AIRPLANE WING LEADING EDGE VARIABLE CAMBER FLAP

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SUMMARY

A design solution to an aerodynamic high lift problem was effected by the application of "flexible skin" and "dynamic structure" concepts. Mechanisms and structures were invented to implement these concepts and provide the desired solution.

The paper covers the following subject matter: (1) Problem Solved (2) Scope (3) Definition (4) Invention and Design Evolution (5) Flexible Skin Technology (6) Actuation Scheme (7) Vibration and Flutter Considerations (8) Operating Experience (9) Applications and Usage (10) Concluding Remarks.

PROBLEM SOLVED

This paper deals with the invention and design of an aerodynamic high lift device which provided a solution to an aircraft performance problem. The performance problem in general was that of converting a high speed cruise airfoil into a low speed aerodynamic shape that would provide landing and take-off characteristics superior to those available with contemporary high lift devices. More specifically, the need was for an improved wing leading edge device that would complement the high lift performance of a triple slotted trailing edge flap. The solution provided was the invention of the wing leading edge variable camber flap.

SCOPE

This paper will deal primarily with the mechanical and structural aspects of the variable camber flap and will present the aerodynamic performance aspects only as they relate to the invention and design of the device.

DEFINITION

What is a variable camber flap? For the purposes of this paper, a variable camber flap is the patented device which was invented and designed for use on the Boeing 747 airplane.

In order to eliminate any misunderstanding regarding the term "variable camber" as applied to this device, the term is used to describe the camber change that occurs to the flap panel as it is extended from its relatively flat shape, when stowed as part of the wing lower surface to its fully cambered shape in the extended high lift position, and not to describe a change in camber after it is extended to its operating position. In other words this device is a two position device that does not have the ability to vary its camber once it is extended. This latter feature, however, is very attractive from an aerodynamic standpoint, and an invention which provides such a feature is described in Patent No. 4,159,089 Three Position Variable Camber Flap. This paper, however, will be restricted to the two position concept.

INVENTION AND DESIGN EVOLUTION

The quotation from Plato, "Necessity is the mother of invention," certainly applies to this invention. It was invented to satisfy an aerodynamic need. The need was for a leading edge device that was more powerful than the familiar leading edge slat and Krueger flap. (See Figures 1 and 2.) Such a device was needed to complement the powerful 747 triple slotted trailing edge flaps in order to provide an airfoil configuration that would have a sufficiently high coefficient of lift to meet landing and take-off requirements. Exactly what was required to accomplish this was not initially clear. However, the shortcomings of the slat and Krueger flap were pretty well known, and it was felt that the correction of these should result in a configuration that would improve the wing stall characteristics at high angles of attack. The needed improvements were as follows: (See Figure 3.)

1. A contour with a larger leading edge nose radius whose shape is similar to a logarithmic spiral.
2. Good extension to provide an increase in wing area.
3. Elimination of any breaks or cut-outs on the wing leading edge upper surface.

In evaluating these improvements and experimenting with various mechanical concepts it became evident that a new approach would be required in order to provide an increase in the upper surface camber. The slat and the Krueger flap are essentially devices that deploy rigid sections of the wing leading edge structure which do not have adequate camber or the right camber when they are deployed as high lift devices. Some means of tailoring the camber of these surfaces was needed. If the shape of the surface was to be changed, it followed that the surface skin would have to be flexible. If the skin was flexible, a means of shaping and supporting it would be required. Some sort of dynamic structure that would simultaneously support the skin and control its camber was required. These "flexible skin" and "dynamic structure" concepts could be applied to either a slat or Krueger flap; however, the flap seemed to be a more promising candidate for the following reasons: 1) It doesn't produce a break in the upper wing surface. 2) There is no loss in the overall chord of the fixed wing structure as with a slat. 3) The cambering and support mechanisms for a flap would penetrate the lower surface of an airfoil, while the mechanism for a slat would penetrate the critical upper surface, creating potential air flow separation problems. 4) A flap is rotated into position providing good relative motion for mechanism slaving purposes. A slat is essentially translated into position providing little slaving motion potential.

A process of design, test and evaluate was initiated in an effort to turn the "flexible skin" and "dynamic structure" concepts into a hardware design that would not only solve the aerodynamic problem, but also would be structurally sound, safe and reliable. Figures 4 through 7 show some of these designs. They are only a portion of the designs involved in this effort, but they are representative of the design evolution. Out of this effort certain requirements and criteria were established. (See Figure 8.) The following is a list of these:

1. The flexible skin panel camber must not exceed the limits imposed by the combination of bending strength, fatigue strength and stiffness requirements.
2. Good extension and nose radius requirements are best met by combining a flexible skin panel with a separate folding nose structure.

