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Thrust Vector Control for (Clustered Modules) Plug Nozzles: Some Considerations

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Thrust vector control (TVC) techniques for plug nozzles, such as canting and displacing the central plug, fluid injection, differential throttling, and use of flaps, are reviewed. Some methods, such as displacing the central plug, may only be of academic interest or useful for small motors. Although emphasis is on annular plug nozzles, reference is made to linear plug nozzles. The analyses are based on limited experimental data and engineering calculations. The results are intended for a first assessment and ranking of TVC methods for plug nozzles. They are based on a reference annular plug nozzle rocket engine with a thrust in the order of 1 MN and a launcher diameter of about 5 m, as may be found on modern launchers, e.g., the Ariane 5 cryogenic first stage. When a particular TVC method is used, the effectiveness may depend on the longitudinal position of the center of mass of the launcher. Therefore, either the TVC is given in terms of the thrust deflection angle or in terms of the moment that may be generated. Only if flaps are used, it is possible to generate roll moments with a single annular plug nozzle.

Nomenclature

a = velocity of sound
c = coefficient
F = thrust
I = impulse
i = local inclination of the plug surface
l = distance
M = Mach number
Mo = moment
m = mass flow rate over flap
Q = mass flow rate main flow
q = mass flow rate fluid injection
R = radius
r = (inner) radius
T = torque
V = velocity
α = plug inclination angle
β = shock angle
γ = ratio of specific heats
δ = thrust vector angle
θ = position angle, flap angle
ϕ = flap rotation angle

Subscripts

c = combustion chamber
e = exit conditions
f = thrust
lat = lateral
max = maximum
sp = specific
t = throat
1 = incoming flow
2 = flow behind shock

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I. Introduction

THRUST vector control on classical rocket motors is usually achieved by swiveling the nozzle. Liquid rocket engines, therefore, are gimbal mounted, and the whole engine is swiveled. Solid rocket motors have nozzles with a flexible joint in the throat region. For plug nozzles such methods are less attractive. Large plug nozzles have a diameter close to the launcher diameter, which makes swiveling and the use of a flexible joint difficult. As classical liquid engines have rather small diameters compared to the launcher diameter, the concentrated thrust is introduced into the launcher structure via a gimbal mechanism and a heavy thrust frame. The latter ensures that the thrust is evenly distributed into the launcher structure. By its nature, the plug nozzle already introduces the thrust in a distributed way into the launcher structure, so that the heavy thrust frame may be eliminated or at least may be reduced drastically in mass.[1,2] This then calls for different methods to generate thrust vector control (TVC).

Over the years a number of TVC methods have been developed for solid and liquid rocket motors; some might also be applicable to plug nozzles, e.g., TVC by fluid injection. Also by using flaps, the thrust vector may be deflected.

Another method is by differential throttling. If one has separate small combustion chambers, each provided with a small bell nozzle (or, even better, a small nozzle adapted to the ring segment) exhausting on a common plug, TVC may be achieved by individually throttling these combustion chambers.[1]

For these TVC methods, a first assessment of the magnitude of the side force or moment that may be generated is given in this paper. The assessment is based on available experimental data (fluid injection) and idealized nominal plug nozzle flow. Only a thorough analysis of each method, supported by experimental data, will provide more precise data. Most of the required experimental data are not readily available. The paper is intended as a guideline to assess which TVC method for plug nozzles may be most suitable for a particular application. Emphasis is on annular plug nozzles.

TVC implies the generation of pitch, yaw, and roll moments. However, not all methods allow the generation of all of these three moments for a single annular plug nozzle. Linear plug nozzles are better in this respect.[1]

II. TVC Methods for Plug Nozzles

A. General Considerations

TVC is required for two purposes: to activate the steering program of a launcher to ensure it follows its required trajectory and to correct for disturbances caused, e.g., by wind, thrust misalignment, separation of boosters, etc. In general one needs to generate pitch, yaw, and roll moments.

Classical liquid rocket motors use swiveling nozzles, where the whole motor is canted, whereas solid rocket motors have a nozzle with a flexible joint. This provides pitch and yaw control, but in case of a single engine, roll control is not possible. Multiple engines, as found on Ariane 4, Atlas booster stage, Titan, or Soyuz also allow for roll control.

As the annular plug nozzle introduces the thrust circumferentially, the heavy thrust frame used on gimbaled classical engines may be eliminated, saving an appreciable mass. For a 1-MN engine, this thrust frame has a mass in the order of 1500 kg. Although the plug nozzle is usually heavier than a classical bell nozzle, the mass savings by eliminating the thrust frame may nevertheless be in the order of 900 kg[2], whereas the knock-on effects on the gross liftoff weight of the vehicle are not negligible.[1]

B. Thrust Vector Control for Plug Nozzles

1. Canting of the Plug

For an annular or linear plug nozzle (with an annular-slit throat), pitch and yaw moments might be achieved (theoretically) by canting or displacing the plug. If the plug is canted over an angle α, the thrust vector will also be canted. As only the external expansion part of the thrust is deflected, the lateral thrust, which actually generates the pitch or yaw moments is $\boldsymbol{F}_{\text{lat}} = \boldsymbol{F}\{1 - c_{f_t}/c_f\}\sin\alpha$, where c_{f_t} is the thrust coefficient, which is obtained if the nozzle were cut off at the throat. For ratios of specific heat ranging from $\gamma = 1.15$ to 1.25, c_{f_t} ranges from ~ 1.23 to ~ 1.25, and the ratio $c_{f_t}/c_{f\max}$ ranges from 0.5 to 0.6.

