Engineering Notes

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Expedient Approach to Nonaxisymmetric Nozzle Performance Prediction

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Introduction

AS nonaxisymmetric nozzles are being considered for incorporation in new aircraft design, flow characteristics computational methods are needed to predict performance. Since the flowfield, especially of the plume, is three-dimensional, any computational method is necessarily complicated if flow details are needed. For performance analysis, however, much simpler methods can be used since only integrated performance parameters, not the detailed local flow properties, are computed.

Because the use of nonaxisymmetric nozzles is fairly new, no standard approach to the performance prediction has been established. It seems to be a common practice to predict the performance of a new nozzle based on available data where possible (for instance, data on a similar nozzle), supplemented by some analytical predictions (see, for instance, the pioneering work of Willard et al.[1]).

Since the aspect ratios of some nonaxisymmetric nozzles are fairly high, it is expected that a two-dimensional analysis is adequate for the performance prediction of these nonaxisymmetric nozzles. The expedient approach presented here is based on the theory of characteristics for two-dimensional inviscid flow. The method has been applied to three types of nozzles: the augmented deflecting exhaust nozzle (ADEN), the plug (or twin throat) nozzle and the two-dimensional converging-diverging (2D-CD) nozzle. A cross-section of the ADEN nozzle and the computed nozzle and plume flowfield are shown in Fig. 1 at near design conditions. Although the two-dimensional characteristics method was used in the past for design of wind tunnels, etc., the present application is complicated by free boundaries, which, in off design cases, introduce strong expansion or shock waves that require particular attention.

Prediction results were compared with experimental data whenever available. Good agreement between predictions and test data was observed for the ADEN and 2D-CD nozzles. A fast computer code has been developed for treating underexpanded to moderately overexpanded nozzle jets involving weak shocks.

Features of Numerical Scheme†

In the usual way of applying two-dimensional characteristics theory, the computation proceeds along one of the two families of characteristics. In the analysis code, however, it was found to be more versatile and convenient to proceed along data lines perpendicular to or at some oblique angles with the nozzle axis. At the initial value line downstream of the throat, general distributions of pressure (or Mach number), flow direction and total pressure may be assigned. The code can also generate suitable flow angles through the instruction of an input parameter. The analysis code can treat cases from high underexpansion to moderate overexpansion that generate weak shock waves, which are smeared. Because of error accumulation, the mass flow suffers a numerical loss after many calculation steps in a marching type procedure such as the present one. In the analysis code, compensatory measures are taken to ensure continuity of mass and, thus, maintain accuracy. Another measure for accuracy is the use of average flow properties between the point being computed and the previous data line to evaluate the coefficients of the finite-difference equations. The Courant-Friedrichs-Lewy condition is used to automatically regulate the step size, and the computational grid structure can be varied to suit a particular case through input parameters. Both these measures are incorporated in the analysis code to save machine time. At the present, the analysis code can treat ADEN, 2D-CD and 2D plug (twin throat) nozzles.

Illustrative Examples

Some examples of computational results are presented and compared with available test data. Depending on the nozzle geometry, there is a lower limit of the nozzle pressure ratio below which the present code cannot be applied because of the existence of strong shock waves.

Unless otherwise noted, a uniform Mach number of 1.02 is used at the geometric throat to provide an initial value line; the performance parameters, such as thrust coefficients and vector angles, are not sensitive to the initial Mach number and the location of the initial value line within a reasonable limit. For instance, a change of initial Mach number from 1.02 to 1.005 resulted in a small fraction of a percent change in the thrust coefficient.

Figure 2 shows the upper ramp of ADEN and the ramp pressure distributions along the center line under cruise static conditions. The prediction by the analysis code agrees fairly well with NASA test data. Hence it may not be surprising to find the good agreement between the performance calculation and test data as shown in Fig. 3. Still, the close agreement of the vector angle is somewhat unexpected.

The cruise static performance prediction of P&WA/NASA 2D plug nozzle is shown in Fig. 4 along with NASA test data.

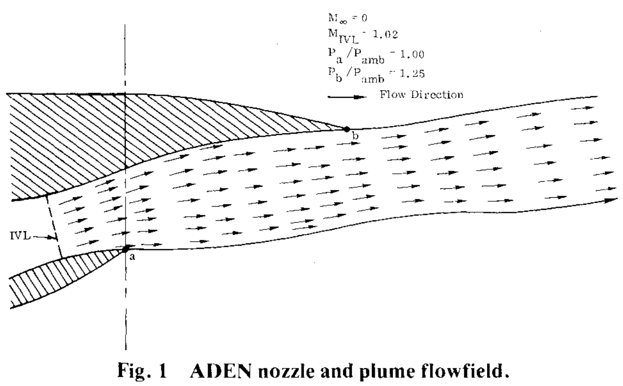

Fig. 1 ADEN nozzle and plume flowfield.

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†This scheme models after a working three-dimensional scheme (see Ref. 2 for details).