3. In order to produce and maintain a given aerodynamic shape the flexible panel thickness must be tailored and the panel curvature must be controlled by at least 3 spanwise supports.
4. The panel must be positively supported throughout its extension and retraction cycles.
5. The panel should not be part of the support load path.
6. The support mechanism should not flex the skin panel to a tighter bend radius during extension than the bend radius at full extension in order to prevent reduction of its fatigue life.
7. The kinematics of the "dynamic structure" mechanism must simultaneously position and camber the flap panel while rotating the folding nose into its extended position to satisfy the aerodynamic angle, gap and shape requirements.
8. The kinematics must move the flap panel parallel to the undersurface of the wing during initial extension to ensure a good panel fair and prevent seal damage.
9. The actuator must be capable of rotating the flap approximately 135^{o}.
10. The flap mechanism must provide maximum flap extension without penetrating the wing nose structure which contains a thermal anti-icing duct.
11. The kinematic solution and flap geometry should be developed so that the same flap hardware can be used on as much of the wing span as possible in order to reduce fabricating and maintenance costs.
12. The retracted flap mechanism must fit into and be compatible with the fixed leading edge structure and must accommodate the systems passing through this area (electrical, flap drive, controls, anti-icing, etc).

Figure 9 shows the mechanism that evolved to fulfill the "dynamic structure" concept. This mechanism, in conjunction with a flexible skin panel and folding nose, was able to meet all of the foregoing requirements and criteria. This mechanism consists essentially of three four-bar mechanisms in a series arrangement. In addition, there is a crank arm and link which program the motion of the center flap panel support. The first four-bar mechanism consists of those members connected at points A, B, C and D, the second at points B, E, H and G, and the third at H, K, M and N. The crank arm is part of the member GHJK which is one solid part, and the center link is JL.

The kinematic solution for this mechanism was obtained primarily by using graphical techniques in conjunction with a computer program. The computer program is essential for a precise solution and for the contour matching process that is required to adapt one common mechanism to an ever-changing wing surface. This process consists of solving for the coordinates of points A, D and C so that the panel attachment points F, L and N will cause the flap panel to fair with the lower wing surface. This obviously is a very important economic feature since it allows one common mechanism to be used in a number of places along the wing span. On the 747 the same mechanism is used in 20 different locations. This would increase to 40 if the same flap chord length was used for all 20 variable camber flaps. Such economies are not possible with a slat or Krueger flap because, as previously stated, they are devices that deploy rigid structural sections of the wing whose cross sections constantly vary.

A kinematic solution by computer alone is certainly possible, but the constraints imposed by the structural envelope are not exact and, therefore, the number of solutions is almost limitless. The problem of defining constraints for a computer program is the most difficult for linkage points in the retracted position. As can be seen in Figure 9 the mechanism is confined in a very compact area. The only points that can be defined exactly are points F, L and N in the extended positions. All other points are free to move within the limits imposed by: 1) the structural envelope; 2) interference with other members; 3) size of the members; and 4) the limits imposed by kinematic requirements 6, 7, 8 and 9.

Needless to say, a great deal of kinematic visibility is required in order to work out a satisfactory solution. It is needed not only in the extended and retracted positions, but also throughout the cycle. A computer combined with a cathode ray tube display can provide this visibility; however, computer simulation of panel flexing is very difficult. Graphical solutions not only provide the required visibility, but with modeling techniques the simulation of skin panel flexing is easily accomplished. Graphical solutions in this application are also more economical from both a time and equipment standpoint. However, once a solution is established, its conversion into a computer program is a must for the reasons previously stated.

FLEXIBLE SKIN TECHNOLOGY

A separate paper is required to make a rigorous presentation of this subject. For this reason, only the highlights of the problem involved and its solution will be discussed.
The problem essentially consists of finding a material and its dimensional proportions that will satisfy the previously stated bending strength, fatigue strength and stiffness requirements imposed on a flexible skin panel by air loads, bending loads and aerodynamic shape.

In the retracted position the skin panel stiffness (thickness and modulus of elasticity) must be sufficiently high to prevent deflections that exceed aerodynamic smoothness requirements when the panel is exposed to cruise airloads. In the extended position the panel thickness (t) and modulus of elasticity (E) must be sufficiently low and the bend radius (R) sufficiently high so that the resulting bending stress (s) does not exceed the allowable fatigue strength of the panel material. This is reflected by the equation

$$s = Et/2R. \qquad (1)$$

At the same time this stress should be higher than the stress imposed by air loads in the extended position to prevent distortion of the aerodynamic shape. To compound the problem, the panel thickness proportions must be tailored to produce the desired aerodynamic shape. This shape is obtained by varying the thickness (t) in accordance with the equation

$$t = (12\,RFx/E)^{1/3} \qquad (2)$$

which is derived from the equation

$$R = EI/M \qquad (3)$$

where (R) is the radius of the elastic curve, the moment of inertia $I = t^3/12$ for a one unit wide strip and the bending moment $M = Fx$ where (F) is the force acting on the panel at a distance (x) from the support point. The force (F) is determined from the transposed equation (2)

$$F = Et^3/12Rx \qquad (4)$$

where the thickness (t) at the critical section (smallest radius of curvature) is determined by the allowable fatigue stress, Eq (1).

