CHAPTER 16

THRUST VECTOR CONTROL

In addition to providing a propulsive force to a flying vehicle, a rocket propulsion system can provide moments to rotate the flying vehicle and thus provide control of the vehicle's attitude and flight path. By controlling the direction of the thrust vectors through the mechanisms described later in the chapter, it is possible to control a vehicle's pitch, yaw, and roll motions.

All chemical propulsion systems can be provided with one of several types of thrust vector control (TVC) mechanisms. Some of these apply either to solid, hybrid, or to liquid propellant rocket propulsion systems, but most are specific to only one of these propulsion categories. We will describe two types of thrust vector control concept: (1) for an engine or a motor with a single nozzle; and (2) for those that have two or more nozzles.

Thrust vector control is effective only while the propulsion system is operating and creating an exhaust jet. For the flight period, when a rocket propulsion system is not firing and therefore its TVC is inoperative, a separate mechanism needs to be provided to the flying vehicle for achieving control over its attitude or flight path.

Aerodynamic fins (fixed and movable) continue to be very effective for controlling vehicle flight within the earth's atmosphere, and almost all weather rockets, antiaircraft missiles, and air-to-surface missiles use them. Even though aerodynamic control surfaces provide some additional drag, their effectiveness in terms of vehicle weight, turning moment, and actuating power consumption is difficult to surpass with any other flight control method. Vehicle flight control can also be achieved by a separate attitude control propulsion system as described in Sections 4.6, 6.8, and 11.3. Here six or more small liquid propellant thrusters (with a separate feed system and a separate control) provide small moments to the vehicle in flight during, before, or after the operation of the main rocket propulsion system.

The reasons for TVC are: (1) to willfully change a flight path or trajectory (e.g., changing the direction of the flight path of a target-seeking missile); (2) to rotate the vehicle or change its attitude during powered flight; (3) to correct for deviation from the intended trajectory or the attitude during powered flight; or (4) to correct for thrust misalignment of a fixed nozzle in the main propulsion system during its operation, when the main thrust vector misses the vehicle's center of gravity.

Pitch moments are those that raise or lower the nose of a vehicle; *yaw moments* turn the nose sideways; and *roll moments* are applied about the main axis of the flying vehicle (Fig. 16–1). Usually, the thrust vector of the main rocket nozzle is in the direction of the vehicle axis and goes through the vehicle's center of gravity. Thus it is possible to obtain pitch and yaw control moments by the simple deflection of the main rocket thrust vector; however, roll control usually requires the use of two or more rotary vanes or two or more separately hinged propulsion system nozzles. Figure 16–2 explains the pitch moment obtained by a hinged thrust chamber or nozzle. The side force and the pitch moment vary as the sine of the effective angle of thrust vector deflection.

16.1. TVC MECHANISMS WITH A SINGLE NOZZLE

Many different mechanisms have been used successfully. Several are illustrated in Refs. 16–1 and 16–2. They can be classified into four categories:

1. Mechanical deflection of the nozzle or thrust chamber.
2. Insertion of heat-resistant movable bodies into the exhaust jet; these experience aerodynamic forces and cause a deflection of a part of the exhaust gas flow.
3. Injection of fluid into the side of the diverging nozzle section, causing an asymmetrical distortion of the supersonic exhaust flow.

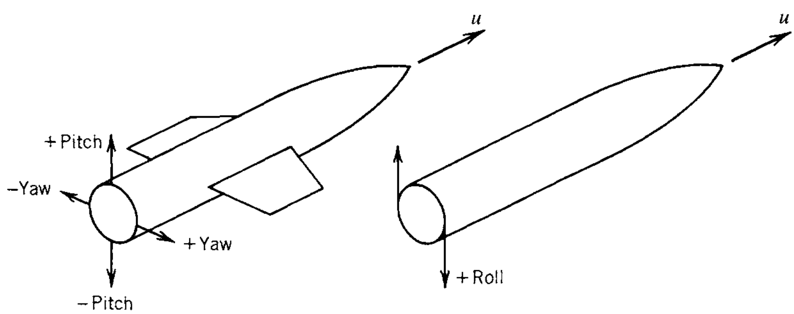


FIGURE 16–1. Moments applied to a flying vehicle.

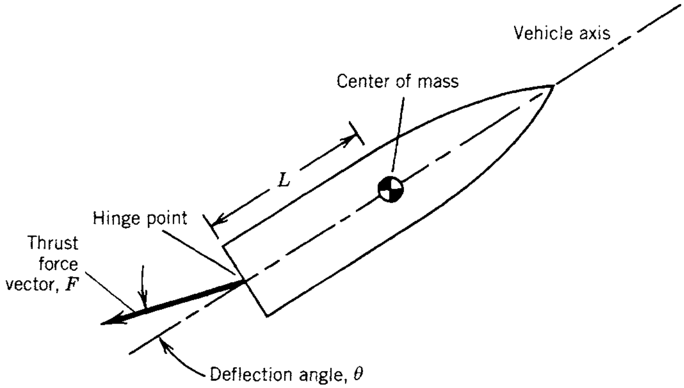


FIGURE 16–2. The pitch moment applied to the vehicle is $FL \sin \theta$.