The moment ***Mo*** exerted on the launcher depends on the position of the center of mass and follows from

$$\boldsymbol{Mo} = \boldsymbol{F}_{\text{lat}} \times \boldsymbol{l} \tag{1}$$

where $\boldsymbol{l}$ is the distance of the center of mass to the application point of the thrust (see Fig. 1). The thrust deflection angle δ follows from

$$\delta = A\sin\left\{\left(1 - c_{f_t}/c_f\right)\sin\alpha\right\} \tag{2}$$

Therefore, the moment also depends on the position of the center of mass, which varies during the flight. For large values of c_f, the reduction factor $(1 - c_{f_t}/c_f)$ may range between 0.4 and 0.5 depending on the ratio of specific heats γ. For small values of α, the deflection angle $\delta \approx (1 - c_{f_t}/c_f)\cdot\alpha$.

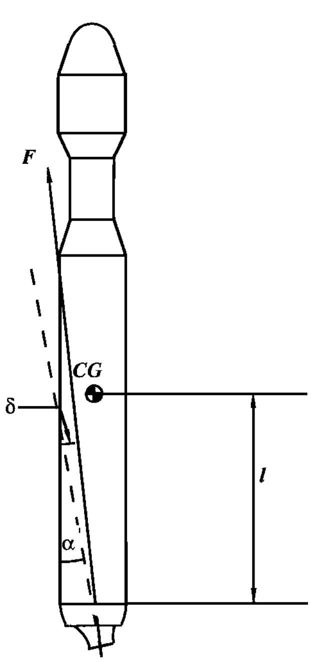

Fig. 1 TVC by canting the plug.

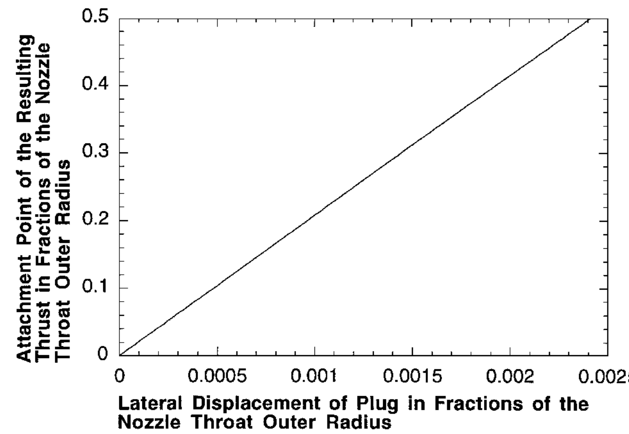

Fig. 2 Effectiveness of TVC by displacing the plug.

Erickson[1] concluded that, for a specific linear plug nozzle, swiveling the plug would lead to a heavier solution than differential throttling. The center of mass not having a fixed position affects all TVC methods where TVC is achieved by directly deflecting the thrust.

2. Displacement of the Plug

TVC may also be effected by displacing the plug with respect to the centerline of the nozzle. With an inner throat radius r and outer throat radius R, the central plug may at maximum be displaced over a distance $R - r$. As an example, a case is taken of a large booster with a plug nozzle with $R = 5$ m. The throat width of such an annular nozzle is small, ~ 6 mm. Therefore, the plug may be displaced laterally at maximum over 6 mm, thereby reducing the thrust on one side and increasing the thrust at the opposite side. For a first approximation, the application point of the thrust may be estimated by assuming that the thrust will remain uniformely distributed. Figure 2 shows that (for these small displacements) the moment arm increases about linearly with the displacement of the central plug. At maximum, a moment arm of about half the throat outer radius can be achieved, leading to a moment ***Mo***

$$\boldsymbol{Mo} \sim \tfrac{1}{2}\cdot\boldsymbol{F}\times\boldsymbol{R} \tag{3}$$

Note that here the moment is independent of the position of the center of mass of the launcher. In practice, pure annular plug nozzles cannot be used on large engines for two reasons: First, the throat width becomes very small,[2] usually less than 6 mm, even for large booster engines. This requires very precise manufacturing on diameters of 4–5 m for large engines. Second, heat transfer loads become prohibitive.[2] Therefore, laterally displacing the plug is only possible for small engines, where heat transfer is limited and diameters remain manageable. Note, however, that its effectiveness is independent of the position of the center of mass. For solid boosters, there is the additional difficulty that mechanisms to move or cant the plug are exposed to the hot combustion gases or interfere with the exhaust. The method cannot be regarded as practicable in most cases, but is useful to illustrate some basic limitations and possibilities for TVC on annular plug nozzles.