The best material evaluated for this application was a solid epoxy fiberglass laminate where, as a rule of thumb, the panel thickness was not less than 1/100th of the bend radius. This material and the foregoing dimensional tailoring were successful in solving the strength and stiffness problems of the flexible skin panel.

ACTUATION SCHEME

The means of actuating the multiple four-bar mechanism was initially an item of concern because linear actuators in the form of either a hydraulic cylinder or ball screw were not able to provide adequate rotation of the main support member ABG. The 135° requirement is a great deal of rotation for a linear actuator acting on a simple crank arm. The moment arms at the ends of a 135° crank arm stroke are so small that the resulting loads are impractical to handle. On previous Boeing aircraft the high-lift devices were actuated with linear actuators, but it was apparent that a departure was needed for this application. The solution was a rotary actuator as shown in Figure 10. This actuator is a planetary gear box with an approximate 240:1 gear reduction. The adoption of this new actuator for this application turned out to be a blessing in disguise since its compact design and high torque resulted in both a space saving and significant weight reduction.

VIBRATION AND FLUTTER CONSIDERATIONS

Because of the many joints in the flap support mechanism plus the high degree of extension and air loading, vibration and flutter were items of initial concern. To satisfy this concern, both laboratory and flight tests were conducted on the variable camber flaps. These tests had a very happy ending and revealed some unanticipated virtues of the design.

Vibration tests were conducted in the laboratory by attaching shaker pots to the flap structure in order to determine its natural frequency. The frequency band was very broad, with no critical peaks. The dampening effect was provided by the flexible fiberglass panel which acts as a large spring under tension. This spring tension preloads the joints of the linkeage mechanism, thereby removing any play due to tolerances and wear. In the retracted position, the panel spring effect is replaced by preloading the mechanism against up-stops.

Flight tests were conducted on a Boeing 707 by replacing the Krueger flaps between the engines with variable camber flaps. The Krueger flaps outboard of the engine were left intact for comparison purposes. These tests confirmed the laboratory tests and demonstrated their freedom from vibration and flutter. The variable camber flaps demonstrated excellent stability under all flight conditions tested, including stall. Their stability was visibly superior to that of the Krueger flaps.

During these flight tests the flap and wing surfaces were tufted in order to observe the aerodynamic flow of the air. Air flow separation occurred on the Krueger flaps and, of course, on the wing at very high angles of attack, but there was no separation on the variable camber flaps even at stall, attesting to their superior aerodynamic shape.

OPERATING EXPERIENCE

Because of the limited nature of this paper, the operating experience will be confined to the following comments:

The 747 has been in operation over 12 years. The overall operating performance of the flap mechanism and structure has been excellent.

Because over one thousand bearings are used in the 747 variable camber flap mechanisms, a self-lubricating bearing design was adopted in place of one requiring grease fittings for periodic lubrication. The self-lubricating feature is provided by a TFE (tetrofluorethylene) fabric liner. Because of some early unsatisfactory experience with TFE bearings it was felt that they might not provide the required service life. However, these bearings have given excellent service to date with little or no replacement required. We feel the following two items have contributed to this good performance: 1) a low bearing stress design; and 2) the elimination of cyclic loading from vibration and flutter provided by the flap panel camber preload.

APPLICATION AND USAGE

The variable camber flap is in use on the following aircraft:

- All Boeing 747 models
- Boeing YC-14 prototype

It was incorporated in the following aircraft designs:

- Boeing B-1 design proposal
- Boeing 727-300 design proposal
- Boeing 7N7 design proposal
- Boeing 7X7 design proposal

Because of the emphasis on fuel economy it is not being used on the initial models of the Boeing 757 and 767 airplanes, but it may be used on short-field versions of these aircraft if Boeing decides to offer them at a later date.

CONCLUDING REMARKS

The wings of a bird are beautiful examples of the "flexible skin" and "dynamic structure" concepts. If we can approach their sophistication and reliability in the design of future aerodynamic high lift devices, then, perhaps, we will realize the aerodynamic versatility required to successfully combine high and low speed flight.

