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F100 EXHAUST NOZZLE AREA CONTROL MECHANISM

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SUMMARY

The current production F100 Turbofan Engine exhaust nozzle area control mechanism represents a highly developed mechanical device comprised of three basic elements: (1) a power driven primary nozzle area setting system, (2) a balance beam or pressure load balanced convergent nozzle system, and (3) an aerodynamically adjusting or floating divergent nozzle system. Installed in the twin engine F-15 and in the single engine F-16 aircraft (figure 1), these systems have been called upon to operate over a wide range of environmental conditions. Design requirements have been modified as a result of accumulated operational experience and changing mission requirements in both single and twin engine aircraft configurations. Durability and life cycle cost improvement without sacrifice to weight or performance are the dominant design goals today.

INTRODUCTION

The convergent/divergent exhaust nozzle of the F100 Turbofan Engine (figure 2) functions primarily to accelerate exhaust gases and maximize propulsive thrust. A second and very important function of the nozzle is to minimize transient pressure fluctuations within the engine flowpath system in order to maintain internal aerodynamic stability through scheduled low pressure rotor speed control. Thirdly, the exhaust nozzle design must integrate well into the installed aircraft configuration to minimize propulsion depleting drag forces. In addition, the nozzle mechanical system must provide reliable operation in a sometimes hostile environment (see figure 3) with internal metal surface temperatures approaching 1477 K (2200°F) and external skin temperatures up to 477 K (400°F) while simultaneously being subjected to nonuniform or asymmetrical external flowfield pressures and aircraft maneuver loadings. To accommodate these requirements in an advanced high performance production engine, the F100 incorporates a sophisticated exhaust nozzle area control mechanism.

This paper highlights details of the F100 Nozzle Mechanism design, placing particular emphasis upon the evolution of design constraints or drivers from initial concept through current operational deployment. A kinematic description of the area control mechanism is given, and several environmental constraints which complicate the normal mechanism design process are discussed.

THE EXHAUST NOZZLE MECHANISM

Three basic elements comprise this mechanical system: (1) a power driven primary (convergent) nozzle area setting system; (2) a balance beam or pressure load balanced convergent nozzle system; and (3) an aerodynamically adjusting or floating divergent system. These systems have been described by Reference 1.

Primary nozzle throat area (Aj) control is achieved through an exhaust nozzle control system which senses critical engine operating parameters (inlet temperature, burner pressure, fan rotor speed, power lever angle), integrates these into a nozzle area requirement and transmits a nozzle positioning command to an air motor. The air motor powers two 0.8 cm (0.3 in.) dia flex cables which rotate at a maximum speed of 20,000 rpm. Aft or downstream of the two airmotor cables is a series of five equally spaced ball screw actuators which extend and retract, in a synchronized system through interconnecting drive cables (see figure 4). The ball screw actuators have a stroke of 18.5 cm (7.3 in.) including adjustment. Retraction opens the nozzle and extension closes. The actuator rod extensions act together through a set of curved links (Link 1, figure 5) to axially position a synchronizing ring which is supported in each degree of freedom except axially by a bearing and track system within the nozzle support structure (see figure 6). Axial degree of freedom is controlled by the actuators. A bellcrank and linkage system is activated by Long Links (Link 2, figure 5) connected to the synchronizing ring. These transform the linear motion of the extended actuator rods into a variable diameter hoop of connecting links (Short Links 3 and 4, figure 5) that bring the nozzle system into equilibrium after changing nozzle throat area. Each Long Link transmits motion and loading to a bellcrank attached to the outer post on each of the Convergent Nozzle Flaps. The bellcrank rotation drives the two tangentially aligned Short Links connecting the bellcrank of one flap to each of the adjacent Convergent Flaps. When connected to all bellcranks and flaps, the short links form a 360 degree contiguous hoop loading element which is set into radial position by synchronized bellcrank rotation.

The balance beam or pressure load balanced convergent nozzle section is comprised of a series of Balance Flaps connected to the Convergent Flaps through a series of hinged joints. The Convergent Flaps pivot about their fulcrum points or support hinges. The Balance Flaps are supported at their forward end by an interconnecting hoop of links. Internal pressure vessel loadings are reacted out of the Balance Flap on the forward hoop of links and at the rear hinge. The hinge loads transferred from the Balance Flap react upon the Convergent Flap forward hinge to counterbalance the internal pressure induced turning moments imposed on the Convergent Flap System. Since it is not practical to null the resulting unbalanced moment for all operating conditions, some actuator loading is required to maintain equilibrium as well as overcome system friction. Spaces between both balance and convergent flaps are sealed by a series of floating seal segments which maintain internal pressures and minimize leakage. Figure 7 shows the schematic loads/reactions for this system.

The floating or divergent nozzle element is a self-adjusting nozzle expansion ratio mechanism providing distinct limits at either of two area ratio extremes (Low Mode and High Mode) for each primary nozzle area setting. Both internally and externally induced static pressures combine to produce floating divergent section static equilibrium at either of the two area ratio extremes or at some intermediate position within the float range. The relationship between Ae/Aj, or the area expansion ratio, is controlled by the pressure balancing parameters acting upon a four bar linkage (figures 7 and 8). The linkage is comprised of: (1) Convergent Flap, (2) Divergent Flap, (3) Mode Strut, and (4) Nozzle Support Structure. The Mode Struts each pivot in a slotted bracket attached to the rear of the Nozzle Support Structure.