The method may be feasible on linear plug nozzles as foreseen on the X-33. Also swiveling of the plug might be employed there.[1] By inclining sections of the linear plug, roll moments may be generated.

Because of heat loads in the throat and manufacturing problems for large diameter nozzles, clustered module plug nozzles have been proposed[1,3] for larger engines. The initial expansion takes place in small internal expansion nozzles, while the remainder of the expansion occurs on the plug. The following sections will be limited to TVC for clustered modules plug nozzles.

3. Fluid Injection

Fluid injection is an effective way of TVC and has been used on the Titan launcher. By the injecting of a fluid at high speed into the nozzle flow, a shock is generated behind which the pressure field has changed, which generates an asymmetric pressure distribution in the nozzle. One may use inert fluids (cold or hot) or reactive fluids. If fluid injection is used, there are two effects: change of the thrust angle and change of specific impulse. The specific impulse, based on the engine main mass flow rate, usually increases slightly. The TVC effectiveness depends on the mass flow rate of the injected fluids and the fluids themselves and is measured by the thrust deflection angle δ. Theoretical predictions are not very accurate, and experimental validation is required. Figure 3 shows the theoretical predicted thrust deflection angle δ for hot gas injection and for a reactive fluid injection N_2O_4 and also some experimental results.

The theoretical predictions tend to overestimate the generated deflection angle for fluid injection, although hot gas injection is more effective than injecting a reactive fluid. The effectiveness of fluid injection (in decreasing order) is roughly as follows[3]: hot gas injection (inert, with $T_{gas} > 2500$ K), liquid oxygen injection, hot gas injection (inert, with $T_{gas} \sim 1500$ K), gaseous hydrogen injection, N_2O_4 injection, gaseous oxygen injection, and liquid hydrogen injection. Hot gas injection, which is tapped off from the main combustion

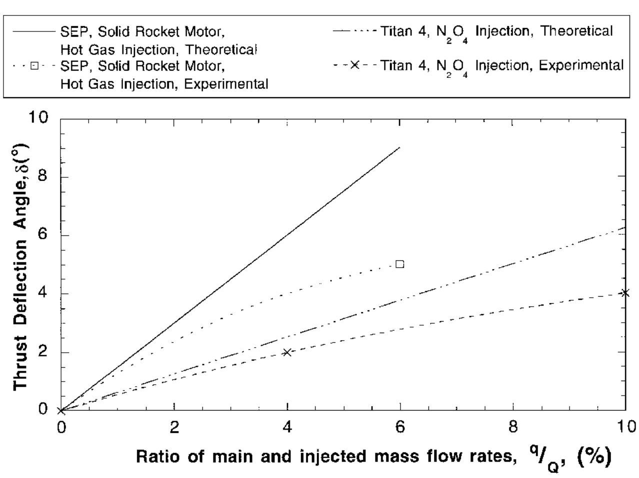

Fig. 3 Effectiveness of TVC by fluid injection.[4]

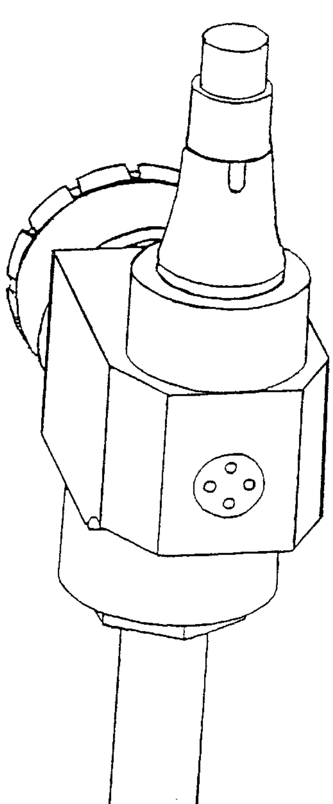

Fig. 4 SEP hot gas valve mounted on a nozzle.[4]

chamber, gas generator, or turbine exhaust, has the advantage that no separate storage for the injection system is required; it requires a valve that can handle the hot gases. The Société Européenne de Propulsion (SEP),[4] in France, has developed a prototype of such a valve in carbon–carbon and carbon/SiC material, which was tested on one of their solid motors see Fig. 4.

To estimate the effectiveness of fluid injection to generate a side force, a 1-MN engine with a mass flow rate $Q \sim 230$ kg/s is considered. According to Fig. 3, by the using of hot gas, a fluid injection mass flow rate $q \sim 0.06 \times 230 = 13.8$ kg/s is required to generate a thrust deflection angle $\delta = 5$ deg. This would require an injection orifice with a diameter of ~ 53 mm in a single nozzle with a sonic throat. Of course, the required deflection can never be accomplished in one single nozzle, and the injection has to be distributed over several nozzles. Using N_2O_4 yields a smaller deflection angle $\delta = 4$ deg and requires 23 kg/s of N_2O_4. As the density of N_2O_4 is much higher than that of hot gas, an orifice of ~ 14 mm suffices (injection pressure drop 6 MPa, injection pressure 1 MPa).

