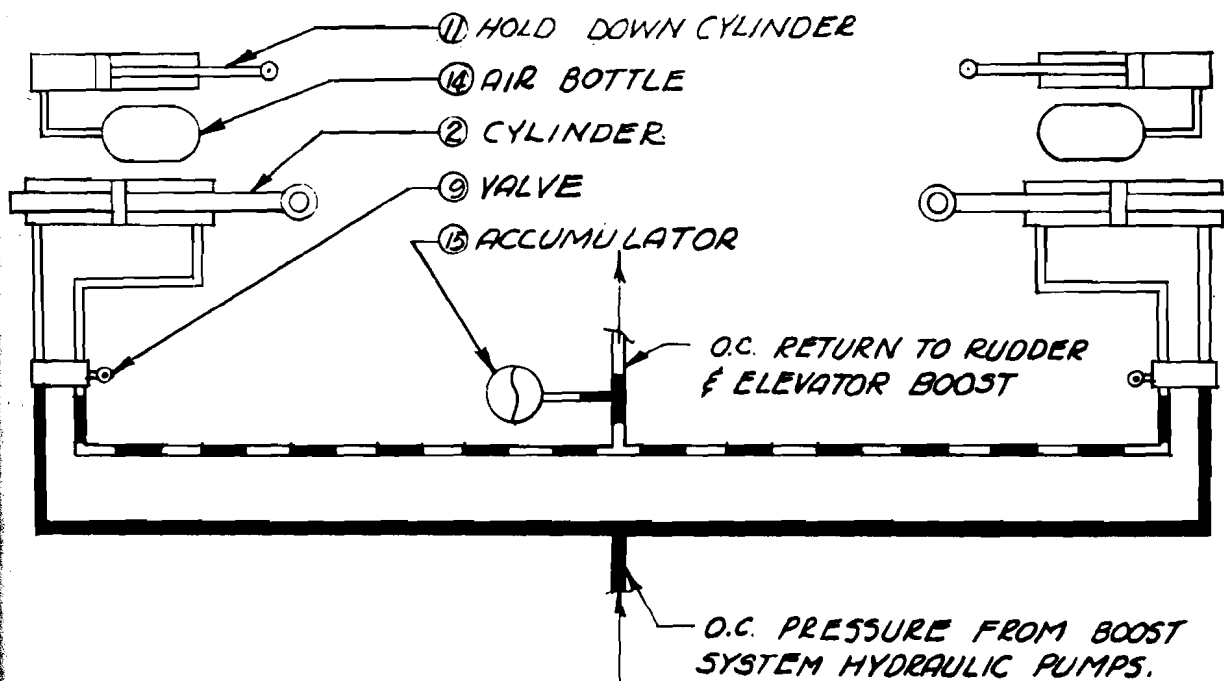
Fig. 3 - Schematic diagram - Spoiler aileron control system.

L.H. SPOILER

R.H. SPOILER




Closed center spoiler hydraulic system.



Open center spoiler hydraulic system.

Fig. 4

- 
- a. The aileron is operated in a normal manner from the conventional cockpit control. Simultaneously the mast (8) is rotated by the operating cables (10) which are connected to the aileron control. The spoiler (1) is held securely down either by air pressure in the down side of the operating cylinder (2) or by air pressure in the hold down cylinder (11).
 - b. As the mast (8) rotates about "A" it drives the cam (6) which rotates about "C" and causes the walking beam (7) to rotate about "B" thus actuating the valve (9). Hydraulic fluid then enters the cylinder (2) which raises the spoiler (1).
 - c. As the spoiler opens it rotates the cam (6) until the valve (9) returns to its neutral position and stops the spoiler.
 - d. When the control is moved in the opposite direction the valve (9) opens the cylinder (2) to the return line of the closed center system, and air pressure moves the spoiler back down. When the same operation is performed on the open center spoiler hydraulic pressure is built up on the down side of the cylinder thus helping the hold down cylinder put the spoiler down.
 - e. A negative airload is encountered with the spoiler all the way down. This is a characteristic of all spoilers. The system is so designed that the pressure from the air bottle (14) is enough to overcome the negative airload on the surface thus holding it firmly down when not in use.

3. Discussion.

- a. The spoiler aileron is a power control. It performs all of its work with no energy input from the pilot other than the very small amount of work required to overcome control system friction and operate the hydraulic valve. In all of the Martin installations control "feel" has been provided for the pilot by using either conventional ailerons (with spring tabs) or small "feel" ailerons in addition to the spoilers. In both cases the auxiliary ailerons give the pilot sufficient lateral control to land the airplane in case of a hydraulic power failure. There is no reason why a spoiler aileron in conjunction with a dual power system and an artificial "feel" source could not be used to give a pilot exclusive lateral control of an airplane.
- b. The spoiler aileron has a tendency to yaw the airplane in the direction in which it is turning, a characteristic which makes it superior to the conventional type aileron which produces yaw in the opposite direction.
- c. Spoiler ailerons were first used at the Martin Company on the XB-48 airplane. In this installation "feel" ailerons are used in addition to the spoilers. The XB-48 spoilers operate from an open center hydraulic system. Instead of running the open center flow from the open center pressure supply to one spoiler, across the airplane to the other spoiler, and then to the return, the flow is divided at the center of the airplane so that half goes to each

[REDACTED]

spoiler valve and then to the return. This arrangement shows a theoretically smaller line pressure loss, but does cause some other complications. In using the split flow type of open center system it was found that valve adjustment is very critical if smooth operation of the spoiler is to be insured.

Additional trouble existed in the form of "hammer" in the hydraulic system when the control was operated rapidly from one extreme to the other. This disturbance was attributed to inertia forces of the hydraulic fluid as the total flow of the system was shifted from one side of the airplane to the other. The trouble was cured by adding a small accumulator near the junction of the return lines from the two spoilers.

The design of the open center boost valves used on the XB-48 spoilers is such that one spoiler is held down under pressure when the other spoiler is up. In addition a separate cylinder is attached to the linkage of each spoiler. This cylinder is always open to pressure from an air bottle and acts to hold the spoiler down when the valve is in neutral.

- d. Spoiler ailerons are also used on the AM-1, the XP4M-1, the P4M-1, and the XB-51 airplanes. They are used in addition to conventional ailerons or "feel" ailerons which provide "feel" and standby control. The conventional ailerons also have spring, trim, and balance tabs. The exception to this is the XB-51 "feel" aileron which has no tabs.

In all of these applications a closed center hydraulic system is used to operate the spoilers. The use of a closed center system makes it possible to install an accumulator near each spoiler and thus have sufficient instantaneous hydraulic flow for operation with a comparatively small continuous source of supply. Hydraulic lines can be smaller without incurring large pressure losses since the high velocity flow is only through a very short length of line.