HIGHLIGHTS/FEATURES

Weight

The F100 exhaust nozzle system weighs approximately 159 Kg (350 lb), or about half of that for the TF30 P100 engine exhaust nozzle, a similar thrust class engine of 1960's vintage used to power the F111 aircraft. Extensive design trades were made before choosing a cooled inner flowpath configuration with titanium structural flaps as opposed to an uncooled system with heavier higher temperature capability superalloys such as INCO 718 and Waspaloy. TF30 operational experience was factored into that trade-study process. The result was the current F100 balance beam concept with a sealed and cooled inner gas path surface, permitting extensive use of titanium structure for both Balance and Convergent Flaps. Further significant weight improvements over the TF30 were made possible through use of the airmotor driven ball screw actuators as opposed to the TF30's hydraulic system and through use of the balance beam concept which greatly reduced actuation load requirements. The TF30 blow in door ejector and tail feather concept for reduced installed drag was not used in the F100 in favor of the integral floating divergent nozzle system.

Since aircraft center of gravity location is highly sensitive to nozzle weight, weight remains a significant consideration in F100 nozzle design modifications, even today.

Bellcrank System

Positive throat positioning, nozzle stability and minimum actuation system loading is enhanced by placement of the bellcrank actuation system near the nozzle throat. This minimizes throat changes due to pressure loading and temperature changes, and reduces actuation system loads.

The Balance Flap

The purpose of the Balance Flap, as mentioned earlier, is to minimize actuator loads required to vary nozzle throat area. The Balance Flap functions to counterbalance gas loads and moments acting on the convergent/divergent portion of the nozzle. The forward end of the Balance Flap is connected to each adjacent flap by a link with a spherical bearing at each end, thereby forming a contiguous hoop. (See figures 7 and 9.)

Convergent Flap

This element is the major structural flap in the nozzle. Its primary function is to provide variable throat area (Aj). This is accomplished by pivoting the flap from the static structure and varying the convergence angle of the flap. Convergence angle is varied by the actuation system through the bellcrank and linkages described above. (See figure 5.)

Divergent Flap

The Divergent Flap forms the divergent portion of the nozzle and provides for complete internal aerodynamic expansion over a wide range of operating conditions. The flap positions itself in low, high or intermediate mode depending upon gas pressures and system friction loadings. (See figures 7 and 8.)

External Flap and Mode Strut

The External Flap acts as the external aerodynamic contour which is exposed when installed in the respective aircraft. External loadings, both static and dynamic, are therefore highly dependent on specific aircraft flowfield conditions. A separate strut (Mode Strut) is used to limit the resultant divergent section position to two extremes — High or Low Mode — or to some intermediate or floating position between those extremes. The Mode Strut is the structural support link for the divergent nozzle section during all operating conditions except when operating in the float range. For relative F-15 and F-16 flight envelope float characteristics see figure 10. Figure 9 shows the External Flap relationship to Mode Strut and Divergent Flap.

Static Structure

The static Nozzle Support Structure or nozzle case (see figure 6) is the major structural element of the balanced beam nozzle. The forward end is flanged and connects the nozzle system to the rear of the cantilevered Augmentor Duct. The center section of the static structure supports the actuator and Synchronizing Ring track loads while forming an aerodynamic external surface. The aft end of the static structure supports both the forward ends of the divergent Mode Struts and the forward ends of the External

Flaps. This section incorporates two rings which support the flap system by transferring radial loads into hoop loads and axial loads into the support case. (Rings A and B, figure 6.)

Flap Liners/Seals

To maintain internal pressurization and avoid hot exhaust gas radial outward flow through the nozzle flap system, a series of seals and flap liners are utilized. These seals (Balance, Convergent and Divergent elements) are hinged together axially (see figure 9) to overlap and fill the gaps between the hinged internal flap system. The Convergent Section liners create the coolant flow passage.

ENVIRONMENTAL CONSTRAINTS

The F100 Exhaust Nozzle is a convergent/divergent system. Exhaust gases from fan and core engine flow streams mix in the Augmentor Duct, are further heated to temperatures approaching stoichiometric during Augmentor operation, and discharge from the rear of the Augmentor into the Convergent Nozzle Section. The Convergent Nozzle accelerates the internal gases to a choked flow or sonic velocity condition at its minimum area constriction, Aj, located at the convergent section aft end. From the choke plane area Aj, a partially constrained aerodynamic expansion takes place to further accelerate the exhaust gases through the Divergent Nozzle Section. Aircraft aerodynamic flowfields pass rearward over the exposed engine External Nozzle Flaps contour to join with engine exhaust gases aft of the Divergent Section exit plane, Ae. Internal aircraft nacelle airflows pass from the engine inlet duct region aft in the cavity between engine and airframe to discharge rearward through openings in the Divergent Nozzle Section, External Nozzle Flap Section, or through Nozzle Support to Air Frame seal openings. These airflow systems comprise the fundamental aerodynamic loading environments in which the exhaust nozzle mechanism must operate. It is an extremely complex flow condition and the resulting pressure loads are hard to predict.

Further environmental constraints in the nozzle system are imposed by mechanical loadings due to aircraft maneuvers (g's and gyro's) and system vibrations fed by rotor induced harmonics and installed acoustical excitations.

In order to control rotor speed and maintain internal engine aerodynamic stability at all operating conditions within the specified flight envelope, the nozzle mechanical system must be extremely quick in response to engine control system command. Response rate cannot be compromised by a sluggish design which is not tolerant of all combinations of integrated system loading constraints. The F100 nozzle capability includes excursions from full open to full closed, or the reverse, in less than one second elapsed time. This high response rate is fully compatible with the very short engine acceleration/deceleration capability required for high performance. The F100 engine accelerates from idle to full intermediate power in only 2.2 seconds and the nozzle must be compatible.