4. Separate thrust-producing devices that are not part of the main flow through the nozzle.

Each category is described briefly below and in Table 16–1, where the four categories are separated by horizontal lines. Figure 16–3 illustrates several TVC mechanisms. All of the TVC schemes shown here have been used in production vehicles.

In the *hinge* or *gimbal* scheme (a hinge permits rotation about one axis only, whereas a gimbal is essentially a universal joint), the whole engine is pivoted on a bearing and thus the thrust vector is rotated. For small angles this scheme has negligible losses in specific impulse and is used in many vehicles. It requires a flexible set of propellant piping (bellows) to allow the propellant to flow from the tanks of the vehicle to the movable engine. The Space Shuttle (Fig. 1–13) has two gimballed orbit maneuver engines, and three gimballed main engines. Figures 6–1, 6–3, and 8–19 show gimballed engines. Some Soviet launch vehicles use multiple thrusters and hinges (Fig. 10–10 shows 4 hinges), while many U.S. vehicles use gimbals.

Jet vanes are pairs of heat-resistant, aerodynamic wing-shaped surfaces submerged in the exhaust jet of a fixed rocket nozzle. They were first used about 55 years ago. They cause extra drag (2 to 5% less I_s; drag increases with larger vane deflections) and erosion of the vane material. Graphite jet vanes were used in the German V-2 missile in World War II and in the Scud missiles fired by Iraq in 1991. The advantage of having roll control with a single nozzle often outweighs the performance penalties.

Small auxiliary thrust chambers were used in the Thor and early version of Atlas missiles. They provide roll control while the principal rocket engine operates. They are fed from the same feed system as the main rocket engine. This scheme is still used on some Russian booster rocket vehicles.

The *injection of secondary fluid* through the wall of the nozzle into the main gas stream has the effect of forming oblique shocks in the nozzle diverging

TABLE 16–1. Thrust Vector Control Mechanisms

Type	L/S[a]	Advantages	Disadvantages
Gimbal or hinge	L	Simple, proven technology; low torques, low power; ±12° duration limited only by propellant supply; very small thrust loss	Requires flexible piping; high inertia; large actuators for high slew rate
Movable nozzle (flexible bearing)	S	Proven technology; no sliding, moving seals; predictable actuation power; up to ±12°	High actuation forces; high torque at low temperatures; variable actuation force
Movable nozzle (rotary ball with gas seal)	S	Proven technology; no thrust loss if entire nozzle is moved; ±20° possible	Sliding, moving hot gas spherical seal; highly variable actuation power; limited duration; needs continuous load to maintain seal
Jet vanes	L/S	Proven technology; low actuation power; high slew rate; roll control with single nozzle; ±9°	Thrust loss of 0.5 to 3%; erosion of jet vanes; limited duration; extends missile length
Jet tabs	S	Proven technology; high slew rate; low actuation power; compact package	Erosion of tabs; thrust loss, but only when tab is in the jet; limited duration
Jetavator	S	Proven on Polaris missile; low actuation power; can be lightweight	Erosion and thrust loss; induces vehicle base hot gas recirculation; limited duration
Liquid-side injection	S/L	Proven technology; specific impulse of injectant nearly offsets weight penalty; high slew rate; easy to adapt to various motors; can check out before flight; components are reusable; duration limited by liquid supply; ±6°	Toxic liquids are needed for high performance; often difficult packaging for tanks and feed system; sometimes requires excessive maintenance; potential spills and toxic fumes with some propellants; limited to low vector angle applications
Hot-gas-side injection	S/L	Lightweight; low actuation power; high slew rate; low volume/compact; low performance loss	Multiple hot sliding contacts and seals in hot gas valve; hot piping expansion; limited duration; requires special hot gas valves; technology is not yet proven
Hinged auxiliary thrust chambers for high thrust engine	L	Proven technology; feed from main turbopump; low performance loss; compact; low actuation power; no hot moving surfaces; unlimited duration	Additional components and complexity; moments applied to vehicle are small; not used for 15 years in USA
Turbine exhaust gas swivel for large engine	L	Swivel joint is at low pressure; low performance loss; lightweight; proven technology	Limited side forces; moderately hot swivel joint; used for roll control only

[a]L, used with liquid propellant engines; S, used with solid propellant motors.