Mechanical springs are used on the AM-1 airplane to hold the spoilers down, thus eliminating the air bottle and air cylinder. On the XP4M-1, the P4M-1, and the XB-51 airplanes the air bottles are retained, but the air cylinders are eliminated by connecting the down side of the spoiler operating cylinders to the air bottles.

- e. Spoiler "chatter" occurred on both the P4M-1 and XB-51 airplanes. The "chatter" on both airplanes occurred as the spoilers were moving down from the up position. This observation seemed to indicate that the initial transient impulse of the spoiler valve as it opened to release the fluid from the cylinder was not being sufficiently damped. This can be understood since the compressed air which is on one side of the piston is compressible and would not tend to produce viscous damping. It was observed that a very light hand force on the trailing edge of the P4M-1 spoiler when it was moving down would stop the "chatter". From this evidence it was concluded that the spoiler would be satisfactory with airload on it; however, a friction type vibration damper was added to the spoiler drive linkage. The damper stopped all "chatter."

[REDACTED]

The XB-51 spoiler "chatter" was cured by tapering the spools of the spoiler valves. This operation made the valves start to meter the hydraulic fluid from the cylinder more gradually thus making the opening impulse smaller and the inherent damping of the valve sufficient.

D. Demand Assist Bungee. (AM-1, PEM-5A)

1. Description: The demand assist bungee is a device which uses hydraulic system pressure to assist a pilot in overcoming high stick forces, especially those encountered in take off and landing. It is an accessory to the standard spring tab system, and uses degree of spring tab deflection as a measure of the amount of assistance to be given the pilot.
2. Operation. (See schematic diagram, Figure 5)
 - a. The pilot moves stick (1). Stick motion is transmitted through rod (2), mast (10), cable system (29), mast (11), rod (4), arm (13), spring cartridge (21), elevator horn (20), to the elevator (19).
 - b. If the air load is sufficiently high the spring cartridge (21) deflects and permits relative motion between arm (13) and elevator horn (20). Motion between these two parts operates rod (3) which in turn moves the tab (28).
 - c. Relative motion between arm (13) and elevator horn (20) also causes relative motion between arm (14) and walking beam (16). This motion moves rod (8), rotates walking beam (17) about the end of rod (9), and operates valve (18) which pressurizes cylinder (22).
 - d. Cylinder (22) extends and stretches spring (23). The load in the spring is transmitted through the cable (27) which tends to rotate arm (15). The cable (27) is dead centered with the arm (15) only when the elevator (19) is in neutral or any down position. As the elevator (19) moves up, the cable (27) moves away from pulley (25) and thus establishes a moment arm for the cable. Rotational forces on arm (15) pass through rods (5 & 7) into elevator horn (20) thus helping the pilot and spring tab to move the elevator.
 - e. Rotation of mast (12) by the hydraulic cylinder (22) is transmitted to walking beam (17) by rod (9) and shuts off valve (18) when a bungee spring deflection has been reached which is proportioned to the existing amount of spring tab deflection.
 - f. The cable (27) is just long enough to wrap around pulley (25) and permit the system to go to full down elevator without the cable becoming taut. Cable spring (26) has a low preload and spring rate. It keeps the slack out of cable (27) when it is in the neutral position and there is no bungee spring deflection.

3. Discussion.

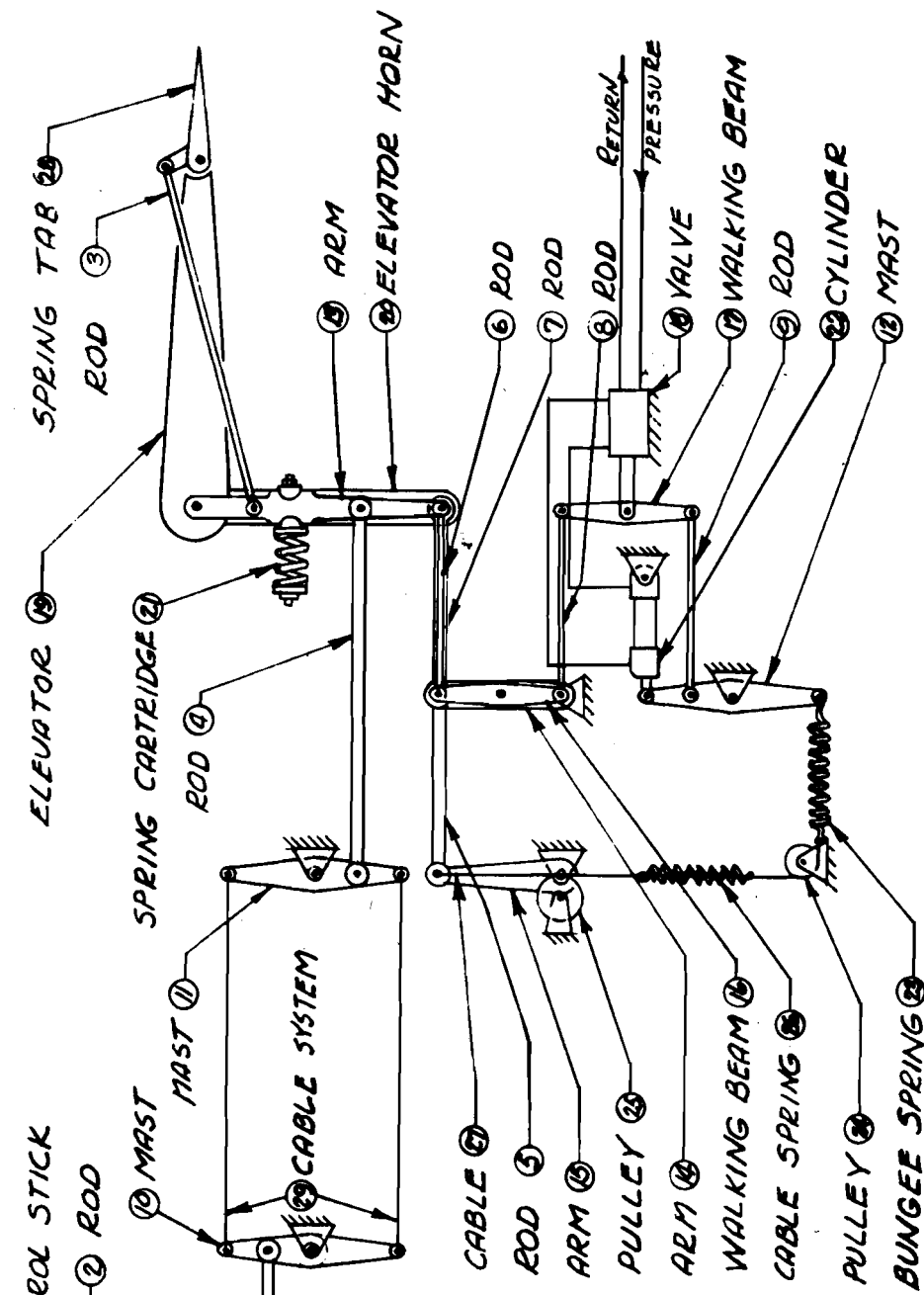


Fig. 5 - Schematic diagram - Elevator demand assist bungee control system AM-1.

