Internal Performance Prediction for Advanced Exhaust Systems

Donald W. Speir* and Jack T. Blozy†
General Electric Company, Evendale, Ohio

The selection of exhaust systems for advanced tactical aircraft is an exercise in the art of compromise. In the last 30 years, the design function of the exhaust system has evolved from an engine control valve to a multifunctional system, which may include requirements for high performance, thrust vectoring, and signature reduction. General Electric employs a systematic approach to the selection and design of exhaust systems which requires accurate estimation of internal performance. This paper presents a summary of that approach and describes the development of prediction techniques by GE for nonaxisymmetric exhaust systems.

Nomenclature

A_{E_8} = effective nozzle throat area
A_8 = nozzle throat area
A_9 = nozzle exit area
C-D = convergent-divergent
C_{D_8} = nozzle discharge coefficient
C_{EMP} = nozzle performance empirical correction
C_{f_g} = nozzle thrust coefficient
$C_{f_{g_{PK}}}$ = peak nozzle thrust coefficient
$C_{f_{g_R}}$ = resultant nozzle thrust coefficient
C_V = nozzle velocity coefficient
$C_{f_{g_X}}$ = axial nozzle thrust coefficient
C_θ = nozzle angularity loss coefficient
DELJ = effective jet vector angle
F_g = nozzle gross thrust
$\dot{M}$ = nozzle mass flow
NPR = nozzle pressure ratio
P_0 = ambient static pressure
P_S = static pressure
SERN = single expansion ramp nozzle
T_{T_8} = total temperature at nozzle throat
V = velocity
2D-CD = two-dimensional convergent-divergent
$+\alpha$, $-\alpha$ = maximum and minimum value, respectively, for each factor
θ = nozzle flap divergence angle

I. Introduction

THE design of exhaust systems for advanced tactical aircraft has become an exercise in the art of compromise. In the earliest applications, the exhaust nozzle was a device for accelerating the exhaust flow to higher discharge velocities. With the advent of afterburning engines, it became a variable engine control valve to allow for the large variations in exhaust gas temperature, still without extensive system engineering. By the 1960s, engine pressure ratios were rising, and the importance of internal performance and closure drag was being recognized in the design of the airplane. Now with the consideration of VTOL, STOL, signature reduction, and in-flight thrust vectoring and reversing, the requirements that may be placed on an exhaust system design are multitudinous, as illustrated in Table 1. In 1950, a simple convergent nozzle could readily be specified for almost any application. By 1965, convergent-divergent (C-D) nozzles with variable exit to throat area ratios, divergent flap lengths, and boattail angles required considerable evaluation to specify a "best" design. Now, the design requirements for new tactical aircraft have become challenging indeed and require substantial trade studies to determine the best compromise between weight, performance, complexity, and cost.

A key factor in the design of exhaust systems is the ability to make rapid, but accurate, estimates of exhaust system internal performance. In the late 1960s and during the 1970s, performance prediction techniques were developed for axisymmetric exhaust systems, including convergent-divergent and plug nozzles. With the emergence of nonaxisymmetric exhaust systems as a major consideration for advanced tactical aircraft applications, the need for similar techniques for these concepts became apparent. Consequently, in 1977, General Electric embarked on a long-term program to develop the necessary data base and prediction techniques for nonaxisymmetric nozzles. This included a cooperative test program with NASA Langley at the 16-ft Transonic Wind Tunnel Jet Exit Facility to develop the major part of the internal performance data base, as well as additional testing at FluiDyne Engineering Corporation.

II. Exhaust System Design Process

General Electric has evolved a systematic approach to exhaust system design which considers the requirements of both the aircraft and propulsion systems in fulfilling the specified mission. This design process is summarized in Fig. 1 and describes the general flow of information between elements of the process. Of utmost importance is the realization that there is no such thing as an "off-the-shelf"

Table 1 Evolution of exhaust system design requirements

1950	1965	1990
Engine control valve	Engine control valve	Engine control valve
	Thrust efficiency	Thrust efficiency
	Minimize drag	Minimize drag
		Thrust reversing
		Thrust vectoring pitch
		Thrust vectoring yaw
		Thrust vectoring roll
		Signature reduction
		Acoustics(?)

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*Manager, Aircraft Engine Business Group, Advanced and Demonstrator Engines Installed Performance Programs. Member AIAA.

†Engineer, Aircraft Engine Business Group, Advanced Engineering and Technology Programs Department.