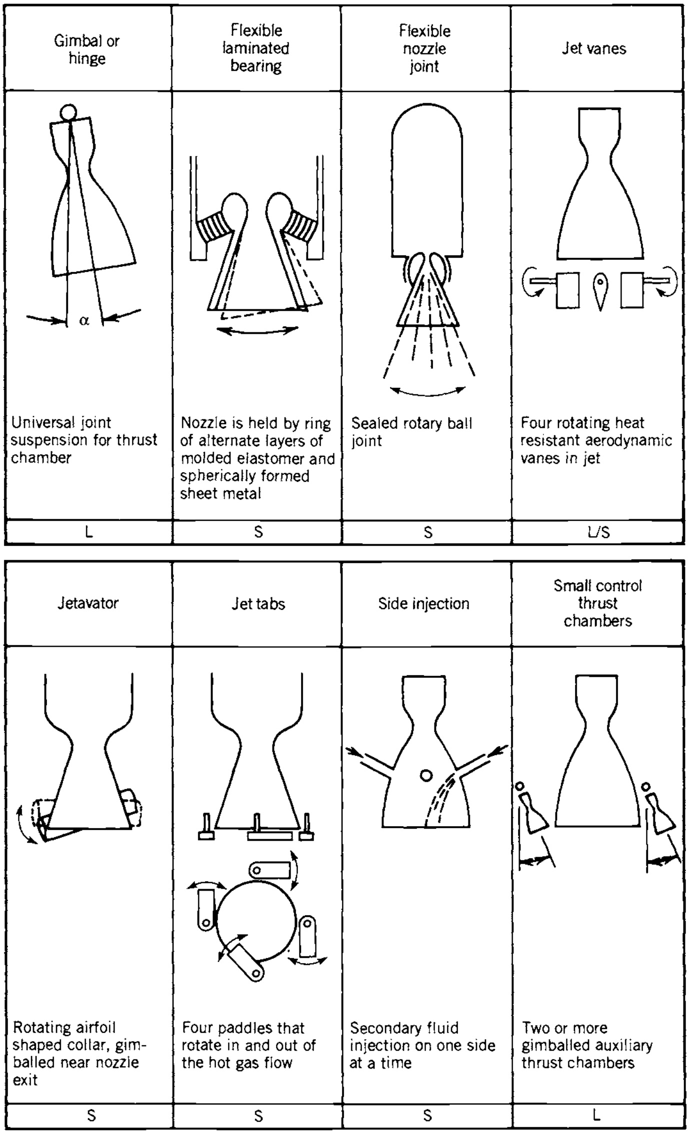


FIGURE 16–3. Simple schematic diagrams of eight different TVC mechanisms. Actuators and structural details are not shown. The letter L means it is used with liquid propellant rocket engines and S means it is used with solid propellant motors.

section, thus causing an unsymmetrical distribution of the main gas flow, which produces a side force. The secondary fluid can be stored liquid or gas from a separate hot gas generator (the gas would then still be sufficiently cool to be piped), a direct bleed from the chamber, or the injection of a catalyzed monopropellant. When the deflections are small, this is a low-loss scheme, but for large moments (large side forces) the amount of secondary fluid becomes excessive. This scheme has found application in a few large solid propellant rockets, such as Titan IIIC and one version of Minuteman.

Of all the mechanical deflection types, the *movable nozzles* are the most efficient. They do not significantly reduce the thrust or the specific impulse and are weight-competitive with the other mechanical types. The flexible nozzle, shown in Figs. 16–3 and 16–4, is a common type of TVC used with solid propellant motors. The molded, multilayer bearing pack acts as a seal, a load transfer bearing, and a viscoelastic flexure. It uses the deformation of a stacked set of doubly curved elastomeric (rubbery) layers between spherical metal sheets to carry the loads and allow an angular deflection of the nozzle axis. The flexible seal nozzle has been used in launch vehicles and large strategic missiles, where the environmental temperature extremes are modest. At low temperature the elastomer becomes stiff and the actuation torques increase substantially, requiring a much larger actuation system. Figure 16–5 describes a different type of flexible nozzle. It uses a movable joint with a toroidal hydraulic bag to transfer loads. There are double seals to prevent leaks of hot gas and various insulators to keep the structure below 200°F or 93°C.

Two of the gimbals will now be described in more detail. Figure 16–6 shows the gimbal bearing assembly of the Space Shuttle main engine. It supports the