Normally, an annular plug nozzle has a number of nozzles exhausting on a central (truncated) plug. If 40 small nozzles are used for the initial expansion, expanding to $M = 2$, i.e., $p_c/p_e \sim 7.5$, the exit diameter of the individual nozzles would be 48 mm, clearly not allowing for a single injection orifice of ~ 50 mm. On the other hand, a 14-mm orifice, using N_2O_4, is possible in one primary nozzle. However, one single small nozzle would never generate the required deflection angle, whereas in that nozzle also the ratio of injected and main flow would not be in accordance with Fig. 3. Hence, hot gas injection has to be distributed over a number of nozzles. To generate thrust deflection, fluid injection will take place in half the number of nozzles. In that case each nozzle would require an orifice of ~ 12 mm. As the lateral part of the thrust vector of each individual nozzle is inclined with respect to the TVC direction, the effectiveness decreases,

$$F_{\text{side,effective}} = F_{\text{side}} \cdot \sum_{n=1}^{10} 2 \cdot \cos\frac{n \cdot 9 - 4.5}{20} = 0.6373 \cdot F_{\text{side}} \quad (4)$$

which follows from geometrical considerations. The initial deflection angle $\delta = 5$ deg has now decreased to $\delta = 3.2$ deg. The same applies when injecting N_2O_4. The injection orifices in the individual nozzles reduce to diameters of ~ 3.1 mm, and the deflection angle δ reduces from 4 to 2.7 deg. A severe disadvantage of using fluid injection is that each nozzle has to be equipped with a (hot gas) valve to ensure short response times. Four centrally located (hot gas) valves with ~ 2.5 m feed lines leading to the individual nozzles would probably lead to unacceptably long response times.

The second option is to use (hot gas) injection on the truncated plug itself. There are no hard data available at present about the effectiveness of TVC by injecting directly on the plug. Assuming it to be similar to conventional nozzles, the orifice size would not pose a problem. A 20% length truncated plug, for a 1-MN engine, would have a diameter of 4.98 m matching the primary nozzles and a diameter of 2.96 m at its truncated base. The length would be ~ 2.9 m. Within the plug, only four hot gas valves would have to be installed, each connected to a slit covering one-quarter of the circumference of the plug. Therefore, if TVC by hot gas injection is to be performed on the plug, four slits, each with a surface area of ~ 2000 mm^2, would suffice. If this slit is located at a diameter of 4 m, its width would only be 0.64 mm. If N_2O_4 is used, the slit width becomes even smaller.

The preceding example highlights some interesting aspects.

1) The use of hot gas is most attractive, especially as hot gas valves have been developed. However, the sizes of the required orifices are relatively large for use in the primary nozzles, and also every nozzle would have to be equipped with a (hot gas) valve.

2) For fluid injection in the primary nozzles, the use of a reactive liquid like N_2O_4 seems most attractive.

3) Injection on the plug itself appears to be the best solution.

For an annular plug nozzle, pitch and yaw control may be effected in this way. For linear plug nozzles, as used, for instance on the X-33, because of the width of the base (~ 6 m), yaw control will be effective. Pitch control would be somewhat less effective because the height of the base is ~3 m. Roll control, in principle, is possible by injecting fluid on one side at the upper part and at the other side at the lower part of the plug.

4. TVC by Differential Throttling

a. Introduction. Rocket motors operate at high pressure for two reasons.

1) High chamber pressures allow large expansion ratios at sea level in conventional bell nozzles, without the danger of flow separation and performance loss and side forces. This is the main reason for high-pressure engines on the (lower) stages of launch vehicles.

2) The specific impulse (or characteristic velocity) is somewhat higher than at low pressures and the same expansion ratio. The effect of increasing the chamber pressure is felt strongest at pressures below 5–10 MPa.

A plug nozzle reduces this need for high chamber pressure. Because the plug nozzle flow adjusts itself to ambient pressures, the plug nozzle can have a high expansion ratio with less danger of flow separation and thrust loss at lower altitudes. A plug nozzle with a cluster of small nozzles experiences a large total heat transfer from the nozzles and from the plug surface. This high heat transfer may be used effectively to drive turbopumps. Therefore, the clustered modules plug nozzle is particularly attractive in conjunction with an expander cycle. Studies[2,5] have demonstrated that an expander cycle in conjunction with a plug nozzle operating at chamber pressures up to or even exceeding 15 MPa is feasible. Its performance would not be much lower than that of a staged combustion cycle engine with a classical bell nozzle operating at 20 MPa chamber pressure. Higher chamber pressures in conjunction with a plug nozzle bring little performance gains.

b. Differential throttling. TVC may be achieved by reducing the pressure in one-half of the set of primary nozzles and increasing the pressure in the other half.[1] The thrust of one nozzle is about proportional to the nozzle stagnation pressure. To increase the pressure in one-half of the set of nozzles, separate booster pumps are required; this may not be cost or weight effective; also response times may become too long. Another option is to use throttling valves.[1] However, if an expander cycle engine operates at 10-MPa chamber pressure, it is possible to boost the stagnation pressure in one-half of the set of primary combustion chambers to 15 MPa, while reducing the pressure in the other half to 5 MPa (Refs. 2 and 5).