- a. The demand assist bungee is a very good device for overcoming high take off and landing loads since its maximum output is obtained at high surface deflections.
- b. The demand assist bungee has been used quite successfully on both the AM-1 with the system fluttering on ground run up. This difficulty was overcome by restricting the speed at which the device could operate. Flight test has shown that the bungee can come in at very slow rates and still be entirely satisfactory.
- c. Some of the advantages of the bungee are small power consumption, easy variation of boost characteristics, low control system friction, and no interference with the normal control system when the bungee is inoperative. It supplies boost only when the air loads on the control surface are high enough to require boost.
- d. Some of the bungee limitations are its complexity, weight, and limited output due to the limiting size of the mechanical springs.

E. Variable Ratio Boost (XB-51)

1. Description: The elevator control system of the XB-51 airplane is a combination mechanical and hydraulic mechanism which gives the pilot a constant boost ratio of 1.5 with hinge moments up to 15% maximum and then increases gradually to 4 at maximum hinge moment. (See curve, Figure 6)
2. Operation. (See mechanical schematic, Figure 7, and hydraulic diagram, Figure 8)
 - a. The control column (1) is displaced by the pilot.
 - b. The column motion is transmitted to the mast (3) by the cable system (2).
 - c. Rotation of the mast (3) causes walking beam (4) to rotate about the end of the follow up rod (5) and displace the spool of the valve (15).
 - d. Displacement of the valve spool builds up pressure in the boost cylinder and causes the elevator (9) to move. In the equilibrium condition the boost valve spool is displaced just enough to maintain a pressure sufficient to balance the surface air load.
 - e. The variable ratio feature is accomplished within the boost valve (15). As the boost pressure increases the hydraulic feed back through the valve spool to the pilot is decreased at a variable increasing rate. The boost characteristics are shown in the curves, Figure 6.
 - f. In case of boost failure the by-pass valve (14) permits flow from one side of the boost cylinder to the other, and the pilot controls the elevator directly through the follow up rod (5).

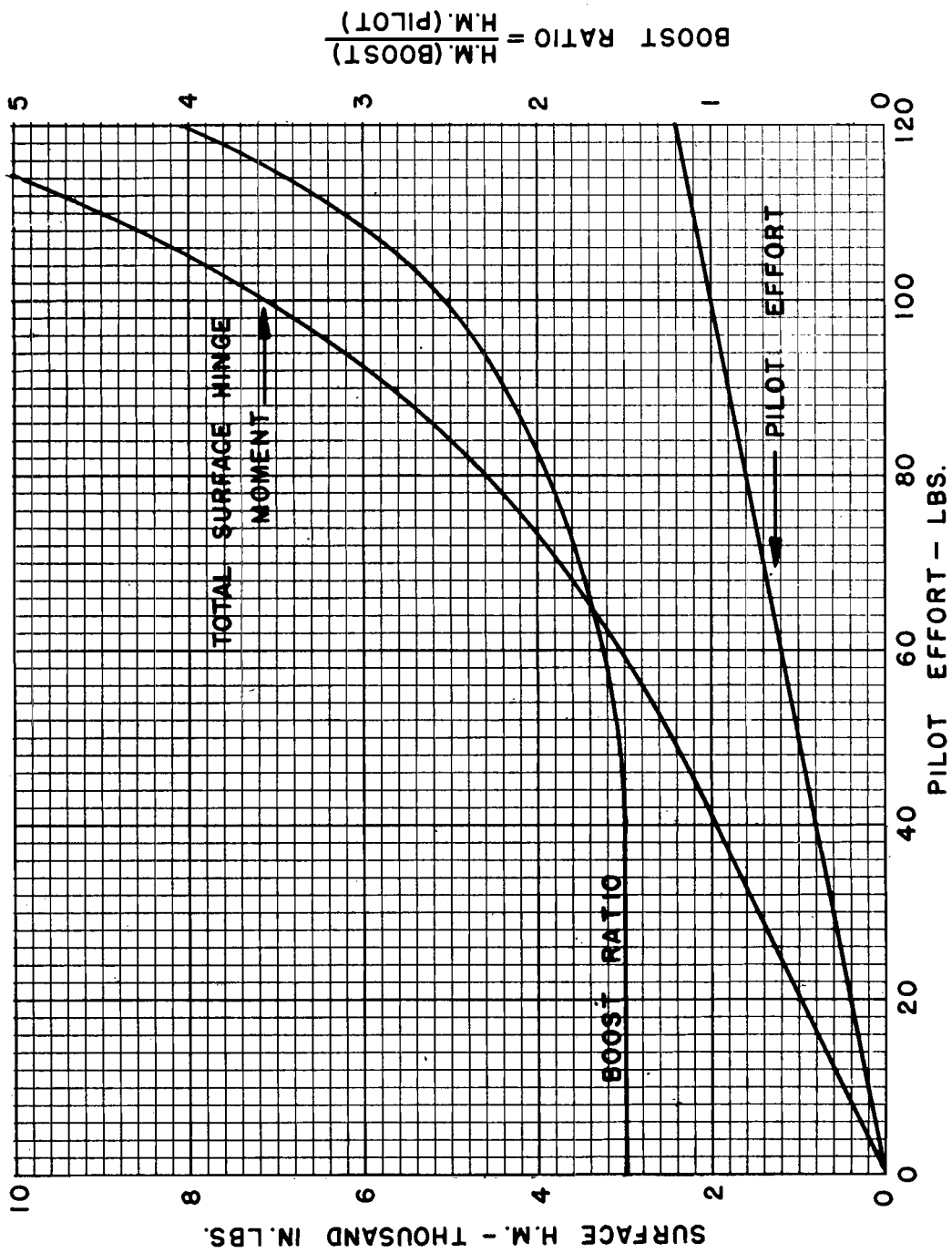


Fig. 6 - Model XB-51 Variable ratio elevator power boost typical performance.