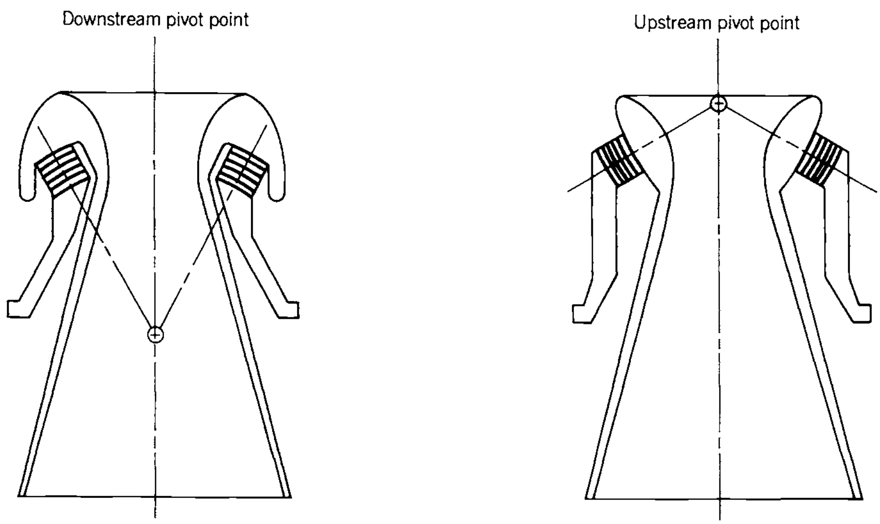
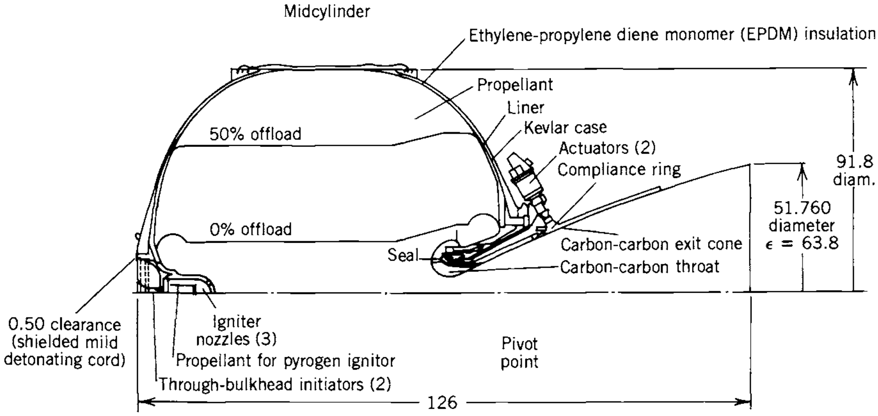


FIGURE 16–4. Two methods of using flexible nozzle bearings with different locations for the center of rotation. The bearing support ring is made of metal or plastic sheet shims formed into rings with spherical contours (white) bonded together by layers of molded elastomer or rubber (black stripes). Although only five elastomeric layers are shown for clarity, many flexible bearings have 10 to 20 layers. (Copied with permission from Ref. 16–1.)



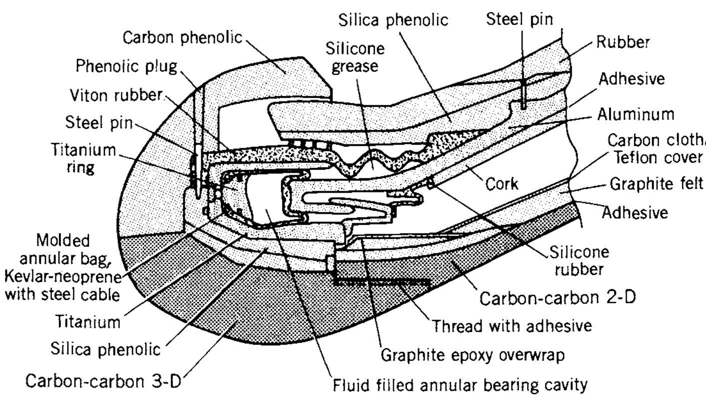


FIGURE 16–5. Simplified cross section of an upper-stage solid propellant rocket motor (IUS) using an insulated carbon-fiber/carbon-matrix nozzle, an insulated Kevlar filament-wound case, a pyrogen igniter, forward and aft stress-relieving boots, a fluid-filled bearing, and an elastomeric seal assembly in the nozzle to allow $4\frac{1}{2}^\circ$ of thrust vector deflection. This motor has a loaded weight of 22,874 lbf, a propellant with hydroxyl-terminated polybutadiene binder, a weight of 21,400 lbf, a burnout weight of 1360 lbf, a motor mass fraction of 0.941, a nozzle throat diameter of 6.48 in., and a nozzle exit area ratio of 63.8. The motor burns 146 sec at an average pressure of 651 psi (886 psi maximum) and an average thrust of 44,000 lbf (60,200 lbf maximum), with an effective altitude specific impulse of 295 sec. Top drawing is cross section of motor; bottom drawing is enlarged cross section of nozzle package assembly. The motor is an enlarged version of Orbus-6 described in Fig. 11–3. (From C. A. Chase, "IUS Solid Motor Overview," *JANNAF Conference*, Monterey, Calif, 1983; courtesy of United Technologies Corp./Chemical Systems.)

weight of the engine and transmits the thrust force. It is a ball-and-socket universal joint with contact and intermeshing spherical (concave and convex) surfaces. Sliding occurs on these surfaces as the gimbal assembly is rotated. When assembling the engine to the vehicle, some offset bushings are used to align the thrust vector. Some of the design features and performance requirements of this gimbal are listed in Table 16–2. The maximum angular motion is actually larger than the deflection angle during operation so as to allow for various tolerances and alignments. The actual deflections, alignment tolerances, friction coefficients, angular speeds, and accelerations during operation are usually much smaller than the maximum values listed in the table.