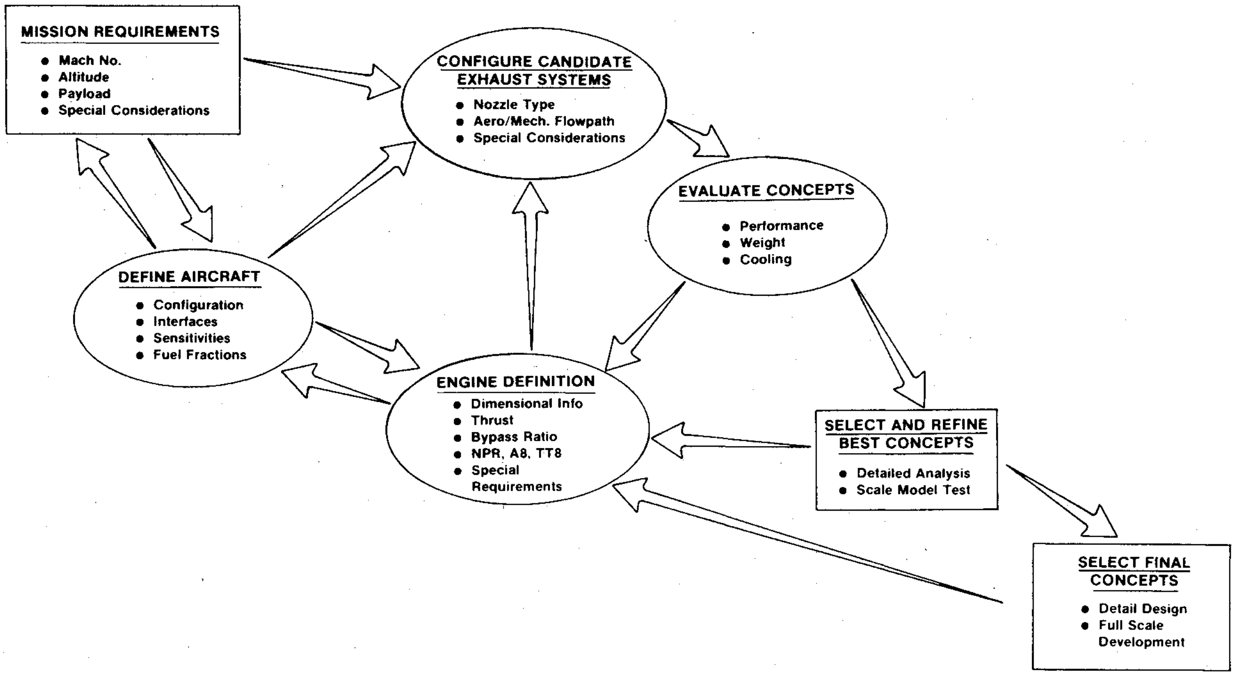


Fig. 1 Exhaust system design process.

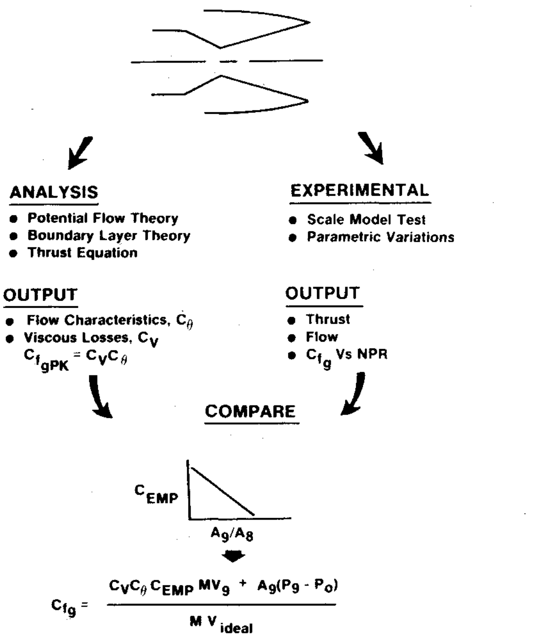


Fig. 2 Internal performance prediction technique development for C-D exhaust nozzles.

exhaust system. Differences in mission requirements, installation, or engine cycle call for different design parameters in the exhaust system. The design process allows for consideration of that information which impacts the exhaust system design, iteration through design studies, and a narrowing process to finally arrive at the exhaust system which best satisfies the engine, aircraft, and mission requirements.

In the initial design stage, it is not unusual to have from 10 to 20 concepts which satisfy the requirements in various degrees. The large number of concepts makes it very important to have reliable evaluation techniques. These techniques permit rapid, accurate evaluation of weight, performance, and cooling requirements. This information, when combined with probable reliability, complexity, control, and actuation requirements and a liberal amount of engineering judgment, permits an initial screening to a workable number of viable concepts.