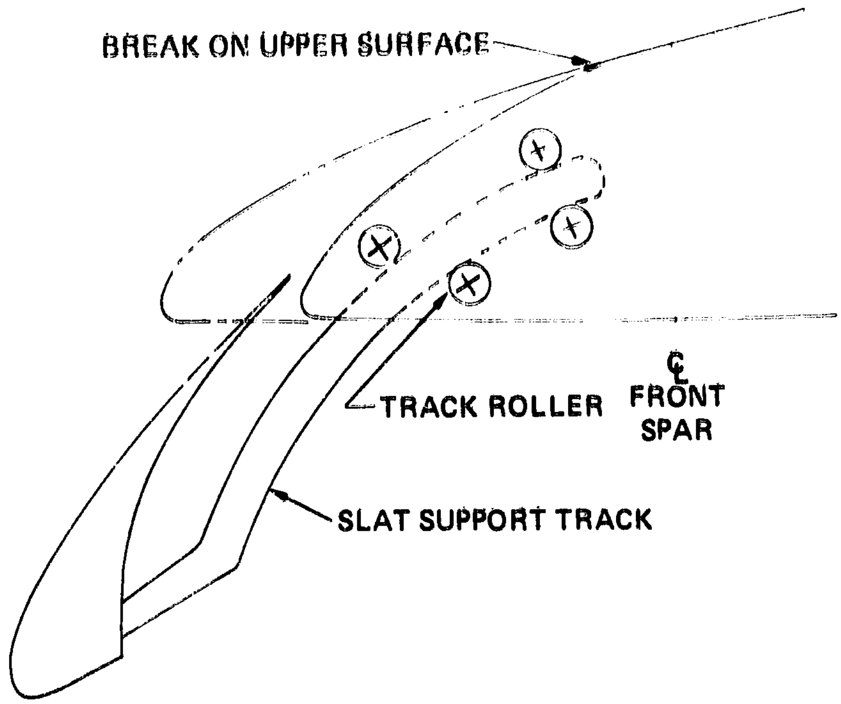

Figure 1.- Wing leading edge slat.

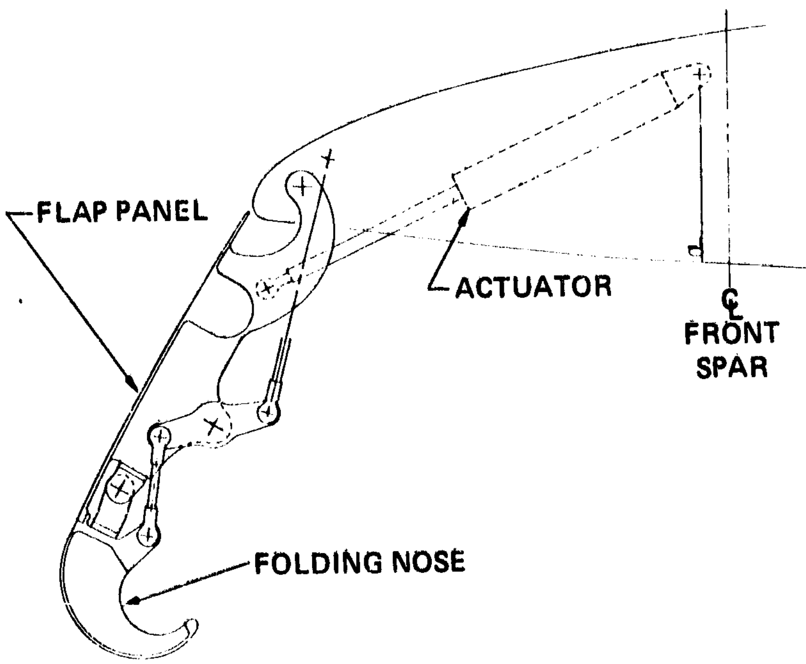

Figure 2.- Wing leading edge flap.