Table 16–3 and Ref. 16–3 give the design requirements for the actuator system for the TVC for a flexible bearing in the IUS solid rocket motor nozzle. This system is shown in Figs. 11–3 and 16–5 and in Table 11–3. One version of this nozzle can deflect 4° maximum plus 0.5° for margin and another is rated at 7.5°. It has two electrically redundant electromechanical actuators using ball screws, two potentiometers for position indication, and one controller that provides both the power drive and the signal control electronics for each actuator. A variable-frequency, pulse-width-modulated (PWM) electric motor drive is used to allow small size and low weight for the power and forces

TABLE 16–2. Characteristics and Performance Requirements of the Gimbal Bearing Assembly of the Space Shuttle Main Engine

Engine weight to be supported (lbf)	Approx. 7000
Thrust to be transmitted, (lbf)	512,000
Gimbal asembly weight (lbf)	105
Material is titanium alloy	6Al-6V-2Sn
Dimensions (approximate) (in.)	11 dia. × 14
Angular motion (deg)	
Operational requirement (max.)	±10.5
Snubbing allowance in actuators	0.5
Angular alignment	0.5
Gimbal attach point tolerance	0.7
Overtravel vector adjustment	0.1
Maximum angular capability	±12.5
Angular acceleration (max.) (rad/sec^2)	30
Angular velocity (max.) (deg/sec)	20
Angular velocity (min.) (deg/sec)	10
Lateral adjustment (in.)	±0.25
Gimbal duty cycle about each axis	
Number of operational cycles to 10.5°	200
Nonoperational cycles to 10.5°	1400
Coefficient of friction (over a temperature range of 88 to 340 K)	0.01–0.2

Source: Courtesy of Rocketdyne, a Division of Rockwell International.

TABLE 16–3. Design Requirements for TVC Actuation System of an IUS Solid Rocket Motor

Item	Requirement
Performance parameter	
Input power	31 A/axis maximum at 24 to 32 V dc; >900 W (peak)
Stroke	10.2 cm (4.140 in.) minimum
Stall force	1.9 kN (430 lbf) minimum
Accuracy	±1.6 mm (±0.063 in.) maximum
Frequency response	>3.2 Hz at 100° phase lag
No load speed	8.13 cm/sec (3.2 in./sec) minimum
Stiffness	28.9 kN/cm (16,600 lbf/in.) minimum
Backlash	±0.18 mm (0.007 in.) maximum
Reliability	>0.99988 redundant drive train, >0.999972 single thread element
Weight	
Controller	5.9 kg (13 lbf) maximum, each
Actuator	7.04 kg (15.5 lbf) maximum, each
Potentiometer	1.23 kg (2.7 lbf) maximum, each
System	22.44 kg (49.4 lbf) maximum

Source: Reproduced from Ref. 16–3 with permission of United Technologies Corp./Chemical Systems.

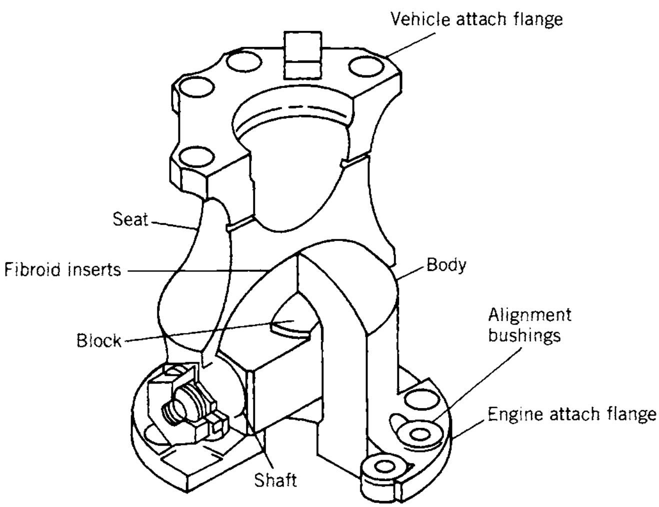


FIGURE 16–6. Gimbal bearing of the Space Shuttle main engine. (Courtesy of the Boeing Company, Rocketdyne Propulsion & Power.)

involved. Also, it has a pair of locking mechanisms that will lock the nozzle in a fixed pitch-and-yaw position as a fail-safe device.

The *alignment* of the thrust vector is a necessary activity during assembly. The thrust vector in the neutral position (no deflection or, in many vehicles, the thrust axis coincides with the vehicle axis) should usually go through the center of gravity of the vehicle. The TVC mechanism has to allow for alignment or adjustments in angle as well as position of the TVC center point with the intended vehicle axis. The geometric centerline of the diverging section of the nozzle is generally considered to be the thrust direction. One alignment provision is shown in Fig. 16–6. An alignment accuracy of one-quarter of a degree and an axis offset of 0.020 in. have been achieved with good measuring fixtures for small-sized nozzles.