More detailed analysis is performed on these selected concepts to evaluate and attempt to maximize performance through parametric variations, refine the mechanical design approach, minimize weight, consider materials selection, and develop the cooling system. In this stage, performance evaluation still relies heavily on prediction techniques but may require scale-model tests to verify predictions or evaluate concepts for which prediction techniques are inadequate or marginal. These selected concepts may be evaluated by the airframe designer by installing and "flying" each through airplane design programs. They may also be tested on wind tunnel models to more thoroughly evaluate thrust minus drag characteristics for each installation.

Through this iterative process, the final exhaust system design will emerge and enter the development process. From this point, major design changes are not likely to occur, but many man-years of effort will be applied to develop the ultimate exhaust system design. Scale-model testing will be performed, both statically and in the wind tunnel, to verify and iterate performance. One of the major efforts is in the mechanical design definition. The design will be iterated to minimize weight, to develop reliable but lightweight actuation and to trade simplified aerodynamic flowpath lines, which may minimize complexity or weight, against the impact on performance. Lightweight design approaches and materials selection are carefully evaluated, along with advanced manufacturing techniques. Finally, full-scale hardware is built and exhaustively tested for performance and reliability. An example of how these trades were made for one exhaust nozzle design is illustrated in Ref. 1.

This final design and development stage may take several years as the product reaches the levels of reliability required. This may compare with a year or less for the conceptual and preliminary design phase which leads to the selection of the final design. Consequently, it is very important that the right selection is made. This can only be done if the data base is in place and the tools utilized are capable of quick and accurate answers.

III. Internal Performance Prediction Development

General Electric has taken a two-pronged approach illustrated in Fig. 2 in developing internal performance prediction procedures. This approach involves use of an analytical model to develop design curves relating the nozzle loss coefficients, C_V and C_θ (the velocity coefficient and the angularity coefficient), to the nozzle geometric variables. Scale-model testing over a wide range of nozzle geometric parameters is then performed.

The experimental and analytical results are compared and an empirical correction, C_{EMP}, to the analytical model is developed to account for the difference between theoretical two-dimensional predictions and three-dimensional experimental results. This final result then allows for accurate internal performance prediction using design curves derived from the analytical model as modified by the empirical corrections.

This approach worked well for C-D nozzles but was inadequate for the single expansion ramp nozzle (SERN). For the SERN, the number of geometric variables was too large for the conventional test approach, and the analytical method was inaccurate at low nozzle pressure ratio. Consequently, a response surface experiment was used for development of the SERN internal performance prediction procedure which is based solely on experimental data.

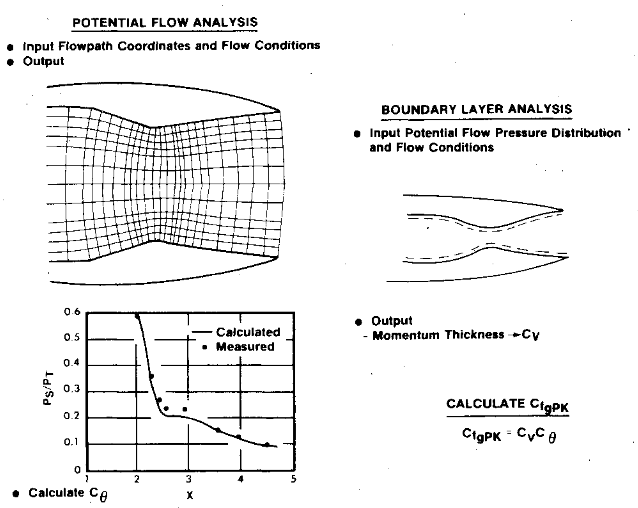


Fig. 3 Analytical model for C-D exhaust nozzles.

Analysis

Two computer programs are used for the analytical prediction of nozzle internal performance. First, the flowfield properties, streamlines, and pressure distributions of the nozzle are calculated using a two-dimensional potential flow computer program.[2] C_θ is derived by integrating the axial and normal thrust at the nozzle exit plane and then determining the thrust loss due to the nonaxial flow. A typical output showing the streamlines and orthogonals for a nozzle is shown in Fig. 3. The wall static pressure distributions are then input into a program, which calculates the boundary-layer momentum thickness and displacement thickness using the Stratford and Beavers technique. The velocity coefficient, C_V, is derived from the momentum thickness. This method has been verified for both axisymmetric and two-dimensional nozzles and has been utilized for the prediction of axisymmetric convergent-divergent nozzles and two-dimensional convergent-divergent (2D-CD) nozzles.

