Dual Flex—A Low Horsepower Flexible Seal Nozzle

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Theme

A FLEXIBLE seal movable nozzle thrust vector control (TVC) system that offers reductions in actuation system requirements of greater than 10:1 for future first stage ICBM motors has been demonstrated on a subscale motor firing.

This system, the Dual Flex, employs two separate flexible seals: a servoseal with a forward pivot location, and the main seal with an aft pivot location. In operation, the servoseal is deflected by an actuator in the normal manner, thus shifting the nozzle blowout load so that it exerts a torque on the main seal, causing it to deflect until its resisting torque equals the generated torque. The nozzle actually pivots about an effective pivot location between the two seals. Required actuator force is very low, resulting in a significant reduction in actuator power requirements.

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The flexible seal movable nozzle has proven to be a highly reliable, low cost TVC system. It is presently used on both stages of a sea launched ballistic missile and has been demonstrated on motors up to 156 in. in diameter. The one major drawback of the flexible seal is its relatively high torque. Numerous design studies have been completed to determine methods of reducing nozzle torques.

One approach would be to accept the highly reliable flexible seal with its high spring rate and superior structural properties and find more efficient means of providing the force to turn the nozzle. It is this approach that the Dual Flex concept takes. By providing a second seal assembly to act as a servoseal, it is possible to use the nozzle blowout load to provide the major portion of the power required for vectoring. The required actuator force is low, as is the actuator stroke, resulting in a significant reduction in actuator horsepower requirements. The Dual Flex nozzle concept therefore uses standard, developed components in a unique configuration designed to utilize the nozzle blowout load as the power source for the major portion of the actuation.

By definition, the nozzle blowout load (*B. L.*) is the resultant force acting on the movable section of the nozzle, consisting of the motor pressure acting on the area enclosed by the seal ($P_c A_s$), and the thrust (F).

$$\mathrm{B.L.} = \mathrm{P}_c \mathrm{A}_s + \mathrm{F} \tag{1}$$

From these three known quantities, the blowout load may be calculated. Neglecting minor circumferential pressure perturbations, the vector $P_c A_s$ always acts on the case centerline (if the seal is fixed to the case) and the vector F always acts on the nozzle centerline. In a normal flexible seal nozzle, these two vectors intersect at the seal pivot point so that no torque is applied to the seal by the blowout load. Consider the example in Fig. 1 where the nozzle is attached through a standard flexible seal, but is purposely canted about a point forward so that the nozzle centerline is displaced from the seal pivot point by an amount Δ.

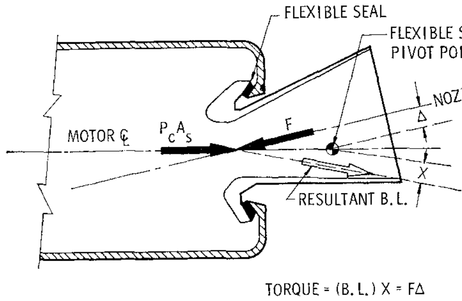

Fig. 1 Torque on offset nozzle.

Since the two components of blowout load now intersect forward of the pivot point, the vector sum is displaced from the pivot point by an amount X. Therefore, the blowout load produces a torque of $(B.L.)X$ in a counterclockwise direction, which deflects the flexible seal such that the present nozzle centerline angle is supplemented. Now, since the $P_c A_s$ vector does pass through the pivot

$$(B.L.)X = F\Delta \tag{2}$$

and it is not necessary to find A_s (a somewhat elusive quantity) to find the torque produced. This principle is employed in the Dual Flex seal nozzle, and the magnitude of the torque produced can be calculated from the thrust and its offset, even though the torque is actually produced by the blowout load.

Figure 2 shows the Dual Flex concept. Its operation is identical to the offset nozzle system just described except that the present angle is replaced by a variable angle produced by deflecting the servoseal. The actuator is attached between the case and nozzle such that it has a large lever arm on the servoseal and a small lever arm on the main seal. A force

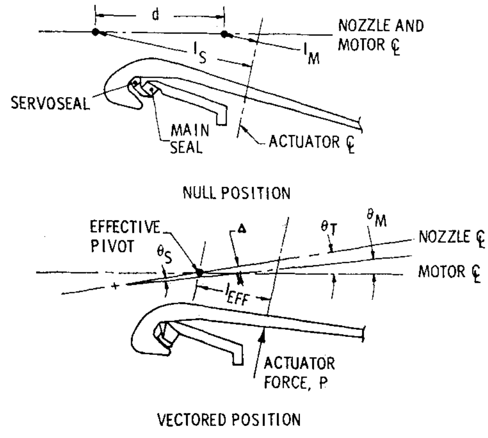

Fig. 2 Dual flex nozzle concept.