The *jet tab TVC system* has low torque, and is simple for flight vehicles with low-area-ratio nozzles. Its thrust loss is high when tabs are rotated at full angle into the jet, but is zero when the tabs are in their neutral position outside of the jet. On most flights the time-averaged position of the tab is a very small angle and the average thrust loss is small. Jet tabs can form a very compact mechanism and have been used successfully on tactical missiles. An example is the jet tab assembly for the booster rocket motor of the Tomahawk cruise missile, shown in Fig. 16–7. Four tabs, independently actuated, are rotated in and out of the motor's exhaust jet during the 15 sec duration of rocket operation. A tab that blocks 16% of the nozzle exit area is equivalent to a thrust vector angle deflection of 9°. The maximum angle is 12° and the slew rate is fast (100°/sec). The vanes are driven by four linear small push–pull hydraulic actuators with two servo valves and an automatic integral controller. The power is supplied by compressed nitrogen stored at 3000 psi. An explosive valve releases the gas to pressurize an oil accumulator in a blowdown mode. The vanes are made of tungsten to minimize the erosion from the solid particles in the exhaust gas.

The *jetavator* was used on submarine-launched missiles. The thrust loss is roughly proportional to the vector angle. This mechanism is shown in Fig. 16–3 and mentioned in Table 16–1.

The concept of TVC by *secondary fluid injection* into the exhaust stream dates back to 1949 and can be credited to A. E. Wetherbee, Jr. (U.S. Patent 2,943,821). Application of *liquid injection thrust vector control* (LITVC) to production vehicles began in the early 1960s. Both inert (water) and reactive fluids (such as hydrazine or nitrogen tetroxide) have been used. Although side injection of reactive liquids is still used on some of the older vehicles, it requires a pressurized propellant tank and a feed system. A high-density injection liquid is preferred because its tank will be relatively small and its pressurization will require less mass. Because other schemes have better preformance, liquid injection TVC will probably not be selected for new applications.

Hot gas injection (HGITVC) of solid rocket propellant or liquid propellant combustion products is inherently attractive from a performance and packaging viewpoint. In the past there has not been a production application of HGITVC because of erosion of materials in hot gas valves. However, two

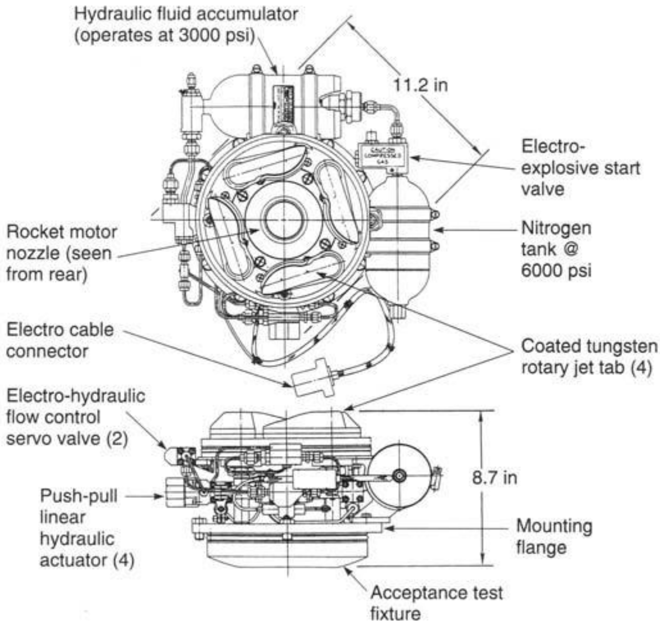


FIGURE 16–7. Two views of the jet tab assembly, packaged in a doughnut shape volume around the nozzle of the Tomahawk cruise missile's solid propellant booster rocket motor. Hydraulic actuators rotate the tabs in and out of the nozzle exhaust jet and are located just beyond the nozzle exit. (Courtesy of Space and Electronics Group, TRW, Inc.)

factors now make hot-gas-side injection feasible: first, hot gas valves can be made with the newer carbon–carbon structural parts and modern insulators. A hot gas system with a limited duration hot gas carbon valve is described in Ref. 16-4. Also, advances in metallurgy have made possible the development of hot valves made of rhenium alloy, a high-temperature metal suitable for hot gas valve applications. The second factor is the development of solid propellants that are less aggressive (less AP, Al_2O_3, and/or fewer oxidizing gas ingredients) and reduce the erosion in nozzles and valves; this helps the hot gas valves and insulated hot gas plumbing to better survive for limited durations but often at the expense of propulsion system performance. Experimental hot gas systems have had difficulties with thermal distortions and in keeping key components cool enough to prevent failure.

With either liquid or solid propellants, the hot gas can be bled off the main combustion chamber or generated in a separate gas generator. The hot gas valves can be used to (1) control side injection of hot gas into a large nozzle, or (2) control a pulsing flow through a series of small fixed nozzles similar to small attitude control thrusters described in Chapters 4, 6, and 11. In liquid propellant engines it is feasible to tap or withdraw gas from the thrust chamber at a location where there is an intentional fuel-rich mixture ratio; the gas temperature would then be low enough (about 1100°C or 2000°F) so that uncooled metal hardware can be used for HGITVC valves and piping.