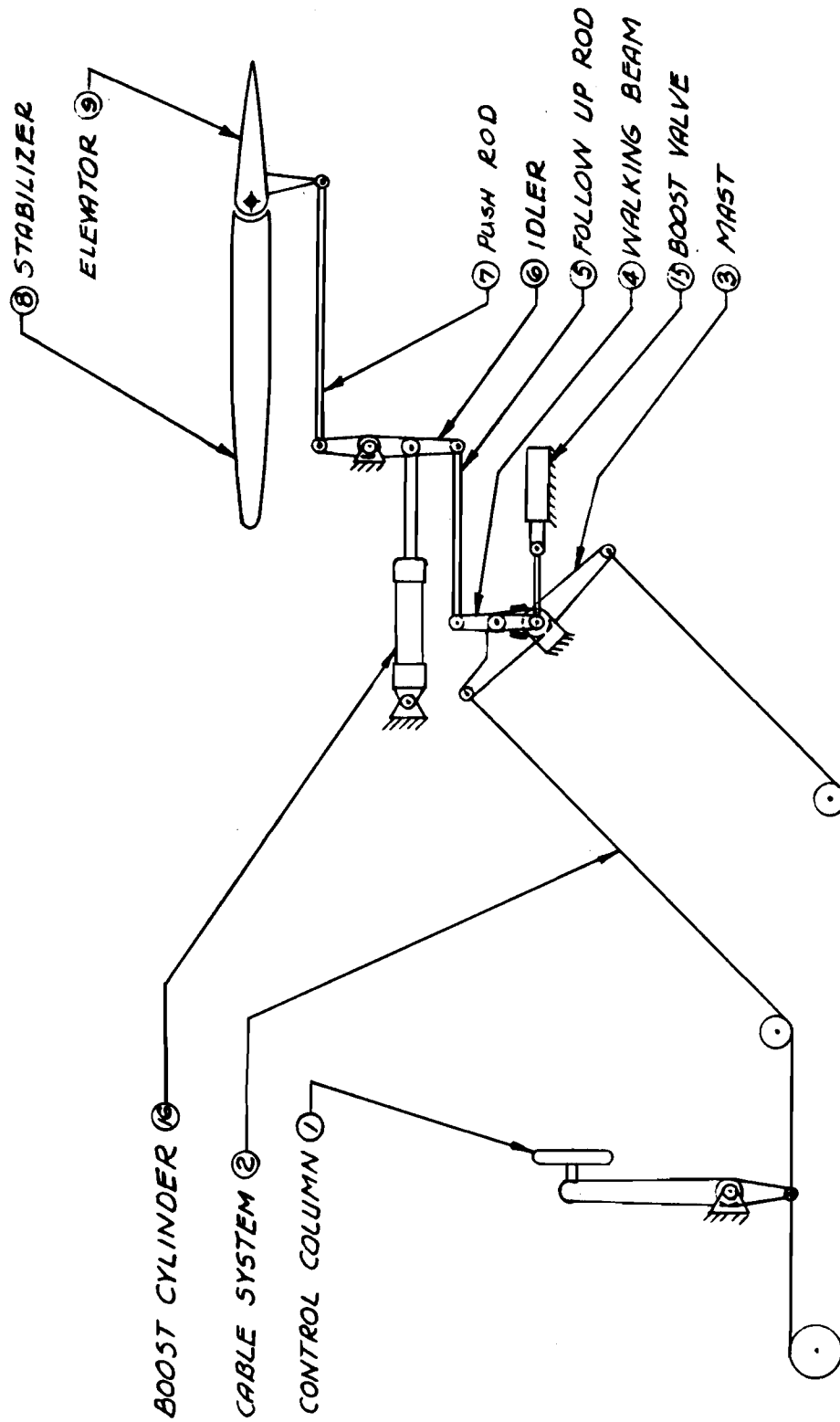


Fig. 7 - Schematic diagram - XB-51 Variable boost elevator control system.