Mechanical friction effects play a major role in the total system design. Increased friction loadings generally aid in damping induced vibratory responses, while at the same time reducing system operational life due to increased wear rates. Heavy wear can result in a loose system which could become more susceptible to structural fatigue and distress. Fits, clearances, and wear resistant coatings therefore become critical design concerns in a highly functional and durable nozzle mechanism design. Trade-offs had to be made between an extremely "loose" system with benefits of high response rate and adaptability to manufacturing tolerance variation; versus a "tight" system with lower response rate due to higher system friction, and minimized flow leakage. The resulting production F100 nozzle configuration is a compromise between the two extremes.

Under conditions of asymmetric pressure (see figure 11) and maneuver loading where the nozzle can become ovalized or distorted, several design considerations are introduced. From a mechanisms design point of view, the most obvious is the distortions under loading conditions which could override the simple kinematic model through which design link loadings are derived. Special consideration must also be given to linkage stability in all actuating environments while in a distorted nozzle condition. Also, aerodynamic excitations of External Flaps are of particular concern since this portion is exposed not only to engine acoustics but aircraft flows as well. A transonic high "G" turn with nozzle in the float range could present a severe mechanisms design point, for example.

The F100 nozzle mechanical system was initially designed with a power driven two position Divergent Section. The originally qualified and produced power driven configuration was attractive from a durability standpoint, providing excellent Divergent System stability but at a higher weight and cost. After performance, cost and weight trades were redone and a successful redesign and test program completed, the current floating system was incorporated. Aerodynamically actuated systems that have reversal of load must go through a null state where the sum of the loads acting on the system is zero. In the region near zero loading, small cyclic loads can drive the system into vibration or instability which can produce accelerated wear or structural damage from high inertia loads. The two-position Divergent Section Actuator restricted the system freedom by providing positive stabilizing loads at the Low and High Mode extremes while eliminating float range positioning.

Successful flight and sea level static testing of the YF100, and the F100 floating nozzles, resulted in removal of the Divergent Exhaust Nozzle Control and actuation system in favor of the floating Divergent Nozzle. This basic change in design resulted in a savings of 10.4 Kg (24 lb) of engine weight, significantly reduced the engine cost, and introduced a new design trade-off for future balanced beam nozzles.

WEAR AND DIRT ACCUMULATION

Wear and dirt accumulation can act in conjunction with system friction to further complicate the nozzle mechanism. As stated above, a worn, or loose nozzle might have a faster response rate due to reduced system friction, while sacrificing leakage and some degree of system damping and inviting increased hardware fatigue and distress. Dirt acts in the same way as increased system friction to inhibit system response time and increase mechanism loadings.

Most of the F100 nozzle mechanism joints utilize uniballs (figure 5). Radial clearance is such that either dirt or surface spalling can accumulate to jam the uniball driving motion and generate wear in the attaching pin and sleeve members. These conditions are further aggravated by the high local environmental temperatures (up to 561 K/550°F) which limit lubrication to a dry film approach. Coatings to seal out foreign materials and corrosives in these environments and to provide increased durability are being successfully developed in an on-going challenge to extend joint service life. Several promising choices such as Nickel-Boron are currently being studied on a life cycle cost trade basis.

Another example of wear problem is at the External Nozzle Flap attachment hinge joints where pins and retaining rings fretted. High speed F-15 flight movies recently showed an External Flap pounding mode of vibration not previously identified. Initial nozzle design requirements called for a symmetrical external static flowfield loading. Later reduced scale model test data were obtained from wind tunnel testing. The design static loads were then modified but kept symmetrical. Further instrumented testing in F-15 flight indicated significant static load increase and a non-uniform flowfield. Of particular significance was speed brake deployment effects. Later, intrumented testing in the F-16 showed even higher loadings. The design loadings history to date is given in figure 12. Dynamic data acquisition is now in the F-15 flight test plan for 1980 since it is likely that operational dynamic loads have exceeded the original design allowables.

The External Flaps are themselves a classic example of advantages and disadvantages of system looseness and friction. When loose in an unstable external aerodynamic environment, the hinges pound and wear until looseness becomes excessive enough to eliminate effective friction damping. Service life can then be substantially reduced through impact loading. Shaker rig tests of External Flaps with simulated flap support systems (figure 13) are currently being conducted at GPD for durability testing in conjunction with the forthcoming measured F-15 dynamic flight test data. Results will be evaluated against the most recent design improvements to upgrade the durability of the External Flap System.

ENGINE/AIRFRAME INTEGRATION EFFECTS

An integrated propulsion system is subjected to the constraints of the installed environment. For the F100 engine, the environments within which the exhaust nozzle mechanism must perform differ significantly between the F-16 single engine installation and the F-15 twin engine configuration (figure 1). Close engine location and spacing to minimize overall installed afterbody drag, as in the case of the F-15 (Reference 2), can result in extraordinary and unstable engine external flap environments, as well as increased sensitivity to engine-to-engine and engine-to-airframe acoustical excitations.

TRADE-OFF FACTORS

The self positioning exit area system resulted from design trade-off studies to provide a desirable balance between weight, cost and performance.