The total side force resulting from secondary injection of a fluid into the main stream of the supersonic nozzle can be expressed as two force components: (1) the force associated with the momentum of the injectant; and (2) the pressure unbalance acting over areas of the internal nozzle wall. The second term results from the unbalanced wall pressures within the nozzle caused by shock formation, boundary layer separation, difference between injectant and undisturbed nozzle stream pressures, and primary–secondary combustion reactions (for chemically active injectants). The strength of the shock pattern and the pressure unbalance created between opposite walls in the nozzle is dependent on many variables, including the properties of the injectant and whether it is liquid or gas. In the case of injecting a reactive fluid, the combustion occurring downstream of the injection port(s) usually produces a larger pressure unbalance effect than is obtained by liquid vaporization only. However, benefit from combustion is dependent on a chemical reaction rate high enough to keep the reaction zone close to the injection port. The TVC performance that is typical of inert and reactive liquids and hot gas (solid propellant combustion products) is indicated in Fig. 16–8. This plot of force ratios to mass flow ratios is a parametric representation commonly used in performance comparisons.

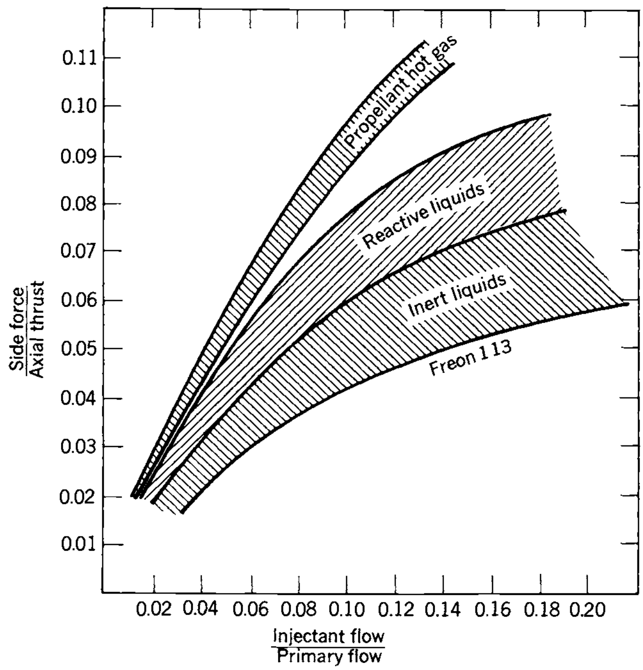


FIGURE 16–8. Typical performance regions of various side injectants in TVC nozzles.

16.2. TVC WITH MULTIPLE THRUST CHAMBERS OR NOZZLES

All the various concepts shown in Fig. 16–3 can provide pitch and yaw moments to a vehicle. Roll control can be obtained only if there are at least two separate vectorable nozzles, four fixed pulsing or throttled flow nozzles, or two jet vanes submerged in the exhaust gas from a single nozzle.

Several concepts have been developed and flown that use two or more rocket engines or a single engine or motor with two or more actuated nozzles. Two fully gimballed thrust chambers or motor nozzles can provide roll control with very slight differential angular deflections. For pitch and yaw control, the deflection would be larger, be of the same angle and direction for both nozzles, and the deflection magnitude would be the same for both nozzles. This can also be achieved with four hinged (see Figure 10–10) or gimballed nozzles. Figure 16–9 shows the rocket motor of an early version of the Minuteman missile booster (first stage) with four movable nozzles. This motor is described in Table 11–3.

The differential throttling concept shown in Fig. 16–10 has no gimbal and does not use any of the methods used with single nozzles as described in Fig. 16–3. It has four fixed thrust chambers and their axes are almost parallel to and set off from the vehicle's centerline. Two of the four thrust chambers are

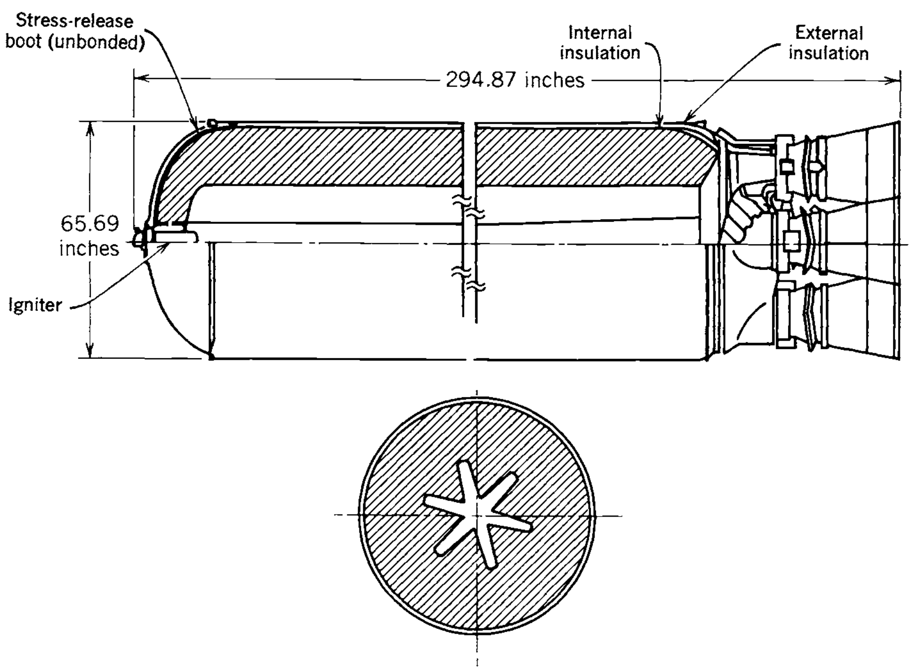


FIGURE 16–9. Simplified view of an early version of the first-stage Minuteman missile motor using composite-type propellant bonded to the motor case. Four movable nozzles provide pitch, yaw, and roll control. (Source: U.S. Air Force.)