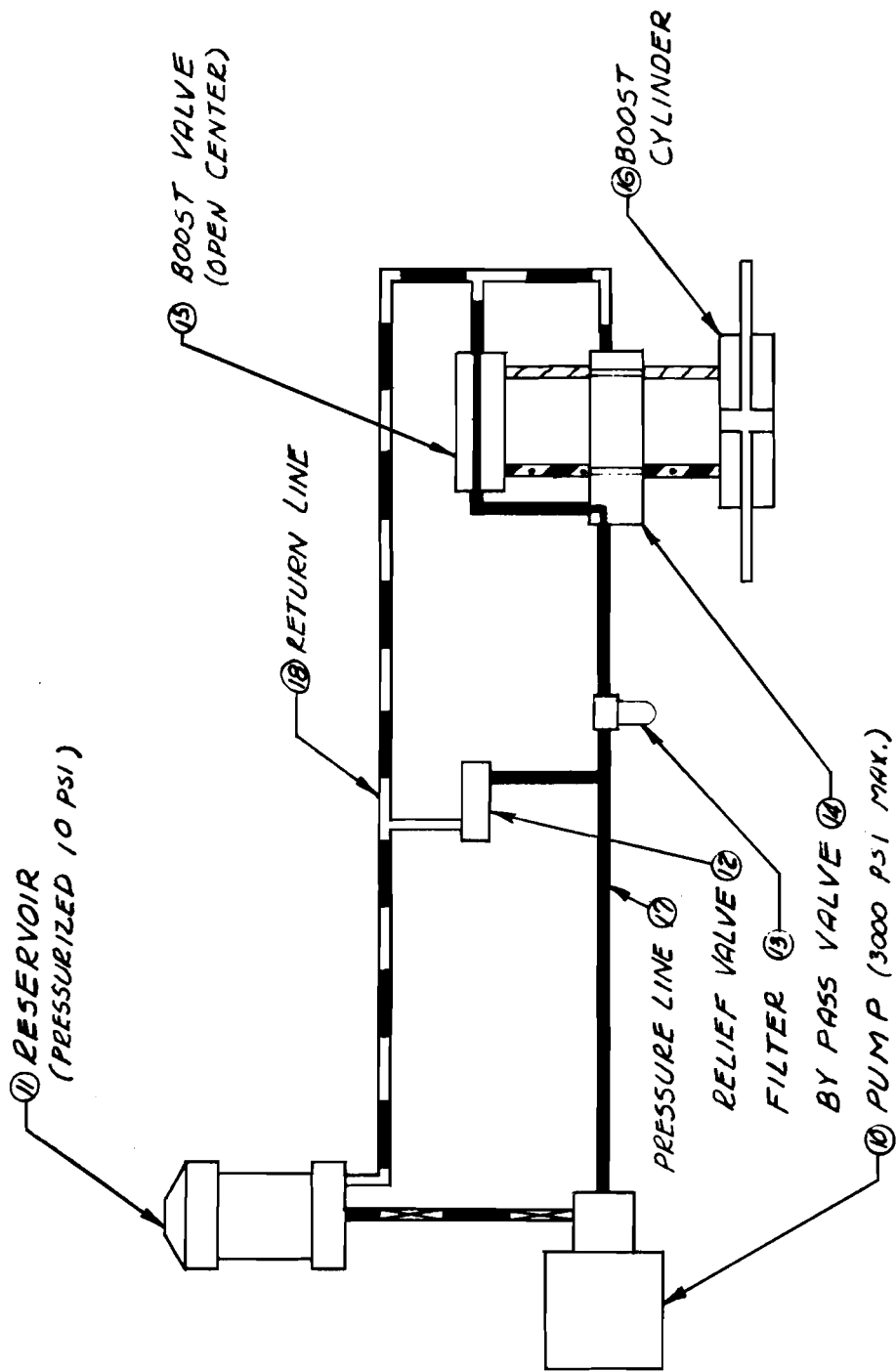


Fig. 8 - Hydraulic system - XB-51 Elevator boost.

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3. Discussion.

- a. The variable ratio boost system was developed to take care of the low gradient, high peak hinge moment curve of the XB-51 elevator. With low boost ratios at low speed the pilot has good control "feel". At high speeds the boost ratio changes to permit the pilot to handle the high hinge moments without undue application of load to the control column.
- b. At the date of this writing the system described has not flown. It has, however, been thoroughly tested in a full size operational mockup, and has promise of functioning in a very satisfactory manner.
- c. The system is very simple for a variable ratio booster. It has no more components than a fixed ratio boost system and has most of the performance of the complicated demand assist bungee.
- d. The chief deficiency of the system as used on the XB-51 airplane is the small force differential on the control column between the lg flight condition and the maximum load factor pull out at dive speed. Another objectionable feature is the valve friction induced by making the valve spool a high load carrying member as in the fixed ratio boost system with hydraulic feed back.

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POWER BOOST EXPERIENCE AT FAIRCHILD

By

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1. Summary

A control boost was installed on the C-119-A Airplane to assist in aileron control. A description of the boost used and its operation is shown in this report.

The aileron boost was tested, resulting in a considerable reduction in the pilot force required for aileron deflection in flight. (See Figure 5).

Lateral stability of the airplane was improved to comply with Specification 1815A by the reduction in control system friction between the control wheel and the boost unit. This was accomplished by decreasing the rigging tension in the cables in this region. (See Table 1).

The tests show that the aileron boost installation is satisfactory.

2. Description and Characteristics of the Boost

The boost is a double acting hydraulic cylinder, having a self-contained valve system, mechanical actuation of which controls fluid under pressure so as to assist in movement in either direction of a load coupled to the output shaft. The cylinder provides output force reaction (load feel), and is designed for use in a 1500 p.s.i. hydraulic system.

Shut-off valve is closed by pressure and spring loaded to open so that when pressure is not supplied to the unit, fluid may move freely through the valve from one side of the piston to the other, minimizing the power-off hydraulic drag of the installation. The valve arrangement of the cylinder itself provides for power-off transfer of fluid through the piston with some back pressure due to spring loading of the exhaust valves.

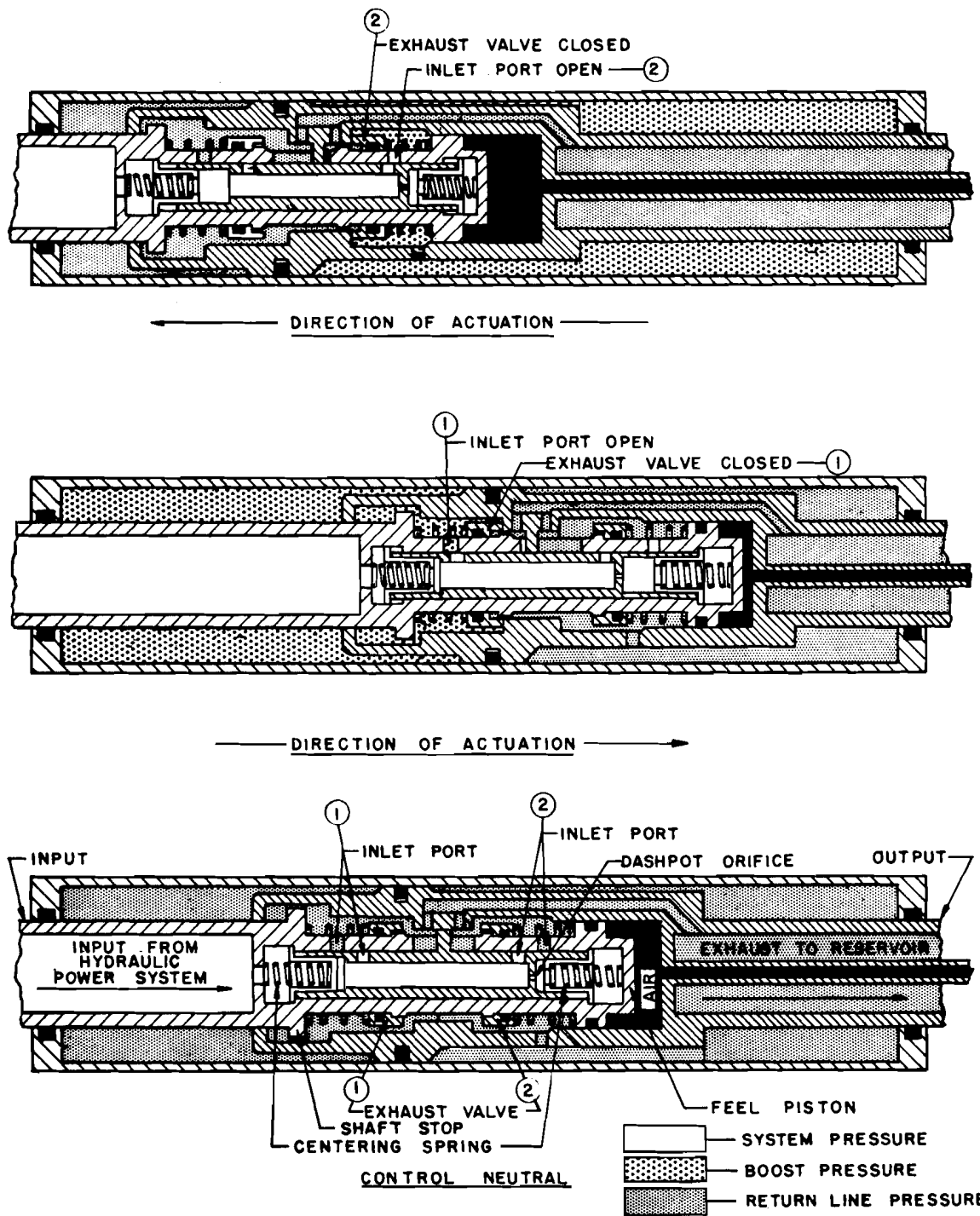
Both exhaust and inlet valves are controlled by the input shaft. Inherent backlash in the unit (relative movability of input end to output end) makes possible this valve operation. This relative movement is limited in the power-off condition by the space afforded between stops for movement of the shoulder on the actuated shaft. This power-off movement is a total maximum of .08". Power-on, a movement of .015" engages the power system so that the total maximum power-on backlash is .03".