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generated by the actuator then produces the following deflections in the two flexible seals

$$\theta_s = Pl_s/K_s \quad (3)$$

$$\theta_{MA} = Pl_m/K_M \quad (4)$$

The additional main seal vector produced by the blowout load is

$$\theta_{MF} = Fd\theta_s/K_M \quad (5)$$

where θ_s = servoseal deflection angle; θ_M = main seal deflection angle; θ_{MA}—due to actuator, θ_{MF}—due to blowout load; P = actuator force; l_s = servoseal lever arm; l_m = main seal lever arm; K_s = servoseal spring rate; K_M = main seal spring rate; and d = distance between seal pivots.

The nozzle actually pivots about an "effective pivot point" between the two flexible seal pivots determined by the ratio of total deflections of the two. As far as the actuator is concerned, then, the Dual Flex nozzle is identical to a single flexible seal system with a very low spring rate and a pivot point located at the effective pivot point of the Dual Flex system. When a given stroke is programed, the two flexible seals will deflect in a given ratio fixed by their spring rates and the thrust level. Actuator force is low, since the lever arm to the servoseal is large, yet the stroke is also short because of the short lever arm to the effective pivot point. Since actuator power is directly proportional to both force and stroke, the power requirements are drastically reduced. Of course, the potential for any given motor depends on a number of variables, including physical size, total vector angle, and the ratio of thrust to the main flexible seal spring rate.

The operating principle of the Dual Flex TVC system was initially demonstrated by cold flow testing. This test was designed solely to demonstrate the vector angle amplification and its predictability. The low pressure, mass flow rate, and thrust coefficient prohibited power gains of major significance.

The excellent correlation between the theoretical and actual cold flow test results led to the decision to conduct a static firing demonstration. The system was built and successfully tested on May 2, 1971. The test results which are summarized in Table 1, showed excellent agreement with the theory. There were no anomalies or unexplainable results which would raise any question as to the feasibility of extending the concept to large motors with power reduction of 10:1 or greater.

Table 1 Static test demonstration

Design Characteristics	
Motor chamber pressure	1100 psia avg
Motor thrust	2640 lbf avg
Duration	23 sec
Distance between pivot points, d	5.67 in.
Servoseal lever arm, l_s	6.7 in.
Main seal lever arm, l_m	1.0 in.
Actuator stroke	± 0.495 in.

Test Data

Parameter	Dry run	Static test
Maximum total vector angle (deg)	± 4.35	± 6.50
Maximum actuator force (lb)	± 255	± 195
Effective lever arm, l_{eff}(in)	6.52	4.35
Effective spring rates (in.-lb/deg)		
Total system	303	64
Servoseal	342	207
Main seal	415	24

The reduction in power levels resulting from the incorporation of a Dual Flex nozzle can permit a number of different actuation system changes, depending upon the particular design involved. In general, a low-power alternate will provide one or more advantages in weight, cost, simplicity, storability, or checkout capability.

Some of the possible system changes are 1) hydraulic-turbine to electric motor drive, 2) hydraulic-recirculating to blowdown, 3) hydraulic to warm gas, and 4) hydraulic or pneumatic to electromechanical.

Theoretical calculations have shown potential power reductions from single flexible seal systems of greater than 20:1 in some cases, including the first stage space shuttle. In an actual design, however, the maximum potential power savings normally would not be incorporated because of certain other considerations.

These include: 1) Thrust Level Variations—Since the Dual Flex concept employs an angular deflection of the main seal proportional to thrust level, the actuators must be designed to compensate for normal variations from nominal. Recent advances in the understanding of the sensitivity of seal spring rate to chamber pressure could be used to design the main seal with a positive relationship to provide partial compensation, but this also would reduce the nominal power gain.

2) Internal Aerodynamic Torque—Although aerodynamic torque can be treated as another spring, its rate generally changes significantly as the propellant grain burns out.

3) Inertial Torque—As the effective flexible seal torque decreases, the torque required to accelerate or decelerate the nozzle becomes a more significant part of the total.

4) Dynamic Stability—The Dual Flex nozzle may be considered a two degree-of-freedom spring-mass system which, not unlike a single seal system, is inherently oscillatory. The mechanical stiffness and lever arm of the actuator plays an important part in determining the natural frequencies, which must be kept relatively high with respect to the operating frequency range.

The relative effect of these considerations will vary with each specific design, but their combined effect will be to reduce the theoretical power gain. It is not possible to establish a specific upper limit, but design studies and analog simulation show that actual reductions of at least 10:1 from single flexible seal designs are feasible. It is important to note that most of the same considerations apply to any type of low torque nozzle system.

Checkout requirements must also be considered during system design. The main bearing cannot be vectored beyond a small percentage of its travel, but the actuation system can be checked completely by designing the servoseal for a small amount (10–40%) of overtravel.

The Dual Flex thrust vector control system feasibility has been demonstrated, and tradeoff studies have shown significant potential advantages for a number of large motor systems in terms of weight and cost (both development and production). Unlike other low-torque movable nozzle systems, these advantages are available with employment of proven flexible seal technology.

References

[1] Test Report for Dual Flex Thrust Vector Control System and Nozzle Materials Evaluations, TWR-5676, March 1972, Wasatch Div., Thiokol Chemical Corp., Brigham City, Utah.