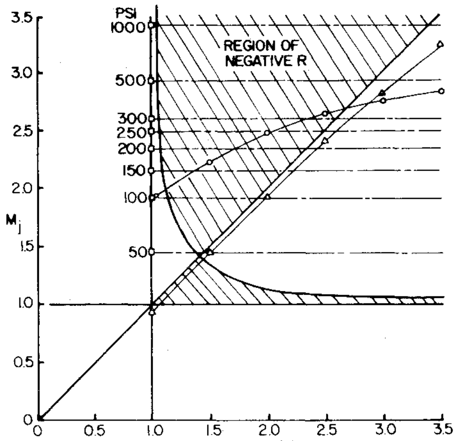

Fig. 1 Curves of M_j vs M_∞ superimposed on the map of reflection coefficient.

of exhaust Mach number. For purpose of reduced exhaust plume signature, elimination of shock diamonds is desirable. The technique is applicable to exhaust from ramjets, rockets, or aircraft gas turbines.

It is of interest to examine the jet Mach number M_j for ramjets, rockets, and gas turbines as a function of Mach number M_∞. Figure 1 shows curves of M_j as a function of M_∞ superimposed on a map of reflection coefficient.

For a rocket, the value of M_j is independent of M_∞. Consequently, the curves are straight lines at constant M_j. Assuming expansion of an ideal gas, the value of M_j is determined by the ratio of heat capacities γ and the ratio of chamber pressure to ambient pressure. Chamber pressures are given in Fig. 1; the rocket is assumed to be at sea level and to have propellants yielding $\gamma = 1.4$. A curve for constant chamber pressure moves upward with increasing altitude. Shock diamonds should be absent for a narrow range of M_∞ near transonic and high supersonic values of M_∞. For a more precise definition of the values of M_∞ with no shock diamonds, it is obvious that Fig. 1 should be recalculated for values of γ more appropriate for rockets; the trends shown by Fig. 1 would be correct at other values of γ.

For an ideal ramjet, $M_j = M_\infty$. When losses are taken into account, the values of $M_j < M_\infty$. The ramjet curve in Fig. 1 is below the diagonal $M_j = M_\infty$. For the case illustrated, there are shock diamonds for $1.0 < M_\infty < 1.4$. For $M_\infty > 1.4$, the diamonds are absent.

A curve of M_j vs M_∞ was calculated for an ideal turbojet with a compressor having a fixed pressure ratio of 8.0. For $M_\infty > 2.6$ and near transonic, the shock diamonds do not occur. For an upper bound on turbine inlet temperature, the optimum compressor pressure ratio decreases as M_∞ increases; eventually the optimum blends a turbojet into a ramjet. A consequence of optimizing compressor pressure ratio with changes in M_∞ would be to lower the turbojet curve in Fig. 1. Also component inefficiencies, e.g., compressor efficiency, would tend to lower the curve.

In summary, the following conclusions can be drawn from Fig. 1. For practical rocket chamber pressures, the shock diamonds will not be eliminated except at high supersonic M_∞ and an insignificant transonic region; a ramjet should operate without shock diamonds for all M_∞ in excess of approximately 1.4; and current supersonic aircraft (e.g., F-4, F-14, F-15) should have shock diamonds whenever M_∞ exceeds unity by a slight amount. However, advanced turbojet-propelled aircraft should not have shock diamonds whenever M_∞ exceeds 2.6 or so.

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[1] Fuhs, A. E., "Wave Structure of Exhaust from Transonic Aircraft," *Journal of Aircraft*, Vol. 8, 1971, pp. 280-281.

Technical Comments

Comment on "Advanced Technology Thrust Vectoring Exhaust Systems"

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GILL[1] recently presented the results of a study aimed at identifying suitable thrust vectoring nozzles for the lift-cruise engine of a specific VTOL aircraft type operating a prescribed mission. Gill's remarks relating to the installational characteristics of the nozzles he considered are in general agreement with the findings of an earlier study.[2] There are, however, comments which can be made relating to the choice of two of the nozzle types considered by Gill.