Testing

Nozzle testing up to a nozzle pressure ratio of 10 was performed at the NASA Langley Research Center 16-ft Transonic Wind Tunnel Jet Exit Facility.[3] A schematic of the test rig is shown in Fig. 4. This facility uses the same clean, dry-air supply as used in the 16-ft transonic tunnel and has a maximum airflow capability of 13 lb/s. Nozzle forces are measured with a three-component balance which measures the axial and normal forces plus the pitching moment. Photographs of typical test hardware are shown in Fig. 5. Testing has included unvectored, vectored, and reverser testing.

Testing at nozzle pressure ratios above 10 was accomplished at FluiDyne Engineering Corporation. Nozzle thrust was determined using a three-component strain-gage force balance. The testing was performed in a sealed test cabin

• Dimensions are in Centimeters Unless Otherwise Noted

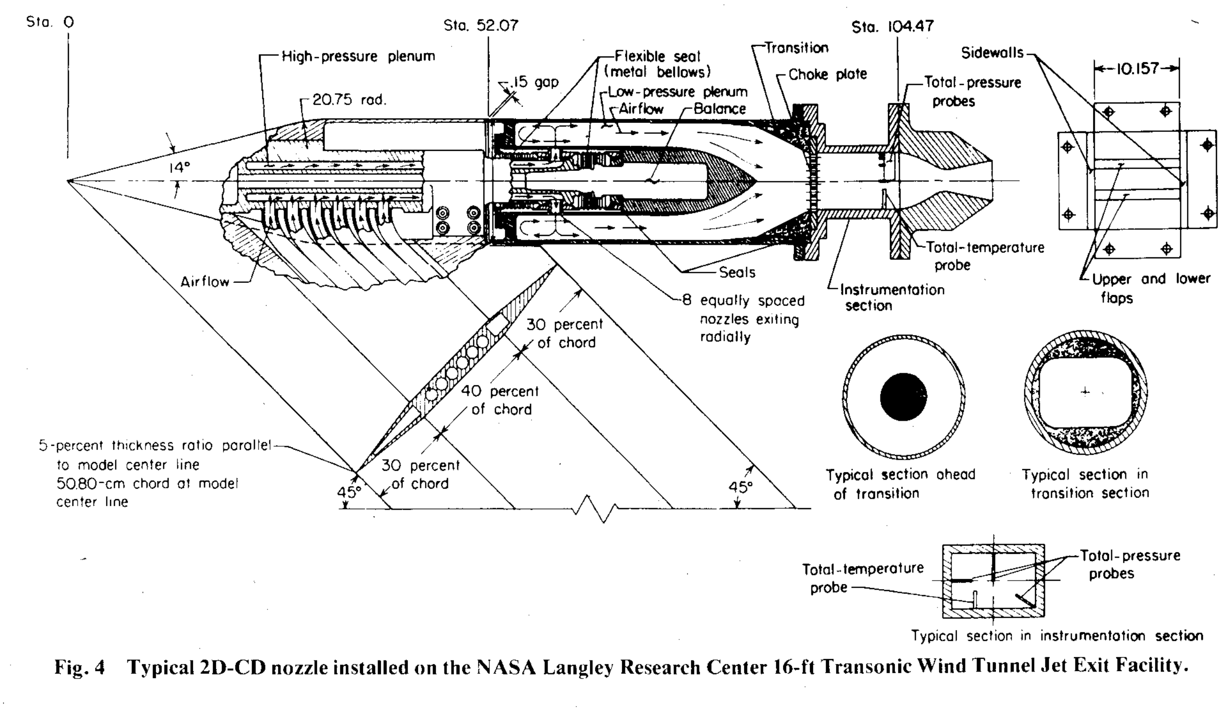


Fig. 4 Typical 2D-CD nozzle installed on the NASA Langley Research Center 16-ft Transonic Wind Tunnel Jet Exit Facility.