Weight and c.g. concerns were and continue to be the prime driver in the design and optimization of the F100 exhaust nozzle mechanism. These concerns conflict with a pure durability approach which might favor a heavier system. Tradeoffs between durability, weight, cost and performance are continually made in attempt to further increase system life. Current efforts are focused on reducing nozzle mechanism wear and increasing overall life without sacrificing weight or cost objectives. An extensive laboratory wear rig and coatings evaluation program is under way and all system fits and clearances have been reevaluated to optimize damping and minimize wear. A further objective of these efforts is to maintain or improve nozzle response capability while reducing system life cycle cost.

CONCLUDING REMARKS

The F100 nozzle area control mechanism was initially designed to operate in a symmetrical aerodynamic loading environment. A series of design and development iterations followed which produced a current production configuration which is highly tolerant of the sometimes severely compromised kinematic symmetry. Further dynamic and static flight test data will be obtained and reduced during 1980 in an on-going program to further understand and optimize the installed system.

REFERENCES

1. Bonner, George A., "Effect of F-15 Aircraft Induced Aerodynamic Loads on the Evaluation of the F100 Balanced Beam Nozzle," Paper No. 76-733, AAIA/SAE 12th Propulsion Conference, Palo Alto, California/July 26-29, 1976.

2. Martens, Richard E., "F-15 Nozzle/Afterbody Integration," Journal of Aircraft, Vol. 13, No. 5, May 1976, pp 327-333.

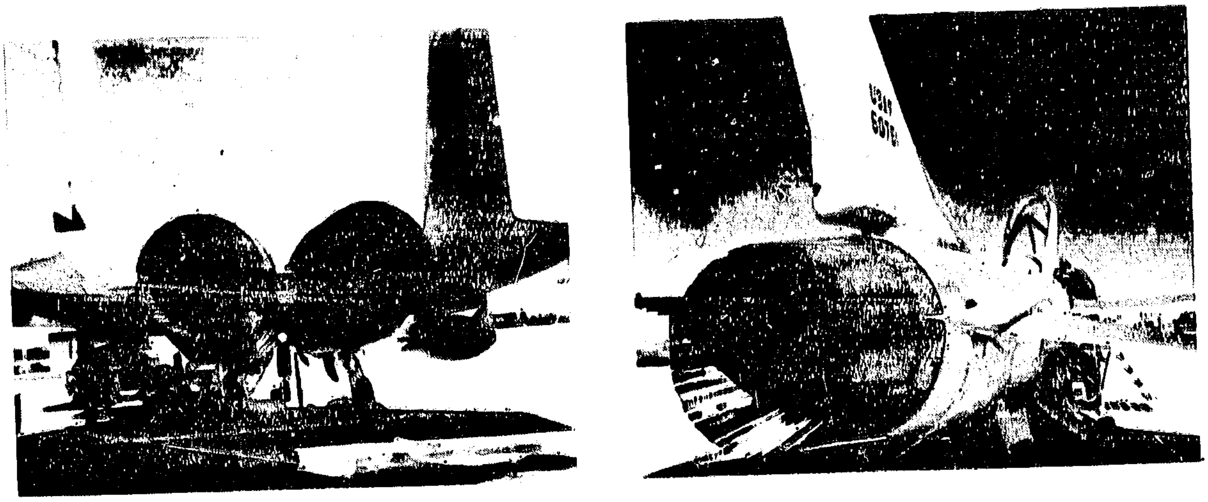

Figure 1.- Rear views of F-15 and F-16 aircraft showing F100 orientation.

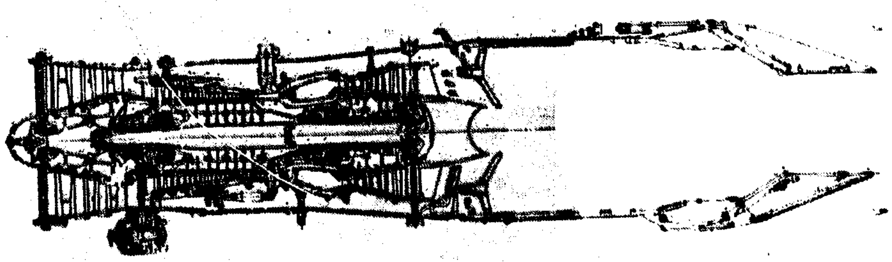

Figure 2.- F100 turbofan - highlighting nozzle mechanism.