Boost ratio is:

$$\frac{(\text{Area Boost Piston}) - (\text{Area Inside Diameter Exhaust Valve Gland})}{(\text{Area Input Shaft}) - (\text{Area Inside Diameter Exhaust Valve Gland})}$$

The operation of the boost can be seen on examination of the schematic drawing in Fig. 1.

The boost ratio for the boost on the C-119 Airplane is 4:1. The mechanical advantage between the rim of the pilots wheel and the boost installation is 1:6.7.



SCHMATIC DIAGRAMS SHOWING ESSENTIALS OF OPERATION

Fig. 1

3. Aileron Control System

The aileron control system prior to the installation of the boost unit is shown in Figure 2. The changes necessary to accommodate the boost unit is shown in Figure 3, where the sector wheel set up prior to the boost installation is compared to the arrangement with the boost.

The boost is located 8.9" forward of the rear spar at the airplane centerline, and the sector wheel centers are 38" to each side of the airplane centerline. A planform of the outer wing panel showing the aileron and spar locations is shown in Figure 4.

4. Test Results

As shown in Figure 5, the presence of the boost decreases the pilot force appreciably. From this consideration the installation in the C-119-A Airplane is satisfactory. However, on preliminary tests, lateral instability has been reported on some of the tests with the boost installed. This instability was attributed to the friction present in the cable system between the pilot's wheel and the boost. Preliminary test results showed a reduction in friction from 9 lbs. to 4 lbs. at the pilot's wheel when rigging tension is reduced from 165 lbs. to 75 lbs. Design changes were made to reduce this friction to eliminate the lateral instability, followed by additional flight tests.

The accompanying load-deflection diagrams are for various type of aileron installation, both with and without the boost unit. The installation type is indicated on the graph.

In further tests the control forces have been reduced to within the limits of specification 1815A. Acceptable static lateral stability and rates of roll have been achieved, thereby demonstrating the satisfactory nature of this aileron boost installation.

These tests showed major friction reductions due to reducing tension in the cables forward of the boost cylinder as follows:

Table 1

Main Cable Tension (Lbs.)	Friction	
	Pilot Wheel (Lbs.)	Co-pilot Wheel (Lbs.)
135	6.2	6.3
105	5.1	5.5
75	3.9	3.9

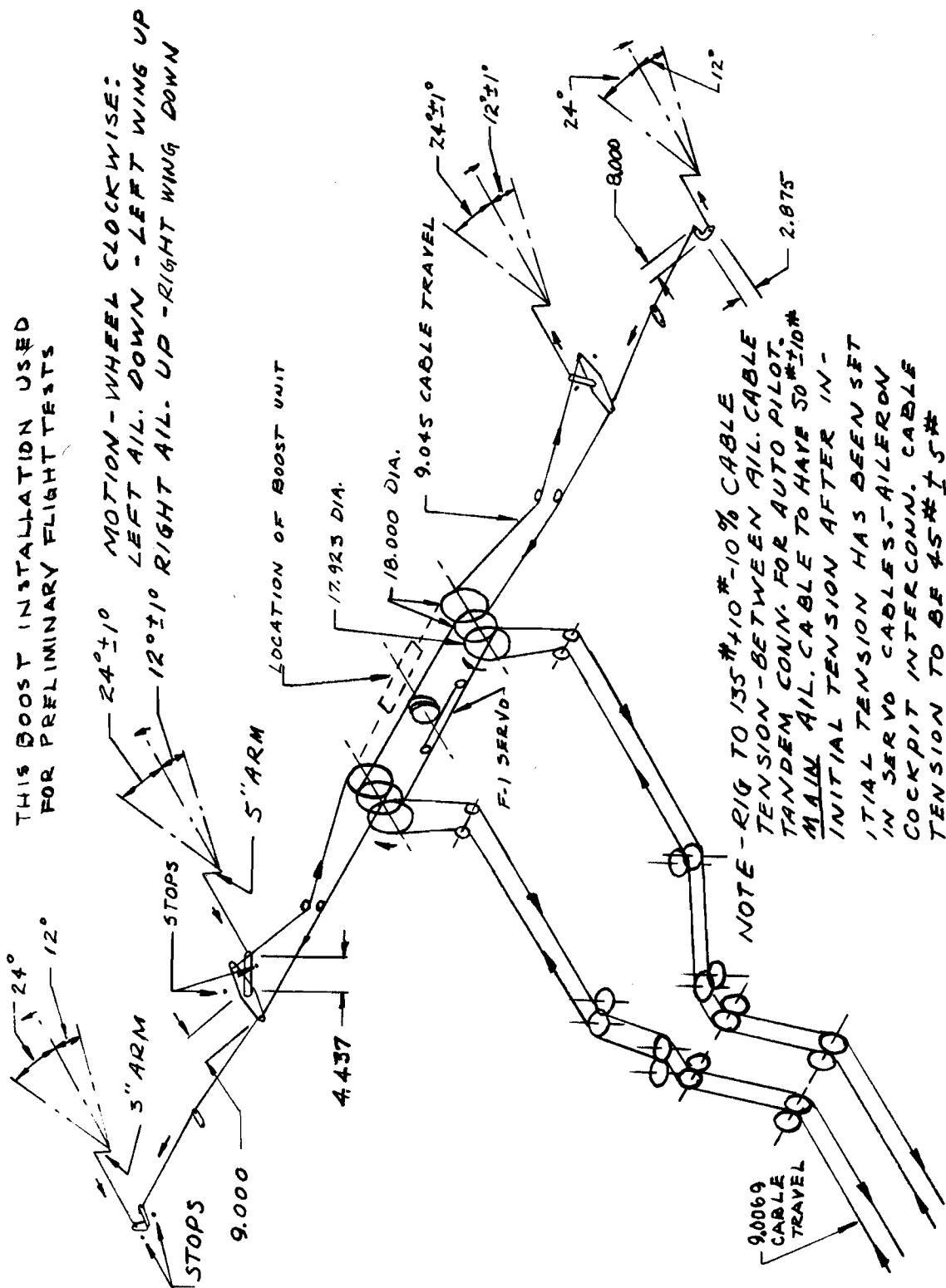
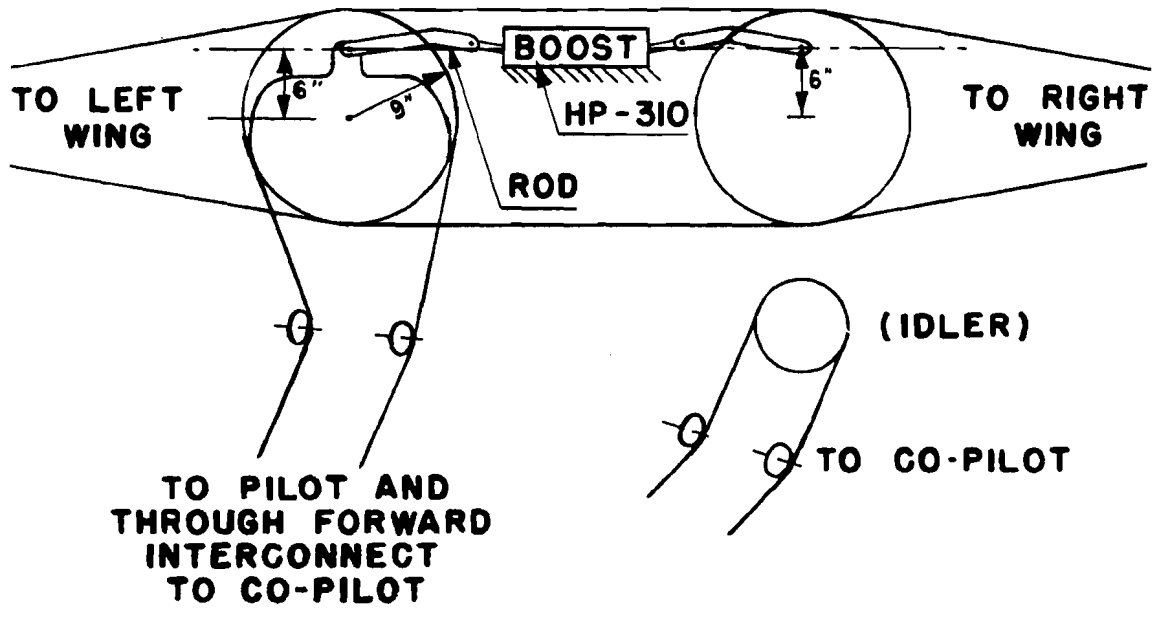