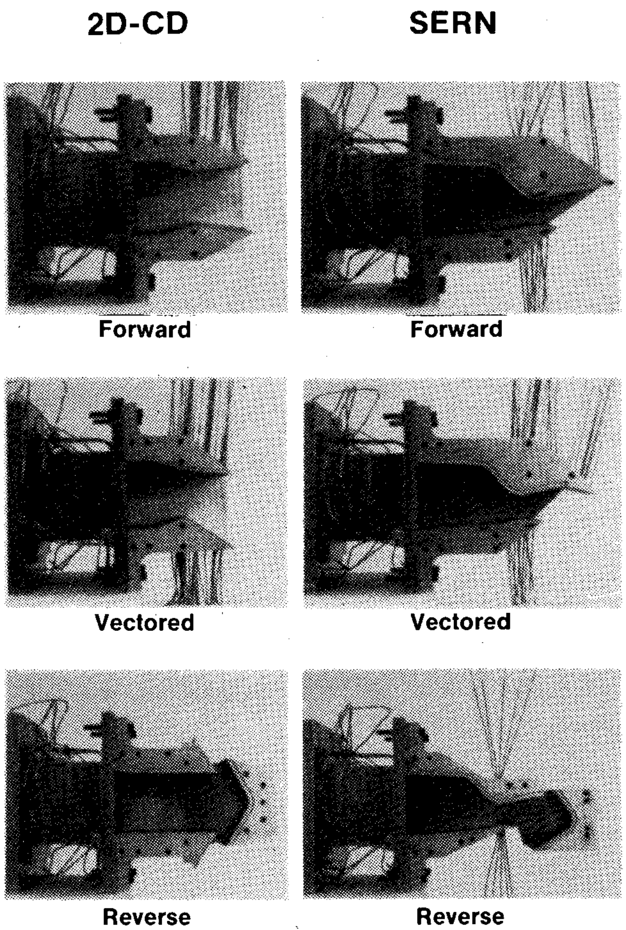


Fig. 5 Typical test configurations.

connected to an ejector system to control the test cabin pressure. By evacuating the test cabin, high nozzle pressure ratios are obtained. Limited low nozzle pressure ratio testing was also performed for comparison with the NASA Langley data.

In defining a test matrix, the usual procedure is to set up a parametric test matrix. This is an acceptable method so long as the number of variables is limited to two or possibly three. For example, if three values of each variable are tested, nine test configurations would be required for a two-variable experiment and 27 configurations for a three-variable experiment. For more than three variables, the number of tests becomes prohibitive. This parametric testing was used by General Electric for development of all internal performance prediction techniques, except for the SERN. For this nozzle, the number of geometric variables (five) ruled out parametric testing because of the large number of tests which would have been required. To reduce the number of test points required, General Electric employed a statistical method called a response surface experiment.

A response surface experiment, Ref. 4, combines the best features of a designed experiment, an analysis of variance and a regression analysis. Designed experiments are used to assure that data are taken in a manner that yields the required information. Analysis of variance is used to specify significant factors and interactions. Least-squares regression analysis is used to express the relationships between variables in equation form.

A designed experiment, which provides specific information about a design or scientific phenomenon, consists of a series of experimental trials arranged in a logical and systematic test pattern. With this technique, information that is desired may be specified. From the specifications, designs and test conditions that are required to supply this information may be mathematically calculated. This orderly approach is in direct contrast to the standard one-at-a-time procedure of conducting a single test, then studying the results before deciding what to do next—a procedure which is very often little more than "hunt and peck" when experimental errors are of significant size.

Nonaxisymmetric Nozzle Internal Performance Prediction Procedure

An internal performance technique has been developed for the 2D-CD using the test data acquired from the NASA Langley and FluiDyne test programs. A SERN prediction technique has been developed using the test data acquired from the designed experiment approach. Each of these techniques is described in the following sections.

2D-CD Nozzle Internal Performance Prediction Procedure

The unvectored 2D-CD nozzle internal performance prediction procedure was developed using a combination of experimental results and analytical predictions. The experimental results were obtained from the static testing at the NASA Langley Jet Exit Facility and FluiDyne Engineering Corporation. The parametric test matrix included 2D-CD nozzles with area ratios (A_9/A_8) ranging from 1.09 to 2.8 and nozzle divergence angles ranging from 1.3 to 20 deg.

Analytical predictions are made using the previously described analytical method to derive the friction and angularity loss coefficients (C_V and C_θ, respectively) for a wide range of unvectored 2D-CD configurations. The peak C_{f_g} is then calculated as

$$C_{f_{g_{PK}}} = C_V \times C_\theta \times C_{\mathrm{EMP}}$$

C_{EMP} is an empirical correction relating the analytical predictions and measured data and is correlated with nozzle area ratio. An empirical correction is required because the 2D-CD nozzles are not modeled completely by the two-dimensional analysis. There are several possible explanations for the additional loss mechanisms not calculated by the two-dimensional analysis. One is that the boundary layer may be thicker in the corner region. Another possibility is vortex flow which may lower the internal performance. The C_{EMP} correction was determined by comparing measured C_{f_g} with the calculated value. The most favorable correlation for C_{EMP} was found to be with the area ratio A_9/A_8. The predicted C_V and C_θ values for 2D-CD nozzles are found to be a function of area ratio and divergence angle similar to axisymmetric C-D nozzle results. Expansion losses at other pressure ratios are calculated using the thrust equation. The form of the 2D-CD internal performance design curves is shown in Fig. 6. Measured and predicted performance is compared in Fig. 7 for two configurations which were not included in the formulation of the prediction technique.