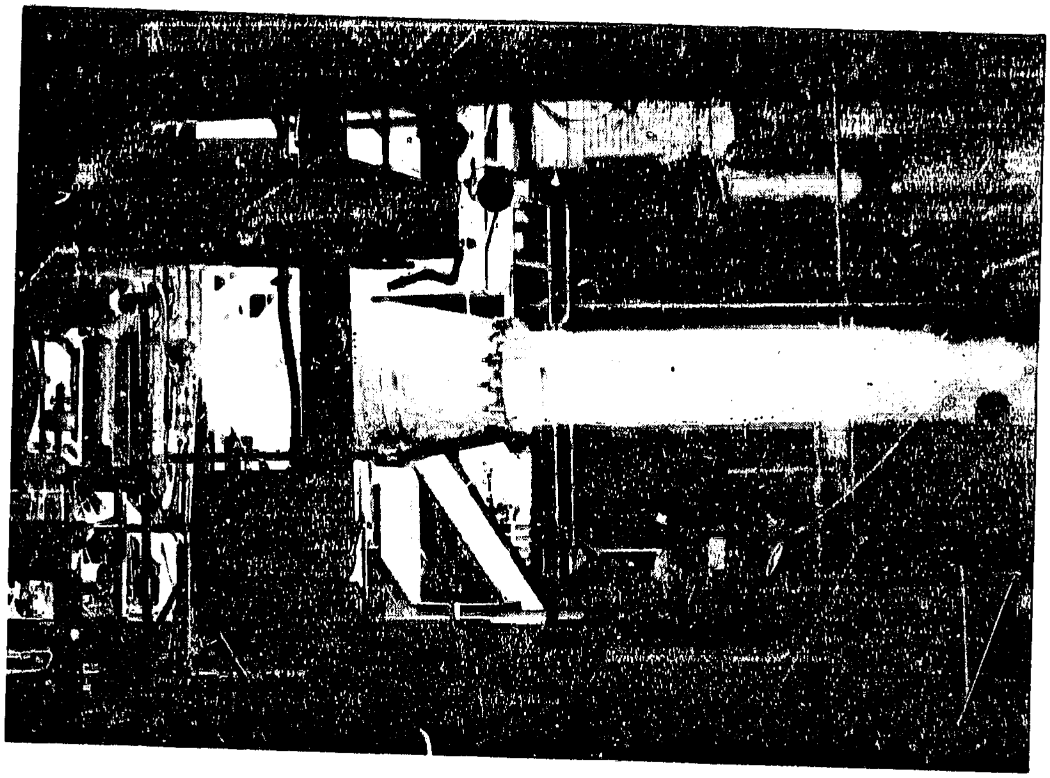

Figure 3.- F100 nozzle during test stand run.

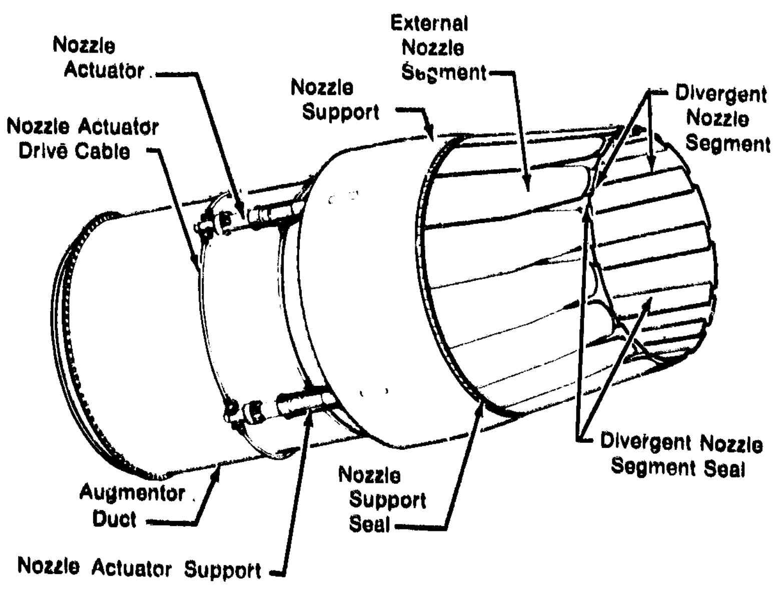

Figure 4.- External duct and nozzle view.

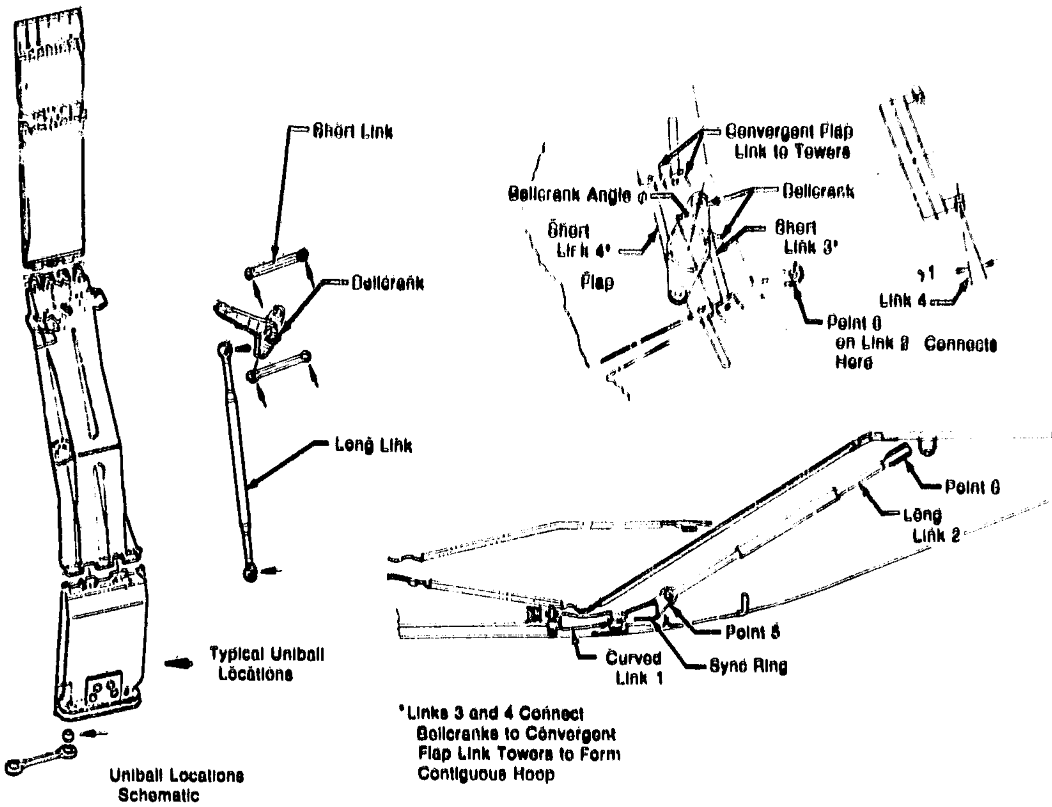

Figure 5.- F100 bellcrank actuation system components.