For turbofans augmented in the cruise mode only (the engine type shown by Gill to be preferred for the mission he considered), the use of a slider instead of a trap door to control the downflow of a ventral nozzle appears to merit consideration. It permits the downward projection, and hence the frontal area, of the engine to be reduced, compared with that of a trap-door nozzle with fixed side plates ($V \approx 0.13$ instead of $V = 0.23$; see Fig. 11 of Gill's paper). A slide-valve controlled ventral nozzle arrangement is illustrated in Fig. 1. Lateral vanes are provided in the ventral opening in order to permit a range of vectoring, with the full engine flow passing through the ventral opening, for approximately 30° aft to about 10° ahead of vertical. The width of the opening is tailored to accommodate the influences of flow vector angle and nonuniformity of discharge coefficient as a function of slider position. With respect to the range of vectoring using only the ventral opening, the slide valve and trap-door concepts appear to be comparable.

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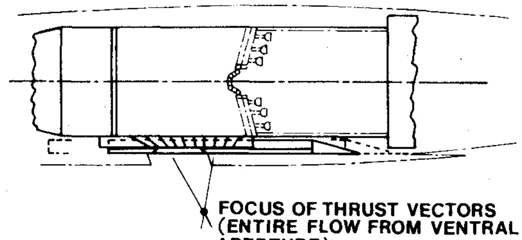

Fig. 1 Slide-valve nozzle, with flat slider, for a turbofan engine augmented in the cruise mode only.

Another advantage of the slide-valve system is its extreme simplicity; only one moving part, the slide valve, is required and the underclosure of the nacelle can be attached to, or operated by, the slide valve thereby eliminating additional actuators and control gear. If the slide valve is curved to conform to the curvature of the engine jet pipe, the engine frontal area can be reduced yet further. With a slide valve of curved cross-section, the opening in the jet pipe requires the addition of longitudinal guide vanes to prevent lateral spreading of the ventral efflux. The network of guide vanes can also serve to brace both circumferentially and in the fore-and-aft direction the aperture in the jet pipe. A disadvantage of the slide valve concept is the increased seal length compared with that of the trap-door nozzle. The slide-valve nozzle is also slightly longer than the trap-door type.

Gill[1] condemned all the systems he studied which incorporated swivel, or rotating, cascades because of the high drag associated with the projection of the elbows into the external flowfield. However, in the case of the unaugmented configuration S1, the nozzle for which appears in Fig. 8 of Gill's paper, the projecting elbows can be virtually eliminated by mounting the planes of the cascades and their swivel bearings at compound angles as shown in Fig. 2. This nozzle has the same area ratio as the nozzle in Fig. 8 of Gill's paper.

An obvious problem with a swivel-cascade nozzle having the planes of the swivel bearings set at compound angles, is a fundamental thrust loss caused by the thrust vectors departing from fore-and-aft vertical planes. In fact, these thrust reductions are relatively small, provided the angles α and β (see Fig. 2) defining the location of the planes of the cascades and swivel bearings are chosen correctly. Appropriate numerical data are presented in Table 1 for two sets of values of α and β. It appears that for excess losses to be avoided, the optimum values of α and β lie within the ranges $45° \leq \alpha \leq 50°$ and $45° \geq \beta \geq 40°$. In practice the thrust losses appearing in Table 1 will be substantially offset because of the higher inherent thrust coefficient, about 2-3% higher than for a conventional swivel-cascade nozzle, which can be expected with the compound-angle cascade nozzle. This is a consequence of the smaller flow turning angle prevailing within the casecade approach duct, and also within the cascade vanes, of such a nozzle.

A situation which occurs between the cruise and lift positions with a compound-angle swivel-cascade nozzle is the impingement of the two exhaust streams on each other. The maximum included angles of impingement are identified in Table 1. Flow tests have been carried out with a model nozzle and an adjacent flat surface, representing the plane of symmetry between the impinging jets, to ascertain the likelihood of the pressure field created by impingement reducing the effective discharge coefficient of the nozzle. The tests indicated that for conditions typical of a compound-angle swivel-cascade nozzle, i.e., $0 \leq S/D \leq 0.2$, there was only a barely perceptible reduction in nozzle discharge coefficient for an impingement angle corresponding to $\alpha = \beta = 45°$ and when $\alpha = 50°$, $\beta = 40°$ there is a considerable margin of safety. The results of the tests are shown, in parametric form, in Fig. 3. The tests were carried out with a nozzle pressure ratio very much less than the critical value, thereby ensuring the sensitivity of the flowfield within the nozzle to conditions downstream of the nozzle exit. Subcritical pressure ratio operation is likely if compound-angle swivel-cascade nozzles are applied to high-bypass ratio turbofans.