Fig. 2

SCHEMATIC DRAWING WITH BOOST-LOOKING FWD.



WITHOUT BOOST

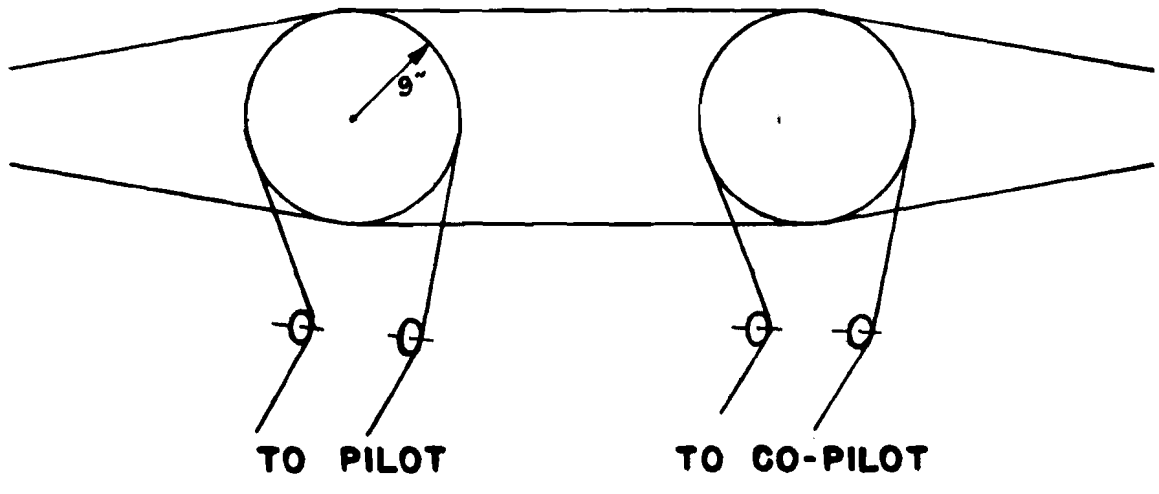


Fig. 3

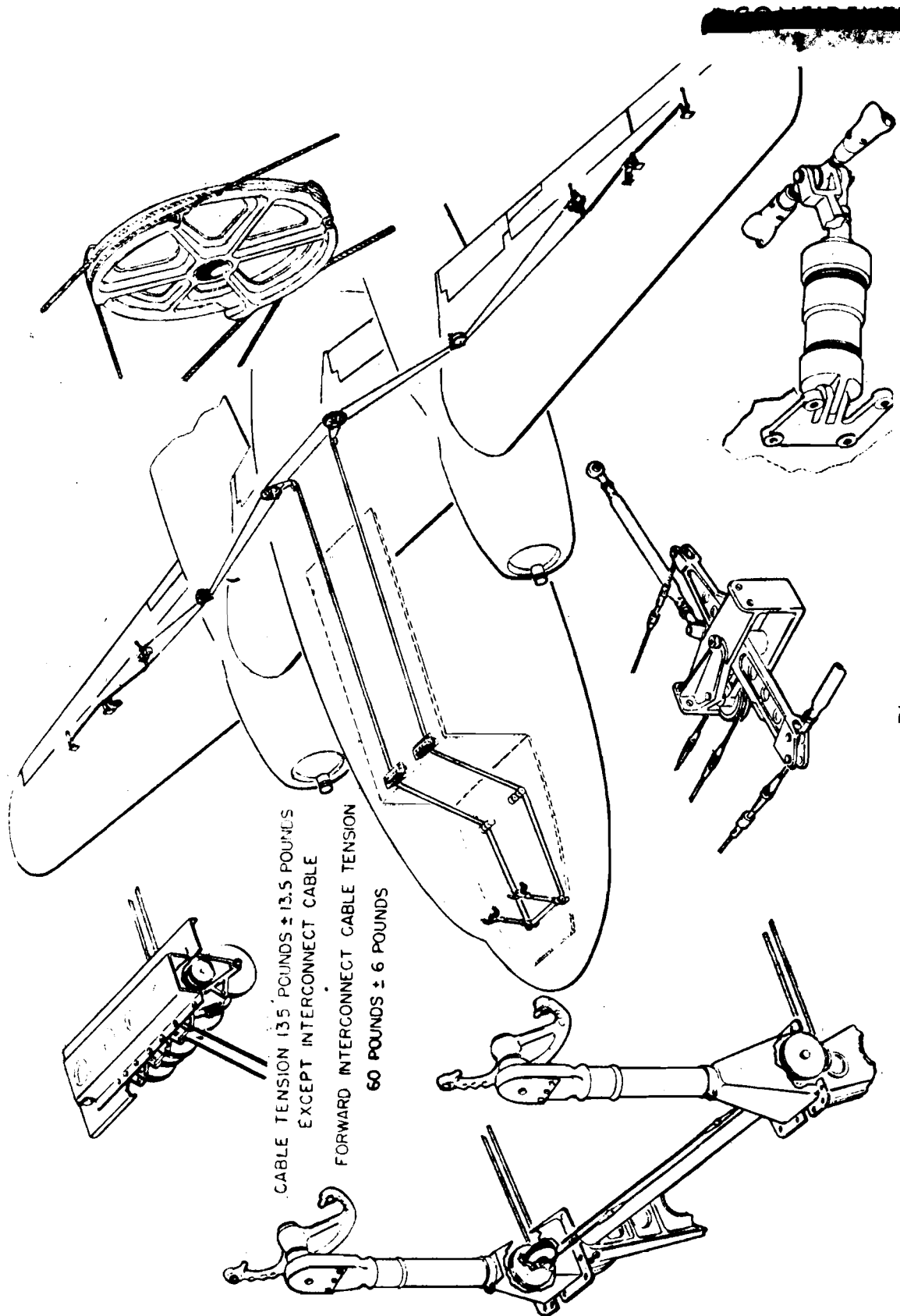


Fig. 4

Pilot force vs. percentage aileron deflection.
 C-119A Airplane - abrupt rudder - locked rolls
 Clean configuration - right rolls
 50,200 lbs. G.W. - 22% M.A.C.
 173 M.P.H. V_c - 58% N.R.P. - Outer wing panel dihedral 0°
 130 psi, 2,250 R.P.M.
 10 lb. Boost centering spring in.

Installation #1

Aileron boost cylinder replaced by beam, balance tabs operative.

Installation #2