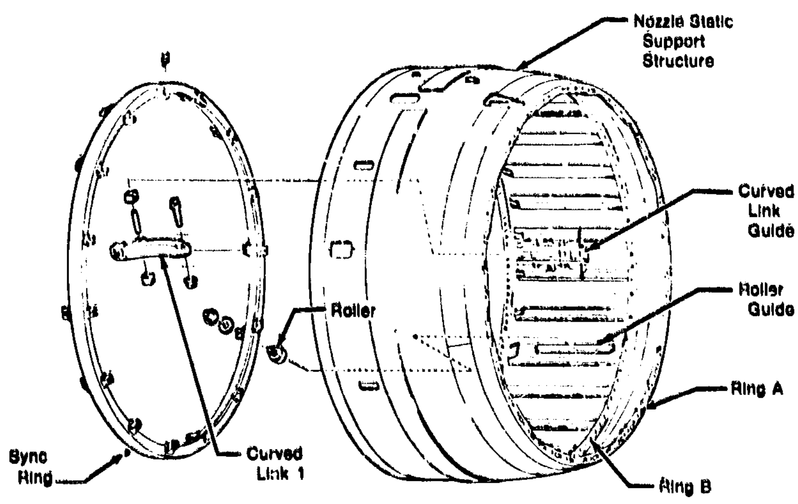

Figure 6.- Exploded-view static support structure and sync ring.

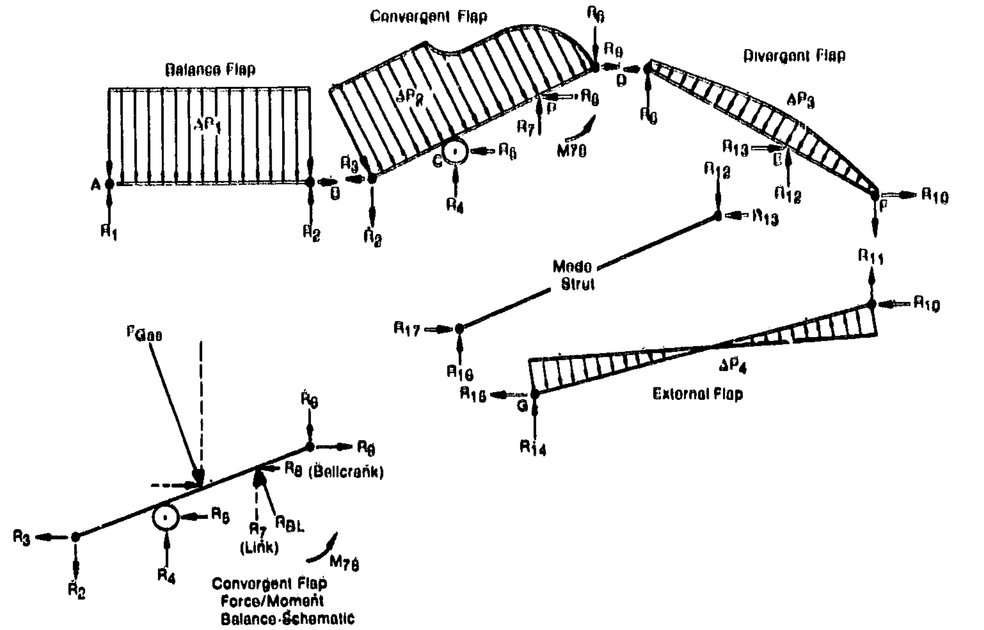

Figure 7.- Free body diagram of flap and mode strut elements.

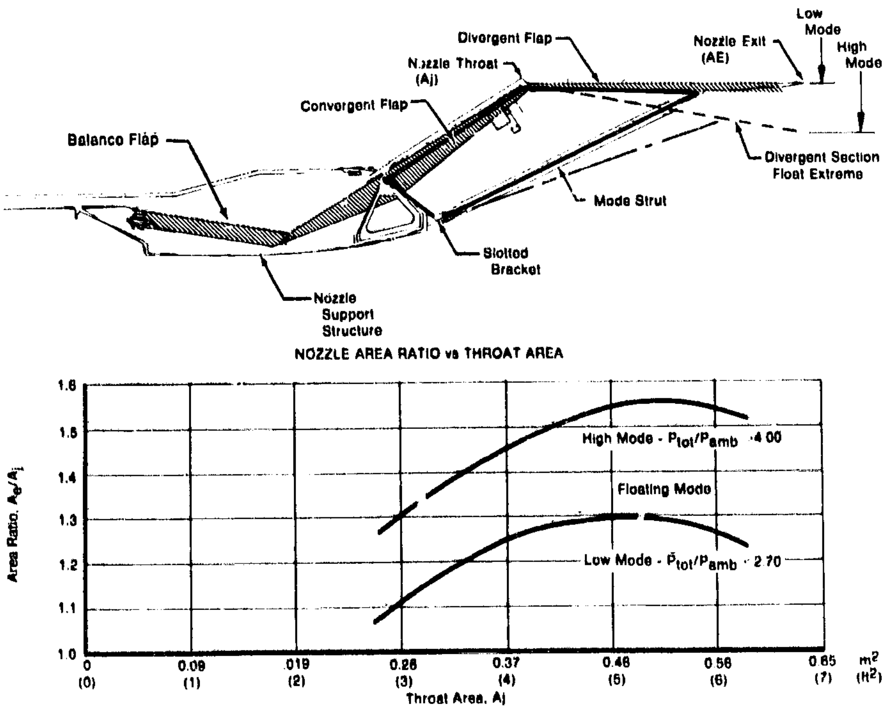

Figure 8.- Four bar linkage and area ratio relationships.