The resulting moment is estimated by the contributions of the individual nozzles. Assuming again 40 clustered bell nozzles exhausting on a central plug, where only on one side the individual thrust of each bell nozzle has been reduced to 50% of its nominal value, yields a moment

$$\boldsymbol{Mo} = 2 \cdot \frac{0.5 \cdot \boldsymbol{F}}{40} \times \sum_{n=1}^{10} \boldsymbol{R} \cdot \cos(n \cdot 9 - 4.5) = 0.16 \cdot \boldsymbol{F} \times \boldsymbol{R} \quad (5)$$

For a 1-MN engine, with an outer diameter of 5 m, the resulting moment is 0.4 MNm. If the thrust on the left-hand side were to be increased by 50%, the resulting moment doubles to 0.8 MNm. These are appreciable control moments. Simulation studies[4] showed that for normal (atmospheric) disturbances the generated moments and response times are sufficient. Stage separation requires larger correction moments. Erickson[1] found this to be the preferred method for a linear plug nozzle.

To accomplish TVC by thrust modulation, i.e., by reducing/increasing the pressure in a set of individual combustion chambers and bell nozzles, the cluster of individual combustion chambers has to be divided into four groups. For each of these groups, a throttling valve is required in the propellant feed lines, and in case booster pumps are used to increase the pressure, valves connecting the outlet(s) of the booster pump(s) to the injectors are required.

Like for TVC by fluid injection, a single annular plug nozzle only allows for pitch and yaw control when using differential throttling. The linear plug nozzle allows for all three types of control, provided the upper and lower part of the plug have individually throttleable combustion chambers.

5. TVC Using Flaps

a. Introduction. Vanes are well-known means to accomplish TVC on launchers. The oldest industrial example is the graphite vanes or rudders used on the German V-2 during World War II. Later, vanes have been used on the American Scout launcher. A disadvantage is that vanes are exposed to the full impact of the hot combustion gases. In fact, the graphite V-2 vanes eroded substantially during operation. Another disadvantage is that the vanes are continuously exposed to the hot combustion gases, thereby reducing the performance of the rocket motor. Notwithstanding this, vanes or flaps have also successfully been used on missiles and may have some advantages in conjunction with plug nozzles.

b. Flaps on the plug. A relatively simple means of generating TVC is by means of flaps, which, when not in use, form the outer surface of the plug contour. By deflecting such a flap, a shock wave is formed, which locally generates a higher pressure, resulting in a side force on the plug. As the flap width can be rather small in comparison to the (local) plug radius, for a first performance estimate one-dimensional gasdynamics analysis may be used.

With an incoming Mach number M_1 and a flap deflection angle θ, an oblique shock results at a shock angle β ($\beta > \theta$). The velocity behind the shock has turned over an angle θ at a Mach number M_2, thereby generating momentum normal to the longitudinal axis of the plug.

The flap deflection angle is limited to a maximum value. This relation may be found in text books on gasdynamics.[6] If this maximum deflection angle is exceeded, the shock detaches. Although this may not be detrimental for TVC, the analysis becomes more complicated, because this affects the boundary layer on the plug, and will have additional three-dimensional effects. A schematic of a deflected flap on a plug nozzle is given in Fig. 5. It may be shown that the thrust angle δ follows from

$$\delta = A\tan\left(\frac{m}{Q} \cdot \frac{M_2 a_2 \cdot \sin(\theta - i) + M_1 \cdot a_1 \cdot \sin(i)}{M_e \cdot a_e}\right) \quad (6)$$

If there are, for example, 16 flaps, $m/Q = 0.0625$ for the deflection of one flap. The thrust deflection angle δ depends on the flap deflection angle θ and the local plug surface inclination angle i. The thrust deflection angle δ depends on the local Mach number M_1, at the beginning of the flap and, therefore, on the position of the flap on the plug. In fact, for every plug configuration there is an optimum flap position, as shown in Fig. 6. It shows the ratio of the side force and thrust due to the maximum deflection of one single flap. Figure 6 applies to a truncated plug nozzle with an expansion ratio $A_e/A_t = 518$ at nominal flow conditions and exit Mach number $M_e = 5.49$. The maximum side force in this particular case is obtained at $M_1 \sim 3.5$. The observation that there is an optimum flap position is generally valid.