Fairing a compound-angle swivel-cascade nozzle can probably best be carried out by ventilating the space between the two jets from the underside of the nozzle and, for a nacelled installation, providing a boat-tail like surface to cover the upper portion. An arrangement of this type is indicated in phantom in Fig. 2. The nozzle shown in Fig. 2 should be considerably lighter than a corresponding conventional swivel cascade because of the reduced surface area of the main body and the complete elimination of the elbows projecting outboard of the swivel bearings. For a given outlet area, the swivel bearings are also about 7% smaller in diameter than those shown by Gill.

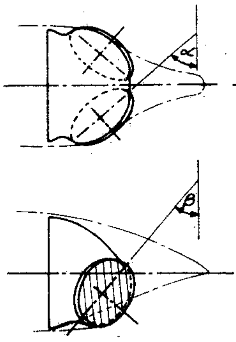

Fig. 2 Compound-angle swivel-cascade nozzle. Cascade vanes, shown in cruise position, rotate in directions of arrows to vector for the lift mode; α and β define plane of swivel bearing and cascade.

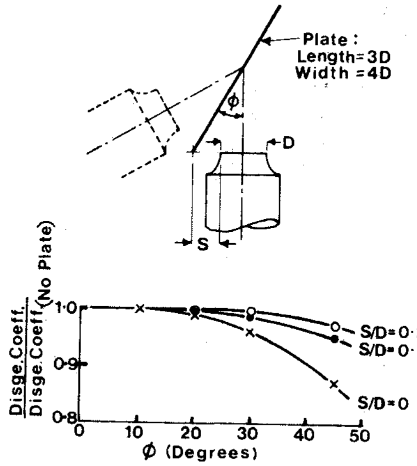

Fig. 3 Results of jet-impingement simulation flow-model tests; ϕ equals half the included angle of impingement. D is outlet diam of axisymmetric, high-flow coefficient, nozzle.

Table 1 Characteristics of compound angle swivel-cascade nozzles.[a]

	$\alpha = 45°$ $\beta = 45°$	$\alpha = 50°$ $\beta = 40°$
Angle of flow to (dowmstream) face of cascade	35.3°	34.5°
Max incl. angle of jet impingement	38.8°	26.2°
Flow deflection at max incl. angle of jet impingement ($\Theta_{max\,I}$)	45.0°	40.0°
Fundamental thrust loss (%) relative to an ideal vectoring nozzle:		
cruise: $\Theta = 0°$	0	0
$\Theta = \Theta_{max\,I}$	5.7	2.6
lift: $\Theta = 90°$	0	0.7
$\Theta = 100°$	1.1	2.7

[a] Θ is the conventional flow deflection, or vector, angle.

It is not likely that the substitution of a nozzle of the type illustrated in Fig. 2 would alter any of the conclusions presented by Gill as a nonaugmented engine was shown to be unsuitable for the particular aircraft type and mission involved. However, for missions for which an unaugmented turbofan is the appropriate choice, particularly if only a convergent nozzle is required, a compound-angle swivel, or rotary, cascade nozzle may be well worth consideration. Both types of vectoring nozzle described here were referred to very briefly in an earlier paper.[2]

References

[1] Gill, J.C., "Advanced Technology Thrust Vectoring Exhaust Systems," *Journal of Aircraft*, Vol. 11, Dec. 1974, pp. 764-770.

[2] Kentfield, J.A.C., "Nozzles for Jet-Lift V/STOL Aircraft," *Journal of Aircraft*, Vol. 4, July-Aug. 1967, pp. 283-291.