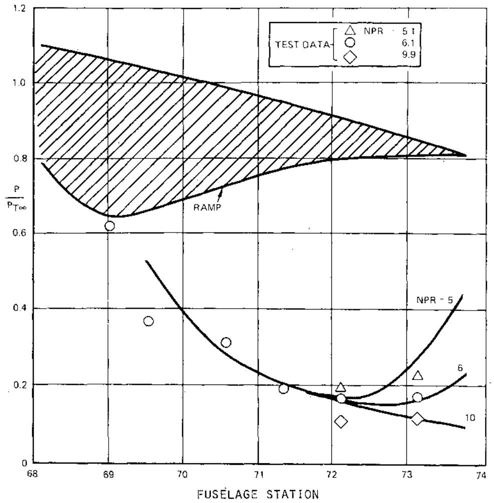

Fig. 2 Ramp pressure distribution for ADEN under cruise static conditions.

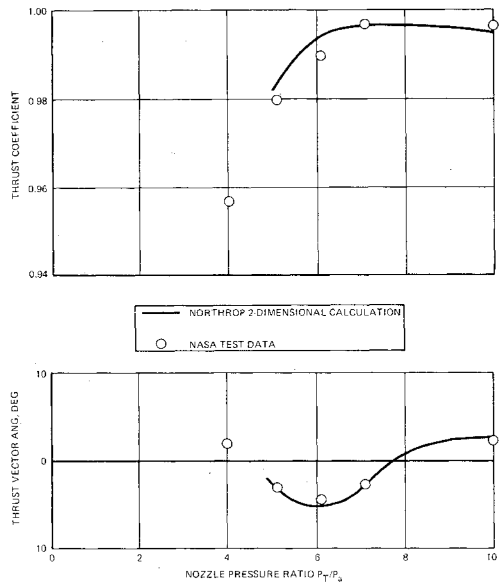

Fig. 3 ADEN cruise static performance.

The agreement between theory and experiment is good around a nozzle pressure ratio of 5, but it becomes appreciably worse in either direction. Since the plug is much longer than the nozzle exit height, any wave at the lower exit will bounce back and forth a few times between the plug surface and the plume boundary before the wave leaves the upper exit. Hence, depending on how many pressure peaks hit the plug, the thrust coefficient should exhibit a wavy nature when plotted against the nozzle pressure ratio if the flow is strictly two-dimensional. Although this wavy pattern is fully borne out by the two-dimensional theory, test results indicate that flow spillage to the side due to the relative lengths of the plugs greatly alters the wave structure. This causes discrepancies between the test data and the two-dimensional predictions.

The analysis code can also be applied to 2D-CD nozzles. An example is given in Fig. 5, where the performance prediction is compared with NASA test data for GE 2D-CD nozzles with

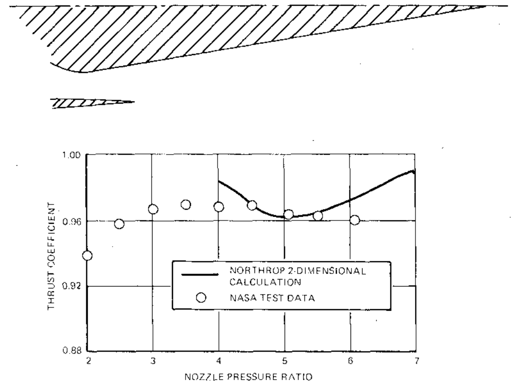

Fig. 4 P&WA/NASA 2D plug nozzle cruise static performance.

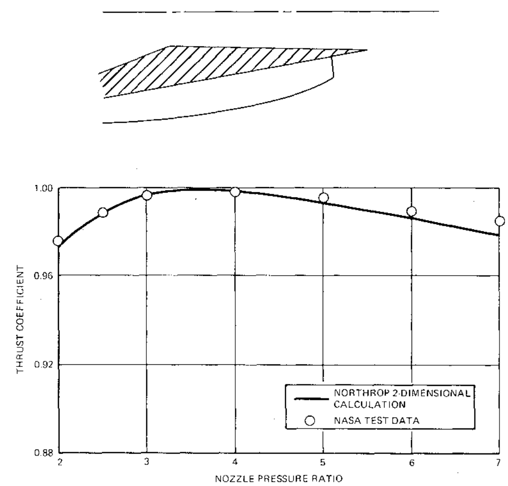

Fig. 5 GE 2D-CD cruise static performance, $\epsilon = 1.15$.

expansion ratio $\epsilon = 1.15$. Agreement between calculation and experiment is very good.

Conclusion

Except for the 2D plug nozzle, which requires three-dimensional analysis or further correlation with experiments, the present expedient computer code based on the theory of characteristics for two-dimensional flow offers acceptable performance predictions for the nonaxisymmetric nozzles for which test data are available. The code can be very useful for preliminary design of nonaxisymmetric nozzles. Future extensions will include an analysis code for treating strong shock waves associated with high overexpansion.

Acknowledgment

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References

[1] Willard, C.M., Capone, F.J., Konarski, M., and Stevens, H.L., "Static Performance of Vectoring/Reversing Nonaxisymmetric Nozzles," AIAA/SAE 13th Propulsion Conference Paper 77-840, July 1977.

[2] Chu, C.W. and Powers, S.A., "The Calculation of Three-Dimensional Supersonic Flows Around Spherically-Capped Smooth Bodies and Wings," Tech. Rept. AFFDL-TR-72-91, Sept. 1972.