The Mach number of the incoming flow, M_1, strongly increases in downstream direction, as shown in Fig. 7. In the given example,

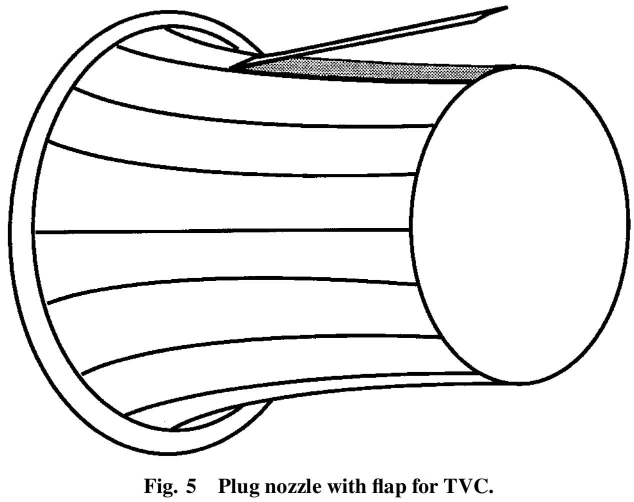

Fig. 5 Plug nozzle with flap for TVC.

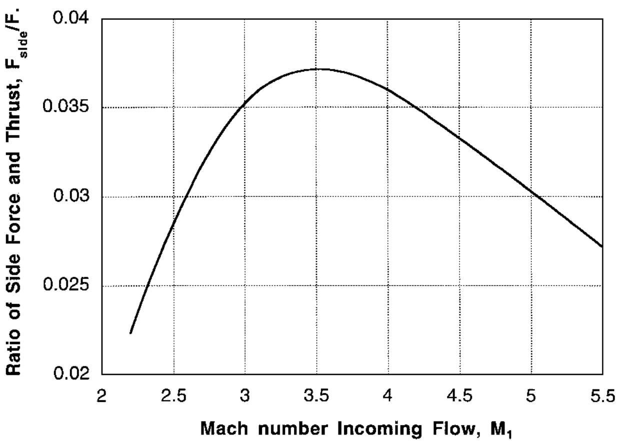

Fig. 6 Side force on a plug nozzle due to the deflection of one single flap, circumferential angle 22.5 deg.

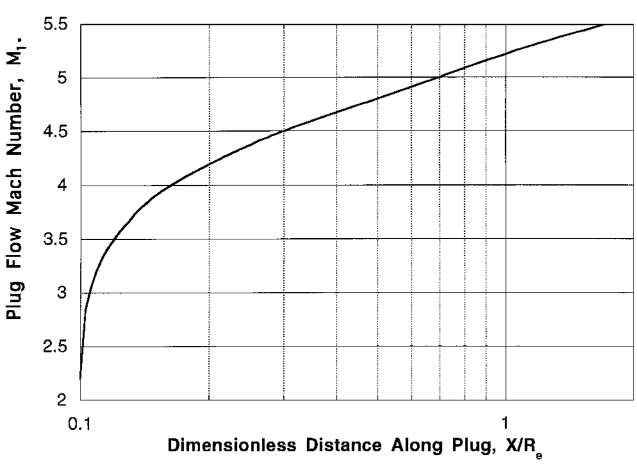

Fig. 7 Mach number along a plug nozzle vs downstream position.

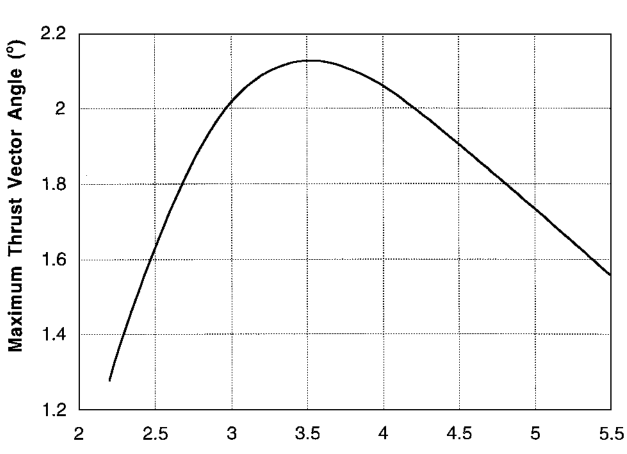

Fig. 8 Maximum thrust vector angle δ due to the deflection of one single 22.5-deg circumferential flap.

the flap has to be positioned close to the primary nozzles, i.e., at about $X/R_e \sim 0.11$. For different plug nozzles, the optimum flap position will be different.

The maximum thrust vector angle δ, which may be obtained by deflecting one single flap, is shown in Fig. 8; in this example, it amounts to ~2.1 deg. For most applications, a thrust vector angle of 6 deg is regarded as more than sufficient. This may easily be obtained by deflecting more flaps. The maximum thrust deflection angle will be obtained by deflecting all flaps on one side of the plug. The effectiveness of deflecting more flaps is shown in Fig. 9.