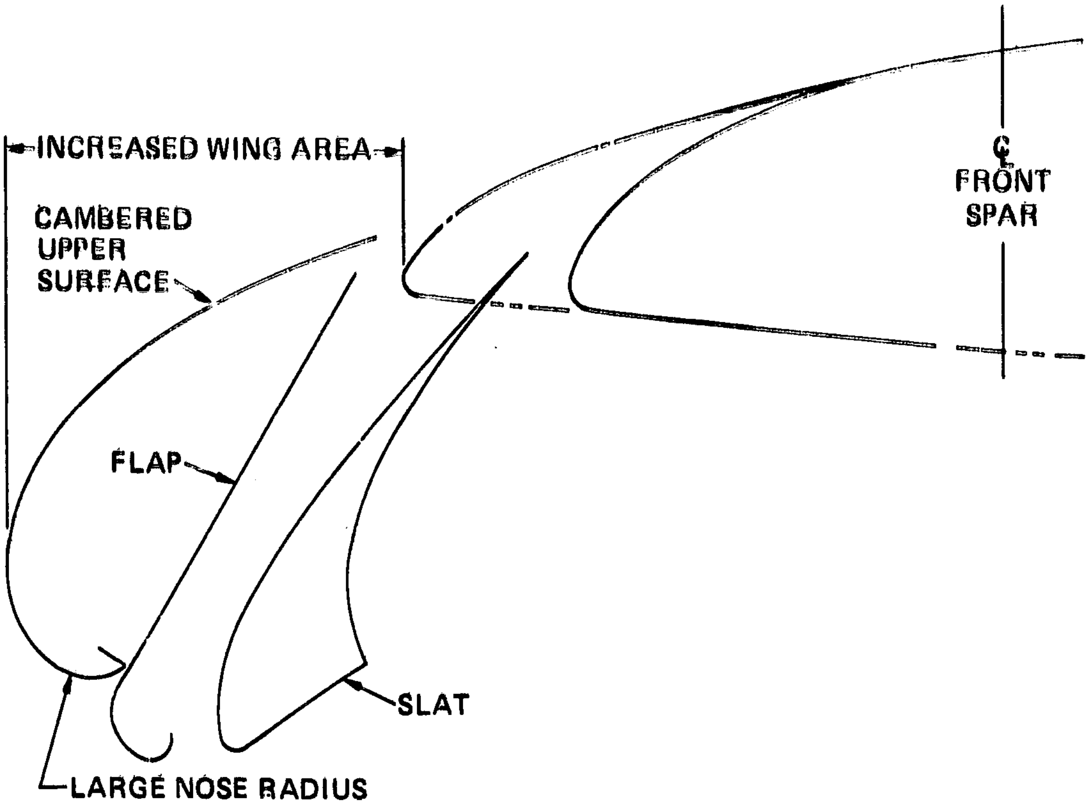

Figure 3.- Aerodynamic improvements.

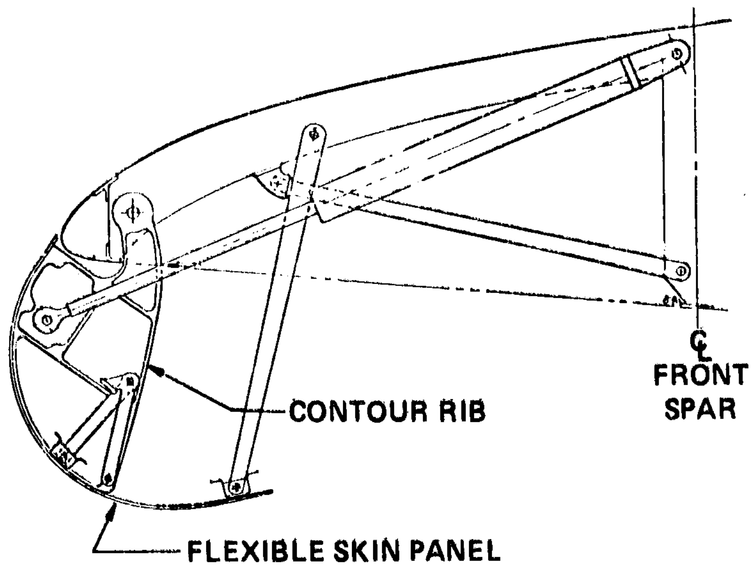

Figure 4.- Flexible Krueger flap.