Aileron boost system in, balance tabs operative.

Installation #3

Aileron boost system in, balance tabs blocked.

(See Ref. 3)

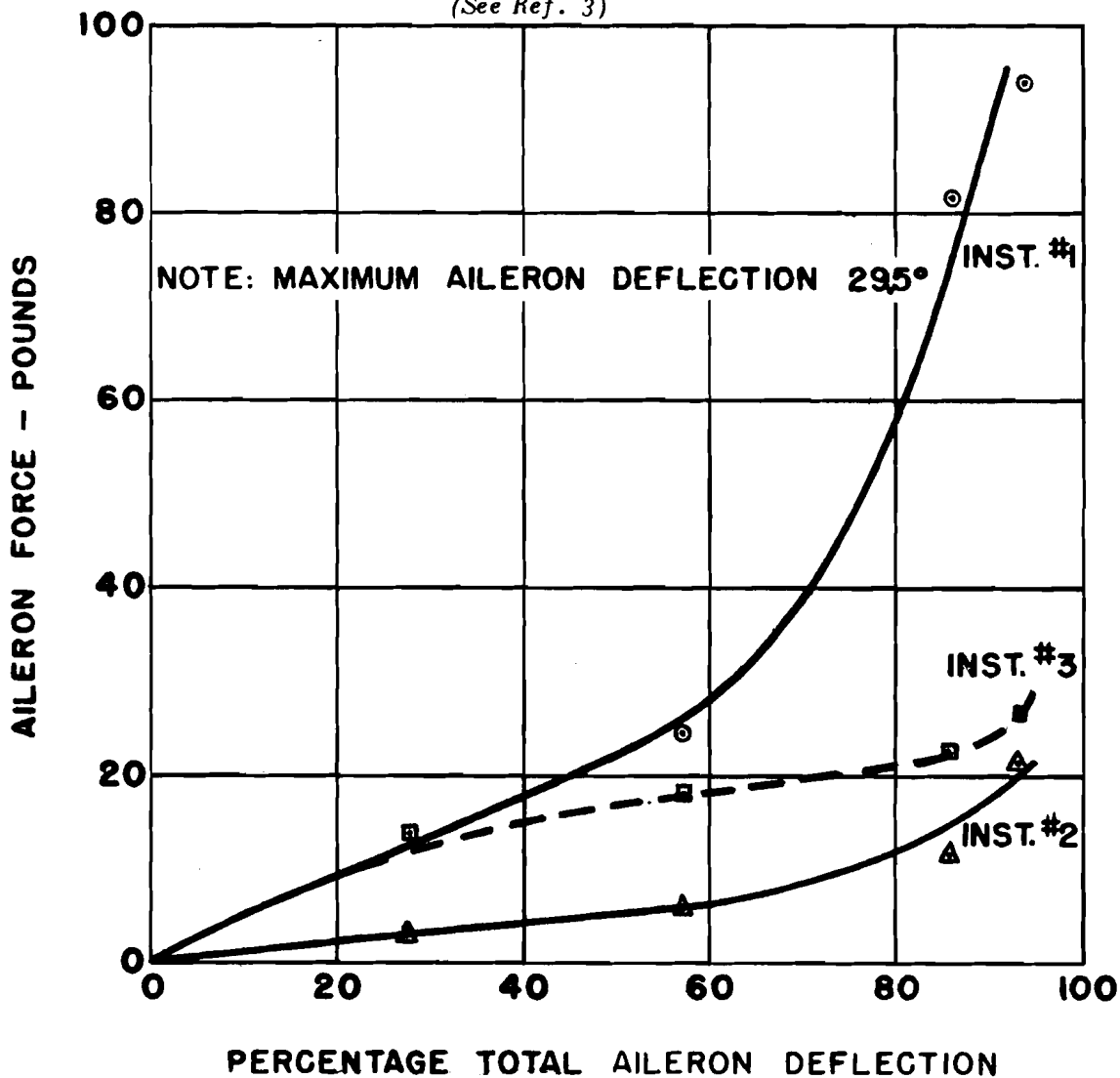


Fig. 5

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References

1. "Operation of Surface Control Boost Model 310" Hydra-Power Corp., New Rochelle, New York.
2. Fairchild Aircraft Engineering Report R110-720 "Control System Analysis".
3. Fairchild Flight Test Report FT105-75.
4. Fairchild Aircraft Engineering Report R110-002 "Mass Moments of Inertia Calculations".