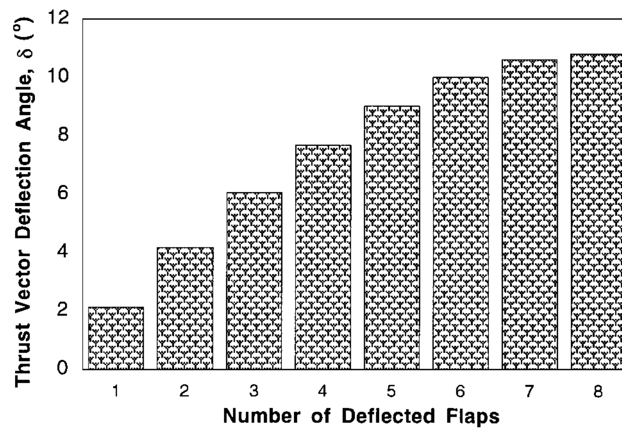

Fig. 9 Thrust vector angle in relation to the number of deflected flaps.

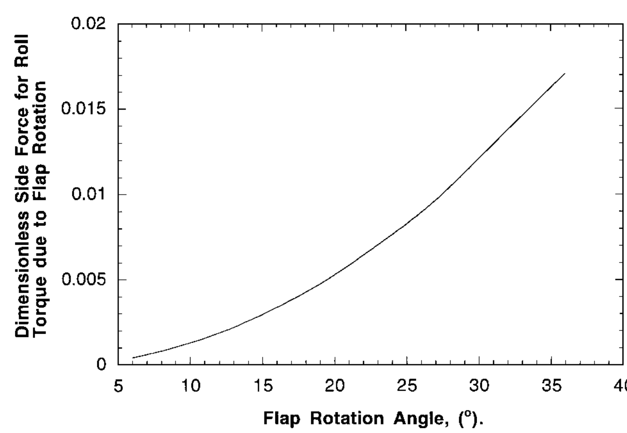

Fig. 10 Dimensionless side force due to the deflection and rotation of one single 22.5-deg flap.

In case 22.5-deg circumferential flaps are being used, eight flaps may be deflected. However, as Fig. 9 shows, deflecting more than five flaps hardly increases the thrust vector angle. By deflecting five flaps, a thrust vector angle $\delta = 9$ deg is already obtained. Deflecting all eight flaps will yield a thrust vector angle $\delta > 10$ deg.

Roll control on an annular plug nozzle is possible by rotating the deflected flap around its longitudinal axis. As a result of this rotation, the wedge angle changes, while the effective incoming Mach number with respect to the deflected and rotated flap also changes. If the flap is deflected by an angle θ and rotated over an angle ϕ, the effective flap deflection angle follows from

$$\theta_{\text{effective}} = A\tan\left(\sqrt{\tan^2\phi + \tan^2\theta}\right) \tag{7}$$

The effective incoming Mach number $M_{1,\text{effective}}$ becomes

$$M_{1,\text{effective}} = M_1 \cdot \sin\left\{A\tan\left(\frac{\tan(\theta)}{\tan(\phi)}\right)\right\} \tag{8}$$

A side force is now created, inclined at an angle ϕ with respect to a normal on the plug surface. The part that is available for torque, therefore, is $F_{\text{side,torque}} = F_{\text{side}} \cdot \sin(\phi)$.

Figure 10 shows the side force available for torque due to one flap being rotated over an angle ϕ. The side force has been nondimensionalized by dividing by the total thrust. In this example, it was assumed that the effective incoming Mach number $M_{1,\text{effective}} = 3$, while the flap is positioned at the point where the incoming Mach number $M_1 = 3.5$. This is quite an effective way of generating roll torque. First, the side force due to the deflection and rotation of one flap may become as high as 1.7% of the total thrust. Second, one would deflect and rotate two opposite flaps, which will yield a torque of $0.034 \cdot \boldsymbol{F} \times \boldsymbol{R}$. With a local radius $R = 2.25$ m and a thrust of 1 MN, which has been used for this example, a torque for roll

Table 1 Summary of TVC performance for annular plug nozzles

TVC Method	Pitch/yaw moment or thrust deflection angle	Roll torque
Canting of plug over angle α	$\delta \sim (1 - c_{f_t}/c_f) \cdot \alpha$	——
Displacement of plug over $R - r$	$\boldsymbol{Mo} \le \frac{1}{2} \cdot \boldsymbol{F} \times \boldsymbol{R}$	——
Hot gas injection	$\delta \le$ 3.2 deg	——
N_2O_4 injection	$\delta \le$ 2.7 deg	——
Differential throttling	$\boldsymbol{Mo} = \sim 0.16 \cdot \boldsymbol{F} \times \boldsymbol{R}$ $\boldsymbol{Mo} = \sim 0.32 \cdot \boldsymbol{F} \times \boldsymbol{R}^{a}$	——
Flaps on plug	$\delta \le \sim 10$ deg	$\boldsymbol{T} \le \sim 0.27 \boldsymbol{F} \times \boldsymbol{R}$
Flaps in base	$\delta \le \sim 7.9$ deg	$\boldsymbol{T} \le \sim 0.20 \boldsymbol{F} \times \boldsymbol{R}$

[a]In case pressure in other half of the engines is increased by 50%.