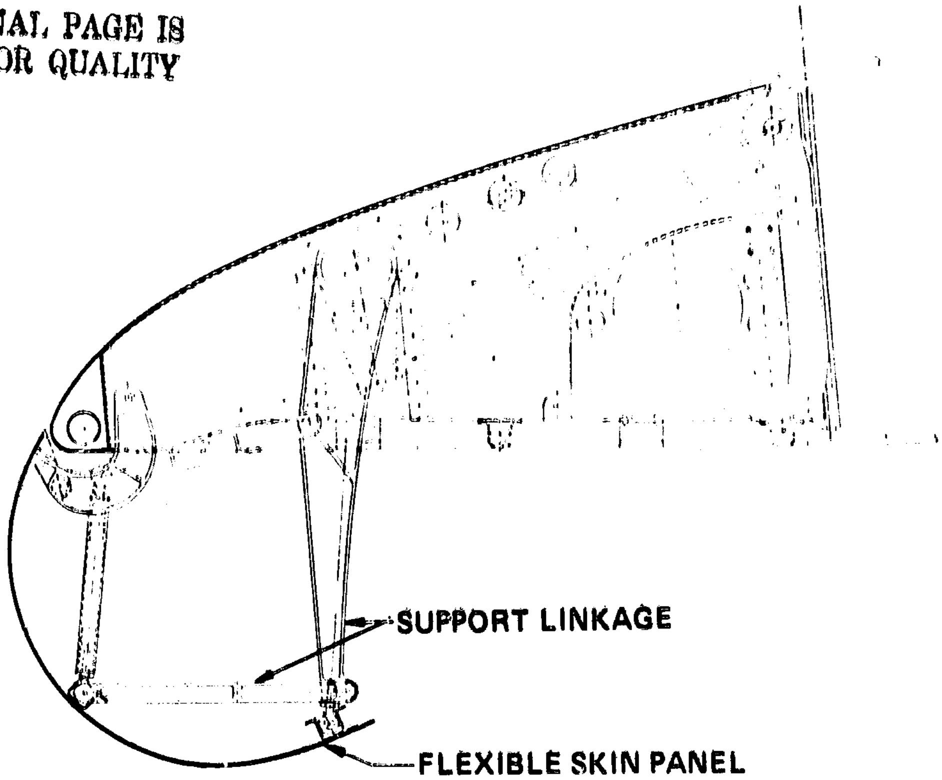

Figure 5.- Flexible Krueger flap.

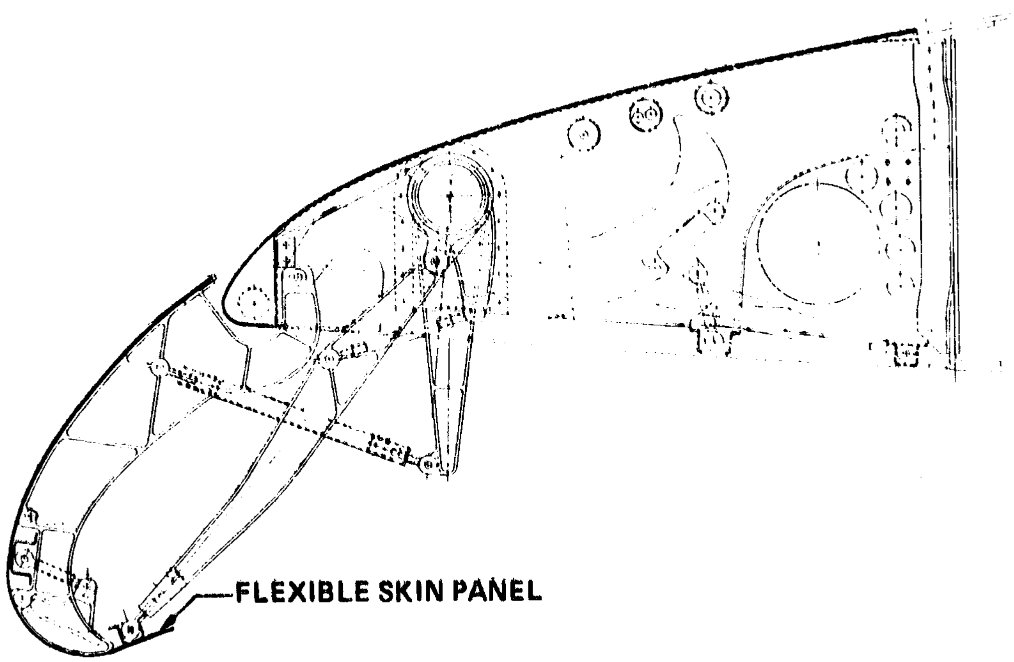

Figure 6.- Flexible Krueger flap.