SERN Internal Performance Prediction

Development of an internal performance prediction procedure for the SERN was complicated by the large number of geometric variables (five) and the fact that the analytical method failed to accurately predict SERN performance at low nozzle pressure ratios (below NPR 5.0). General Electric utilized a response surface experiment for development of an empirical prediction procedure as previously described.

Development of the SERN prediction technique began with the identification of five nozzle geometric parameters having the largest influence on SERN internal performance. These five parameters were determined by regression analysis of existing test data and are illustrated in Fig. 8.

The designed experiment for the SERN defined a total of 43 configurations. The internal performance characteristics were measured for each configuration at the following nozzle pressure ratios: 2.0, 2.5, 3.0, 3.4, 4.0, 5.0, 6.0, 7.5, 8.6, and 10.0. The internal performance characteristics evaluated

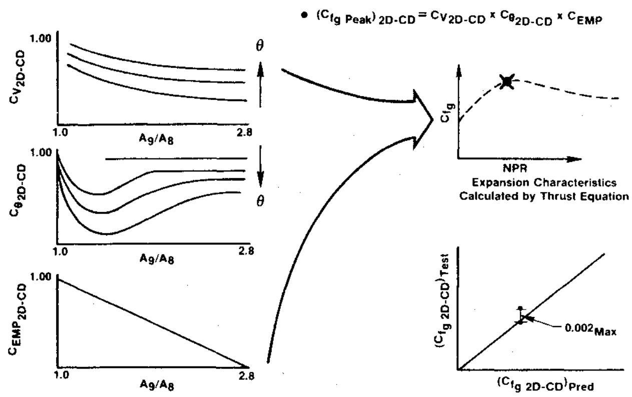


Fig. 6 2D-CD nozzle performance prediction technique.

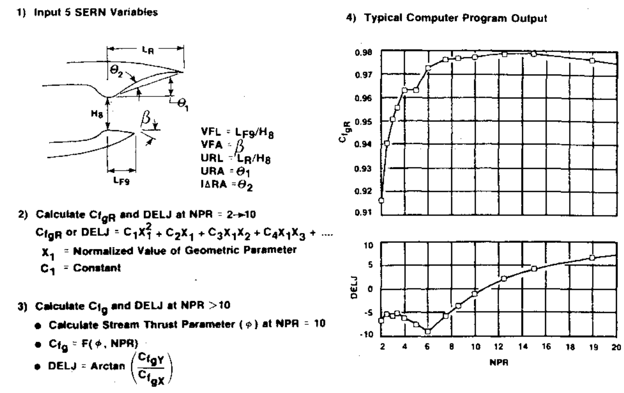


Fig. 9 SERN prediction technique.

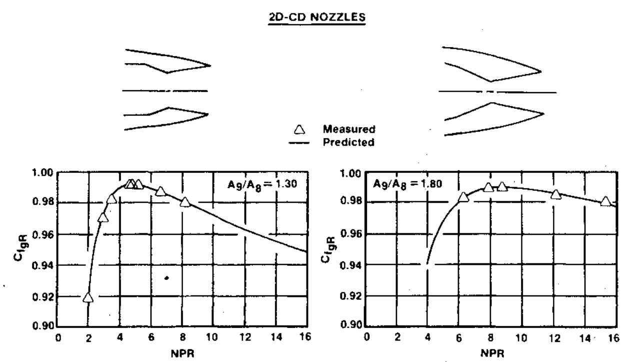
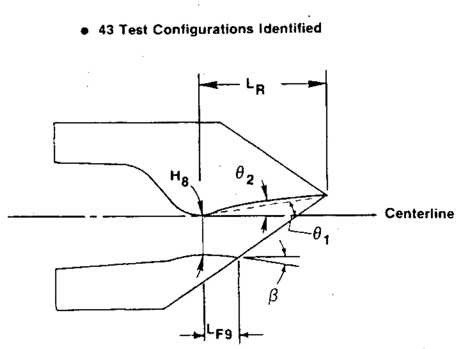


Fig. 7 Comparison of predicted vs measured performance for 2D-CD nozzles.