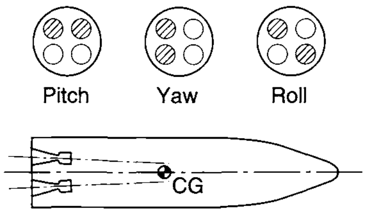


FIGURE 16–10. Differential throttling with four fixed-position thrust chambers can provide flight maneuvers. In this simple diagram the shaded nozzle exits indicate a throttled condition or reduced thrust. The larger forces from the unthrottled engines impose turning moments on the vehicle. For roll control the nozzles are slightly inclined and their individual thrust vectors do not go through the center of gravity of the vehicle.

selectively throttled (typically the thrust is reduced by only 2 to 15%). The four nozzles may be supplied from the same feed system or they may belong to four separate but identical rocket engines. This differential throttling system is used on the Aerospike rocket engine described in Chapters 3 and 8 and on a Russian launch vehicle.

16.3. TESTING

Testing of thrust vector control systems often includes actuation of the system when assembled on the propulsion system and the vehicle. For example, the Space Shuttle main engine can be put through some gimbal motions (without rocket firing) prior to a flight. A typical acceptance test series of the TVC system (prior to the delivery to an engine manufacturer) may include the determination of input power, accuracy of deflected positions, angular speeds or accelerations, signal response characteristics, or validation of overtravel stops. The ability to operate under extreme thermal environment, operation under various vehicle or propulsion system generated vibrations, temperature cycling, and ignition shock (high momentary acceleration) would probably be a part of the qualification tests.

Side forces and roll torques are usually relatively small compared to the main thrust and the pitch or yaw torques. Their accurate static test measurement can be difficult, particularly at low vector angles. Elaborate, multicomponent test stands employing multiple load cells and isolation flextures are needed to assure valid measurements.

16.4. INTEGRATION WITH VEHICLE

The actuations or movements of the TVC system are directed by the vehicle's guidance and control system (see Ref. 16–5). This system measures the three-dimensional position, velocity vectors, and rotational rates of the vehicle and compares them with the desired position, velocity, and rates. The error signals between these two sets of parameters are transformed by computers in TVC controllers into control commands for actuating the TVC system until the error signals are reduced to zero. The vehicle's computer control system determines the timing of the actuation, the direction, and magnitude of the deflection. With servomechanisms, power supplies, monitoring/failure detection devices, actuators with their controllers, and kinetic compensation, the systems tend to become complex.

The criteria governing the selection and design of a TVC system stem from vehicle needs and include the steering-force moments, force rates of change, flight accelerations, duration, performance losses, dimensional and weight limitations, available vehicle power, reliability, delivery schedules, and cost. For the TVC designer these translate into such factors as duty cycle, deflection angle, angle slew rate, power requirement, kinematic position errors, and many vehicle–TVC and motor–TVC interface details, besides the program aspects of costs and delivery schedules.

Interface details include electrical connections to and from the vehicle flight controller, the power supply, mechanical attachment with fasteners for actuators, and sensors to measure the position of the thrust axis or the actuators. Design features to facilitate the testing of the TVC system, easy access for checkout or repair, or to facilitate resistance to a high-vibration environment, are usually included. The TVC subsystem is usually physically connected to the vehicle and mounted to the rocket's nozzle. The designs of these components must be coordinated and integrated. Nozzle–TVC interfaces are discussed in Refs. 6–1 (TVC of liquid rocket engines and their control architecture) and 16–5.

The actuators can be hydraulic, pneumatic, or electromechemical (lead screw), and usually include a position sensor to allow feedback to the controller. The proven power supplies include high-pressure cold stored gas, batteries, warm gas from a gas generator, hydraulic fluid pressurized by cold gas or a warm gas generator, electric or hydraulic power from the vehicle's power supply, and electric or hydraulic power from a separate turbogenerator (in turn driven by a gas generator). The last type is used for relatively long-duration high-power applications, such as the power package used in the Space Shuttle solid rocket booster TVC, explained in Ref. 16–6. The selection of the actuation scheme and its power supply depends on the minimum weight, minimum performance loss, simple controls, ruggedness, reliability, ease of integration, linearity between actuating force and vehicle moments, cost, and other factors. The required frequency response is higher if the vehicle is small, such as with small tactical missiles. The response listed in Table 16–3 is more typical of larger spacecraft applications. Sometimes the TVC system is integrated with a movable aerodynamic fin system, as shown in Ref. 16–7.

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