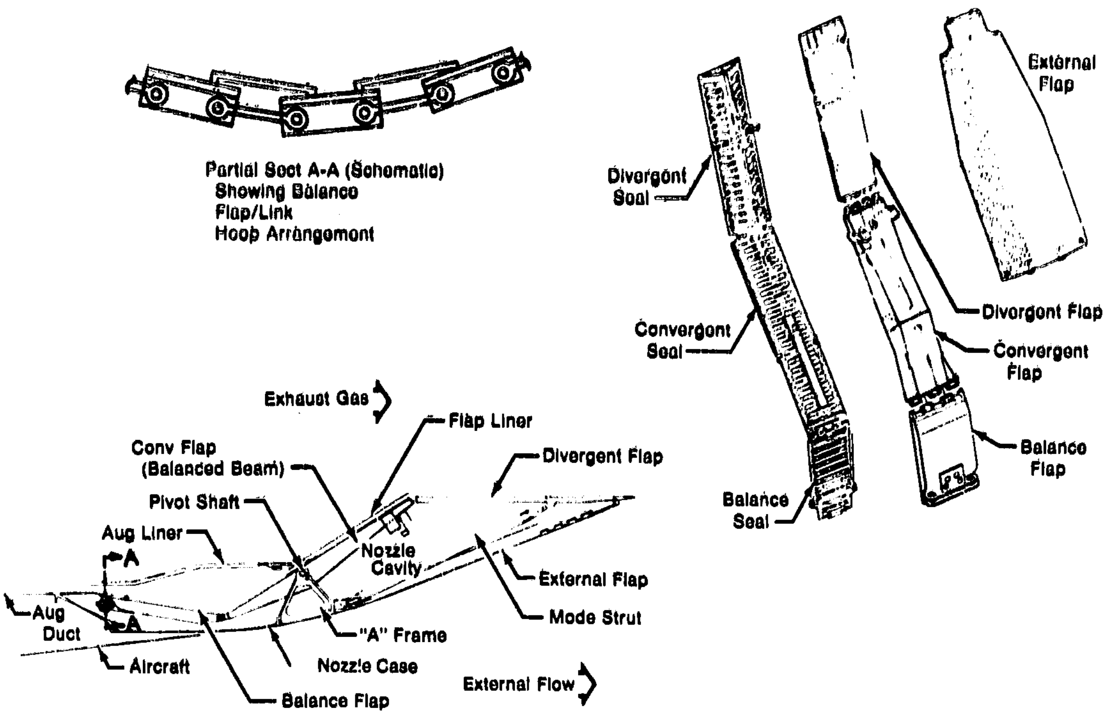

Figure 9.- F100 exhaust nozzle structural components.

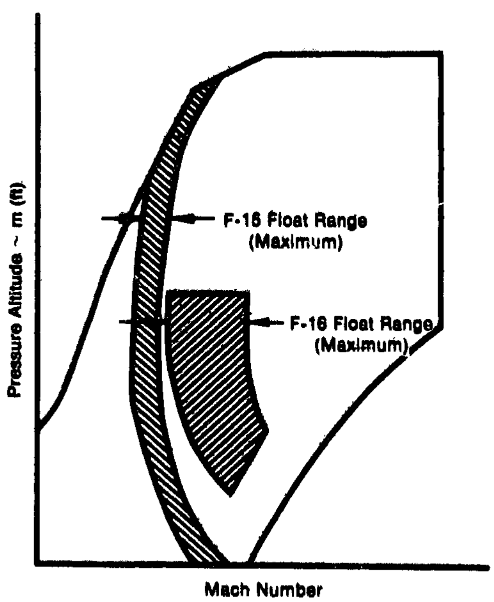

Figure 10.- F100 floating nozzle F-16 float envelope compared to the F-15 estimated float envelope based on test data.