Variables	Symbols	Variable Range	
Ventral Flap Length (VFL)	L_{F9}/H_8	0.4	1.4
Ventral Flap TE Angle (VFA)	β	-10°	+10°
Ramp Length (URL)	L_R/H_8	2.0	7.0
Initial Ramp Deviation Angle (IΔRA)	$(\theta_2 - \theta_1)$	2.0°	8.0°
Ramp Chordal Angle (URA)	θ_1	4.4°	13.4°
Nozzle Pressure Ratio	P_{T8}/P_o	2	10

Fig. 8 SERN variables selected for test.

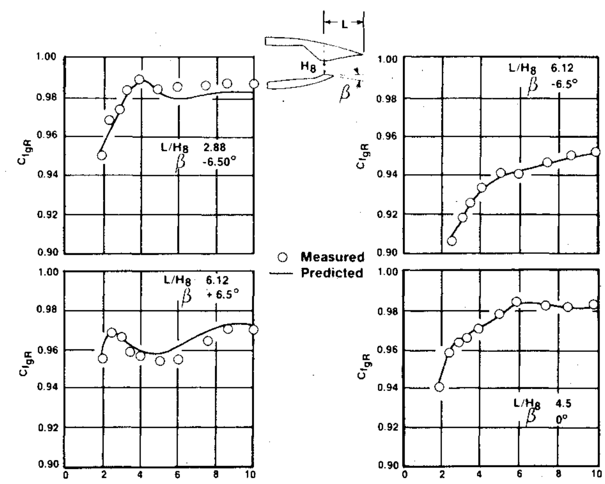


Fig. 10 Comparison of measured and predicted SERN thrust coefficients.

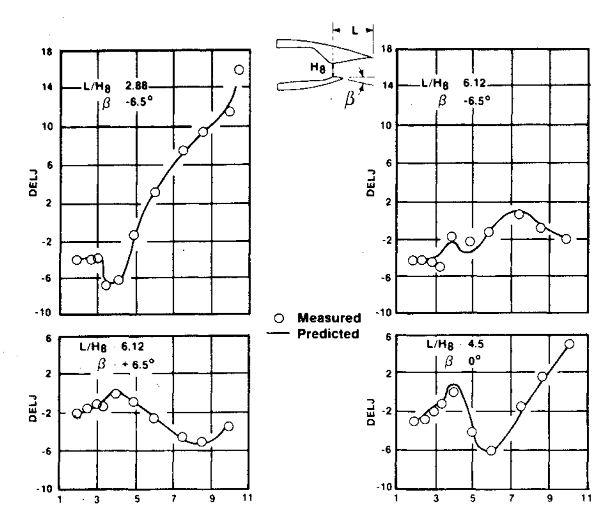


Fig. 11 Comparison of measured and predicted SERN thrust vector angles.

included resultant nozzle thrust coefficient (C_{fg_R}), effective jet vector angle (DELJ) and nozzle discharge coefficient (C_{D_8}).

At each of the ten nozzle pressure ratios tested, regression analysis was used to develop an equation for C_{fg_R} and DELJ. The method was extended to fully expanded nozzle pressure ratios using a constant stream thrust calculation. The empirical technique has been computerized for efficiency of utilization in a General Electric computer program called SERN. A description of the input parameters, the computations, and the computer program output is shown in Fig. 9. For C_{fg_R}, the equation correlated all the measured data for the 43 configurations to within about ±0.5%. For DELJ, the equation correlated all the measured data to within about ±2 deg.

Comparisons of the measured data for several of the 43 configurations with that predicted by the equations are shown in Figs. 10 and 11 for C_{fg_R} and DELJ. Excellent agreement is seen for configurations having both high and low levels of C_{fg_R} over the NPR range. For DELJ, excellent agreement is demonstrated for configurations having large differences in the variation of DELJ with NPR.

Comparisons of the predictions from the empirical procedure with measurements on SERNs not included in

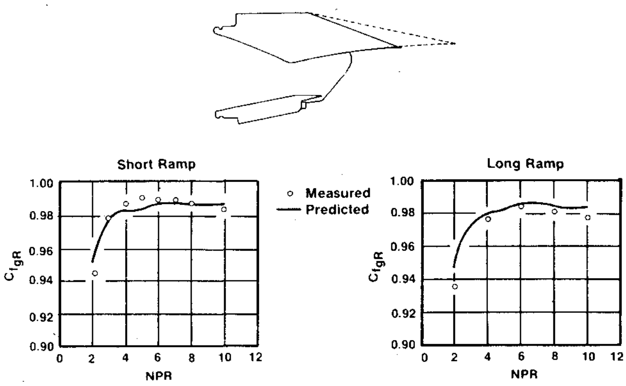


Fig. 12 Comparison of measured and predicted performance for SERN configurations not included in data base.