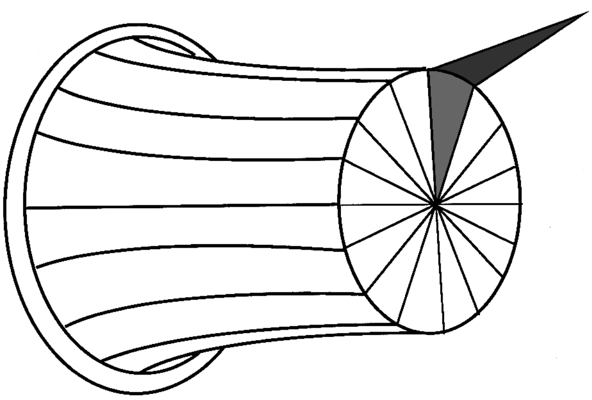

Fig. 11 Schematic of flaps folded in the truncated base area, with one flap deflected.

control, or to induce roll maneuvers, of 76.5 kNm is well possible. Because at maximum all 16 flaps may be actuated, a total roll torque of more than 600 kNm can be generated.

c. Flaps at the end of the plug. It was stated before that there is an optimum position for the flap on the plug (see Figs. 6 and 7). However, there may be various reasons (see Sec. II.C) why one may not want to position a flap on the plug surface. An alternative and very attractive solution is to use triangular flaps, which fold in the base area when not active. A schematic is given in Fig. 11. The dimensionless side force now reduces from 0.037 to 0.027 (see Fig. 6). This reduces the thrust deflection angle, due to the deflection of one flap, from 2.1 to 1.56 deg. Nevertheless, deflecting five flaps would yield a thrust deflection angle $\delta = 6.6$ deg, whereas deflecting all eight flaps would give a thrust deflection angle $\delta = 7.9$ deg. In a similar way, as described earlier, roll moments may be generated.

The most important global characteristics for TVC on annular plug nozzles are summarized in Table 1.

C. Some Considerations with Respect to Heat Loads and Cooling

Flaps on the plug surface are continuously exposed to hot combustion gases, which may cause structural or material problems. Therefore, the flaps may have to be cooled (regeneratively). This could be advantageous in combination with an expander cycle. On the other hand, a flap that is actively cooled and that also may have to rotate on its centerline to generate roll torques would make the construction complex and might introduce failures.

Alternatively, such flaps may be manufactured from ceramic composite materials, such as carbon/carbon, carbon/SiC or SiC/SiC. The surface below the flap may still be cooled regeneratively to keep the inside temperature of the plug within acceptable limits. Ceramic materials have shown to possess excellent thermal and mechanical characteristics. That the plug outer surface is not actively cooled may not be too severe a disadvantage because studies[7] have shown that the plug will, at most, absorb 10% of the total heat flux for an expander cycle, and only part of this is not recuperated.

In case cooling of the plug outside surface is considered necessary, the flaps may be located in the truncated base area. Here, the choice of ceramic materials for the flaps seems most attractive.

III. Conclusions

A first assessment of a number of TVC methods for annular plug nozzles was made. This allows the systems engineer to select the most attractive TVC system for a particular application for further detailed evaluation. The performance estimates and analyses are based on engineering correlations, limited available experimental data, and one-dimensional gasdynamics for nominal flow conditions. Nevertheless, the results yield a first estimate of the magnitude of moments or thrust deflection angles that may be generated by the different TVC methods, and some inherent limitations have been indicated. Table 1 summarizes the most important global characteristics for TVC on annular plug nozzles. The only method where it is obvious that roll moments may be generated easily on a single annular plug nozzle is by flap deflection and rotation; none of the other methods immediately offers a simple means to generate roll moments.

It is not always possible to directly compare the methods with each other. The moments of TVC methods that generate a side force or a thrust deflection angle depend on the (variable) position of the center of mass of the launcher. The methods where the plug is being displaced sidewards, or where differential throttling is applied, generate a moment, independent of the longitudinal position of the center of mass.

For a linear plug, roll moments may easily be introduced by most methods. For differential throttling, it is necessary that there are at least four groups of independently throttleable combustion chambers: at the left and right side and at the upper and lower part of the linear plug. A combination of canting and displacing the linear plug may provide for pitch, yaw, and roll moments.

Displacement or canting of the plug is not practicable for larger annular plug nozzles and for plug nozzles on solid rocket motors.

Fluid injection is a well-proven technology and hot gas injection has been demonstrated to be quite effective. It eliminates the need to store an additional fluid under high pressure.

Differential throttling has been investigated theoretically, but no experimental data seem to be available at this moment. Nevertheless, the method looks interesting and has been selected for linear plug nozzles.

Flap deflection, although also not investigated experimentally on plug nozzles, has its precursor in the vanes or rudders used on the V-2 and Scout, where it proved to be quite effective. Also many military missiles have used this in conjunction with classical nozzles. Flap deflection yields the highest potential thrust deflection angle δ, whereas by combining this with flap rotation, roll torques can be generated on a single annular plug nozzle.

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