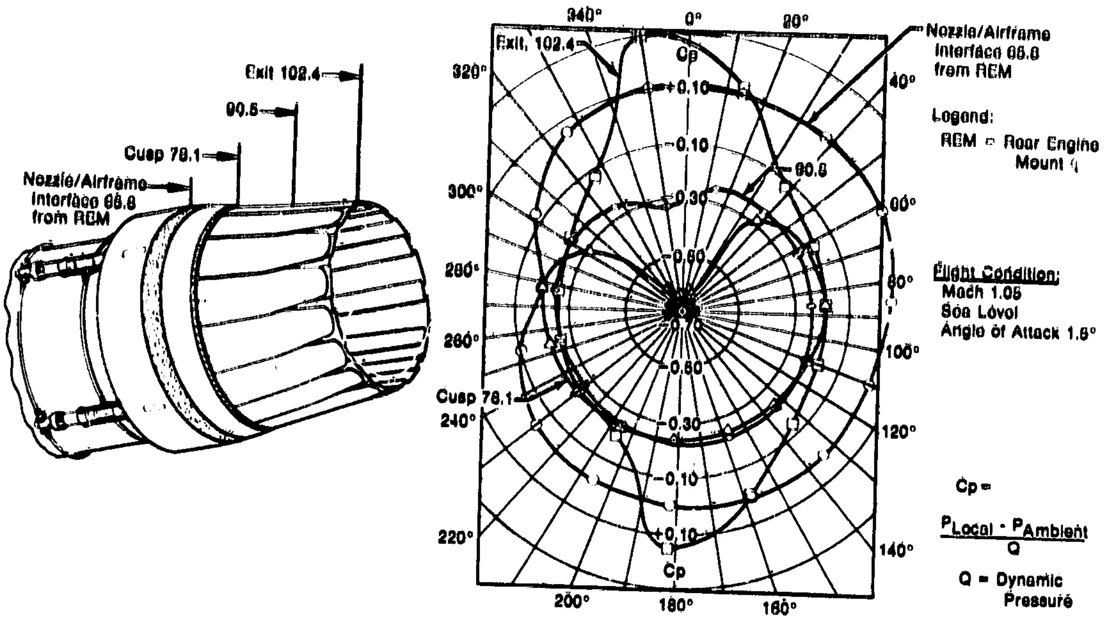

Figure 11.- External flow field pressure coefficient (Cp) distribution.

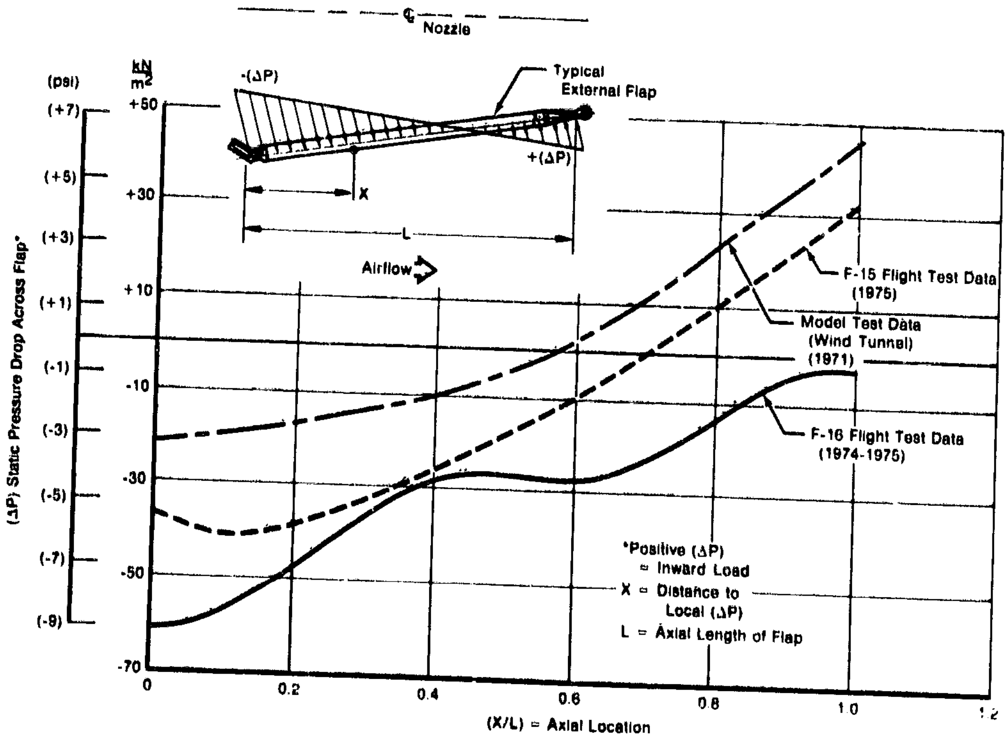

Figure 12.- External flap design loadings history.

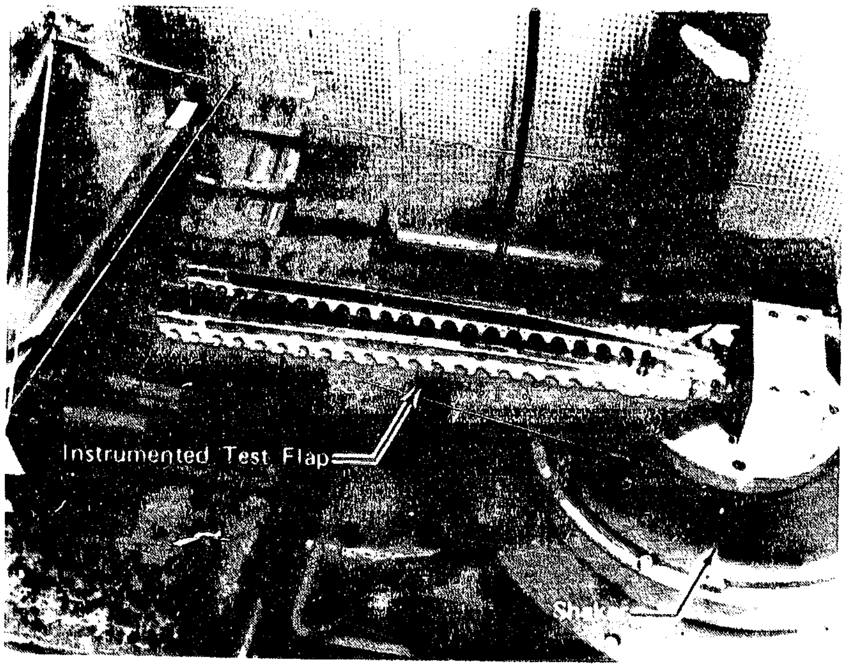

Figure 13.- External flap shaker test.