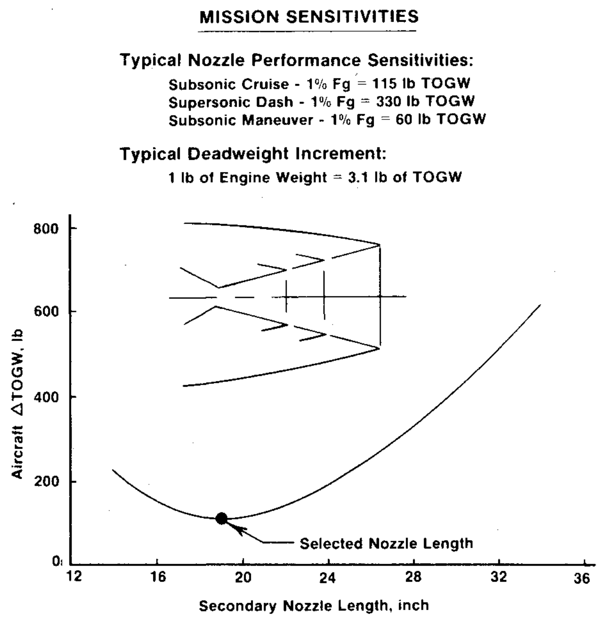


Fig. 13 C-D nozzle flap length sensitivity study.

development of the procedure have been made. Good agreement was obtained for a large number of SERN configurations. Two typical examples are shown in Fig. 12.

Other Uses for Internal Performance Prediction Techniques

Besides being essential for evaluating nozzle concepts in the preliminary design process, these techniques are also valuable for detailed nozzle design and in the formulation of control schedules.

For example, one common trade study is to determine the optimum secondary nozzle flap length. As this length changes, the nozzle weight, internal performance, external boattail drag, and the nozzle actuator sizes all change. Detailed performance estimates are required as a function of flap length along with the mechanical design parameters, such as weight and actuator requirements. The best secondary nozzle flap length is then determined by finding the secondary flap length which gives the minimum aircraft takeoff gross

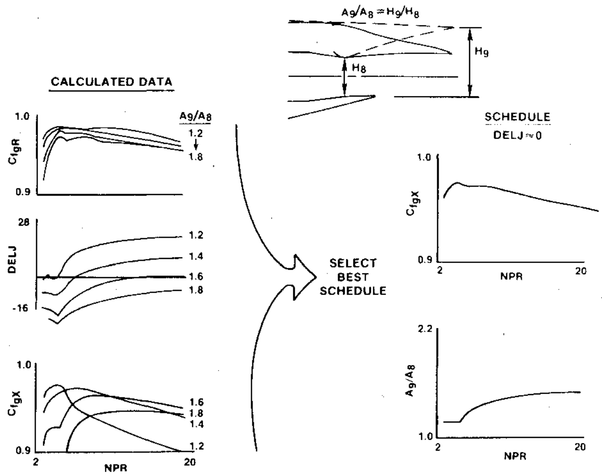


Fig. 14 Use of SERN program to schedule nozzle for best performance.

weight (TOGW) as shown in Fig. 13 using airframer-supplied sensitivities.

Another important use for these internal prediction procedures is for the development of control schedules for the nozzles. For example, a SERN may be continuously trimmed to keep the effective thrust vector angle as close as possible to 0 deg relative to the engine centerline for forward mode flight. In Fig. 14, the resultant thrust coefficient $C_{f_{gR}}$, thrust vector angle DELJ, and axial thrust coefficient $C_{f_{gX}}$ are plotted as a function of nozzle pressure ratio for a range of upper flap positions. The desired control schedule is then achieved by selecting the upper flap position (A_9/A_8) such that $C_{f_{gX}}$ is maximized and DELJ remains near zero.

IV. Concluding Remarks

An approach is described for design of advanced exhaust systems. This approach emphasizes the need for fast and accurate prediction of internal performance.

Techniques have been developed for SERNs and 2D-CD exhaust nozzles. These methods, together with previously developed techniques for axisymmetric nozzles, satisfy the requirement for evaluating initial exhaust nozzle concepts and for performing trade studies in later design stages.

The 2D-CD prediction method was developed through conventional parametric testing and analysis. The SERN, however, has too many design parameters for conventional parametric testing. Consequently, a response surface experiment was utilized very successfully to develop an accurate prediction technique.

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