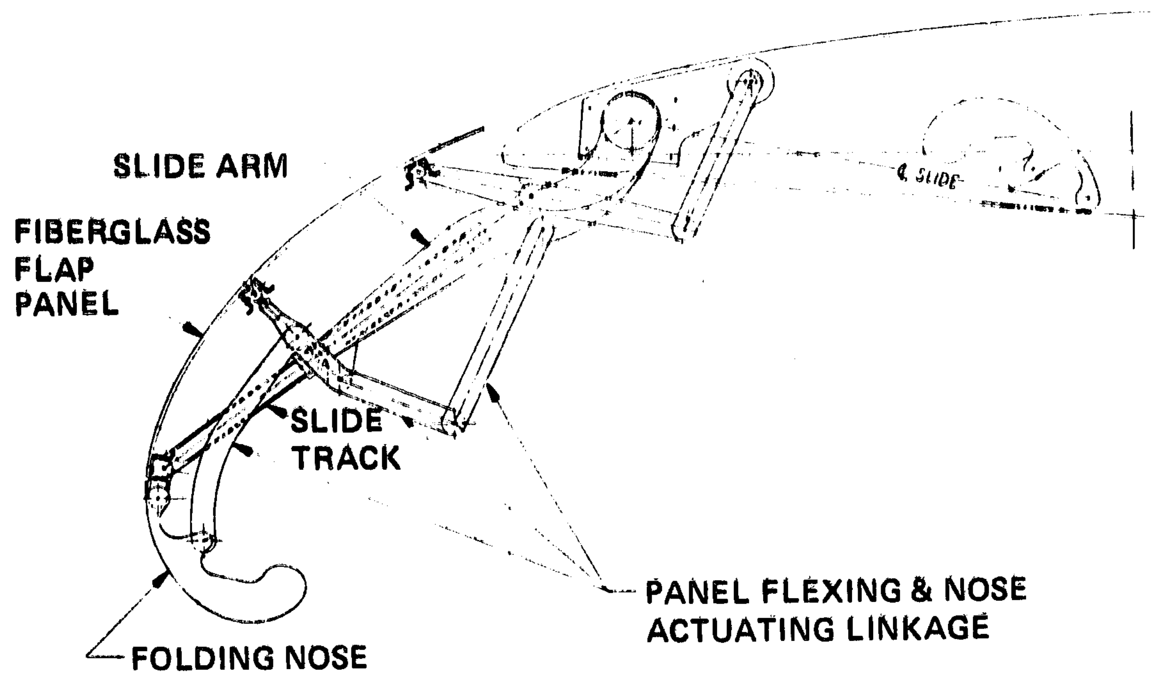

Figure 7.- Variable camber flap with slide.

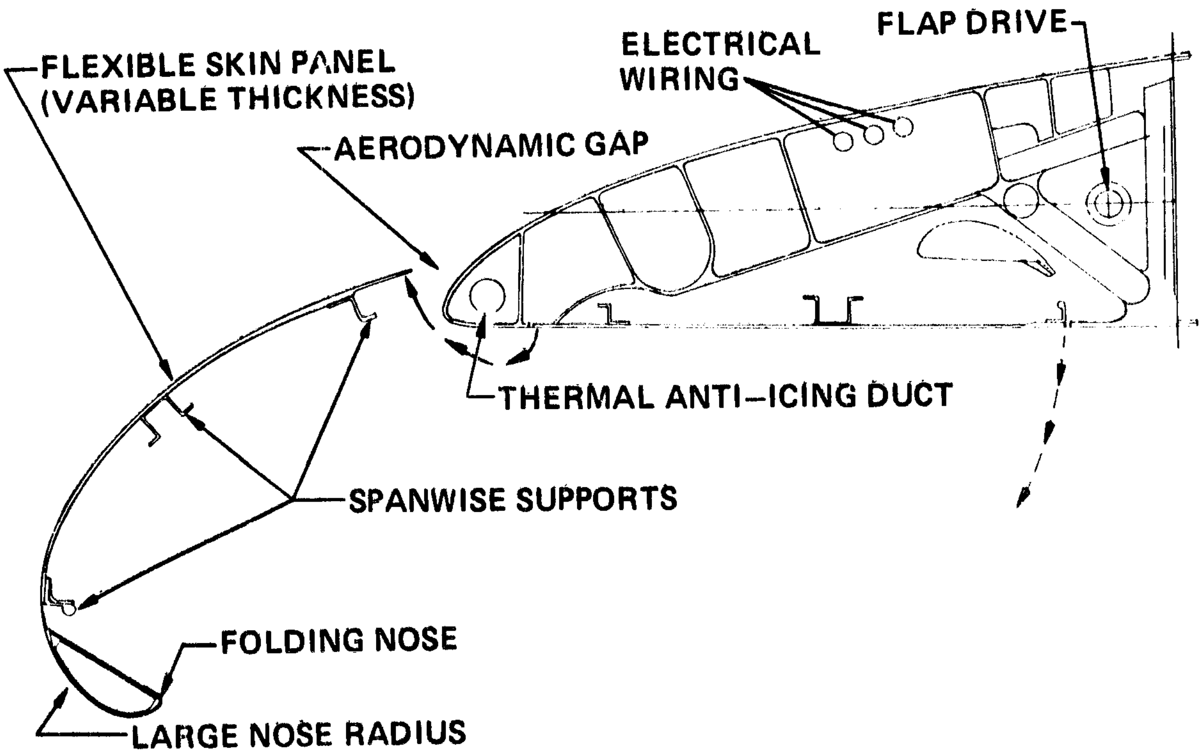

Figure 8.- Leading edge flap requirements.

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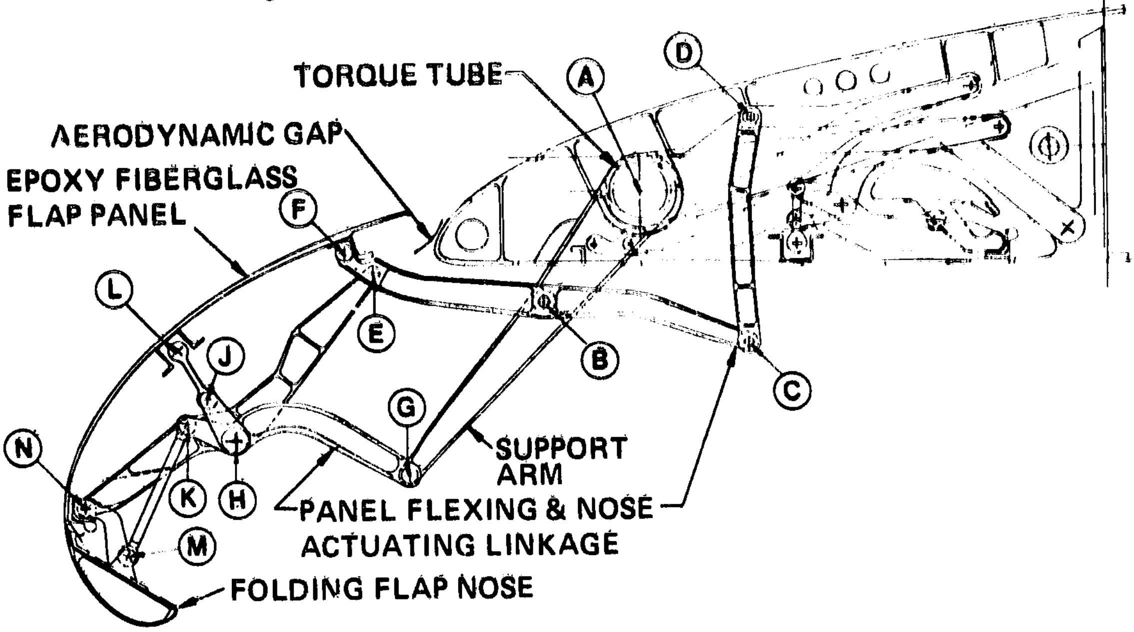

Figure 9.- Wing leading edge variable camber flap.

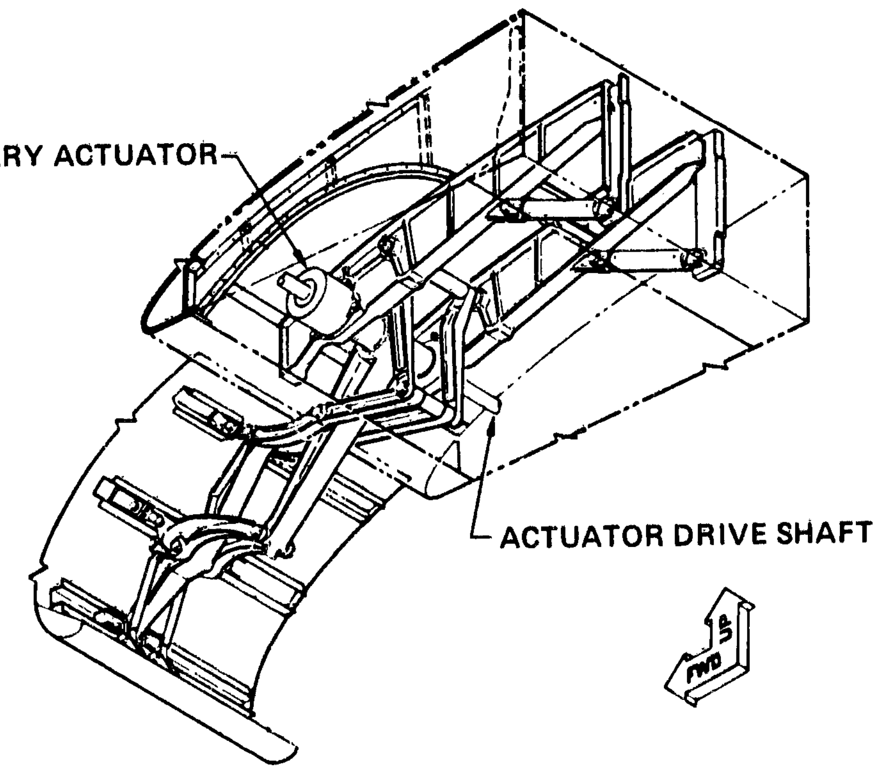

Figure 10.- Variable camber flap with rotary actuator.