Design and Development of a Mixer Compound Exhaust System

Walter L. Blackmore* and Craig E. Thompson†
Garrett Turbine Engine Company, Phoenix, Arizona

Lower engine fuel consumption has become a dominant factor in turbofan engine design owing to rapidly increasing fuel costs. One engine component with a large impact on engine performance is the exhaust system. Previous exhaust system studies have demonstrated the significant exhaust system efficiency gains available through mixing of the core and bypass flows. Typically, an extensive, costly rig and engine program is required to develop and optimize these gains. The purpose of this paper is to present the results of the low-cost design system used for the NASA/Garrett quiet, clean, general aviation turbofan (QCGAT) mixer nozzle design and development. The scale model and full-scale engine test results confirm the predicted 3-5% reduction in cruise fuel consumption. This unique design system, which is based on integrating advanced three-dimensional viscous numerical methods with empirical optimization techniques, is summarized and detailed comparisons with test data are presented. The ability to accurately predict relative performance of mixer systems with substantially reduced development time and cost savings is demonstrated.

Nomenclature

A	= area, cm² (in.²)
$\AE$	= lobe aspect ratio
BPR	= bypass ratio
C_D	= flow coefficient
C_{DS}	= splitter or mixing plane flow coefficient
C_F	= thrust coefficient
CFA	= compound flow analysis
C_{FT}	= total thrust coefficient
CP	= contact perimeter, cm (in.)
CRDP	= cruise design point
D	= mixing duct diameter, cm (in.)
D_E	= diameter of equivalent area circle, cm (in.)
D_H	= hydraulic diameter, cm (in.)
D_{HE}	= equivalent hydraulic diameter, cm (in.)
F_N	= net thrust, N (lb)
$f(\ )$	= functional parameter
K	= loss ratio
M	= Mach number
N_1	= low rotor speed, rad/s (rpm)
N_2	= high rotor speed, rad/s (rpm)
P_S	= static pressure, kPa (psi)
P_T	= total pressure, kPa (psi)
P_∞	= ambient pressure, kPa (psi)
s	= lobe spacing, cm (in.)
SLS	= sea-level static
T_T	= total temperature, K (°F)
T_{T5}	= total temperature at rig measurement station, K(°F)
TR	= lobe taper ratio
TSFC	= thrust specific fuel consumption, kg/h/N (lb/h/lb)
V	= velocity, m/s (ft/s)
w	= lobe width, cm (in.)
W	= total air weight flow, kg/s (lb/s)
WP	= wetted perimeter
X	= mixing duct length, cm (in.)
Z_C	= characteristic length at onset of coalescing core region
$(\ )_1$	= core stream properties
$(\ )_2$	= bypass stream properties
$(\ )_{5.2}$	= core nozzle rating station
$(\ )_{14.0}$	= bypass nozzle rating station
3-D	= three dimensional
γ	= specific heat ratio
Δ	= difference
δ	= pressure divided by standard sea-level static day pressure
η_{mix}	= percent mixing (mixing efficiency)
θ	= temperature divided by standard sea-level static day temperature
π	= constant = 3.14159265
τ_w	= wall shear stress, kPa (psi)
$\bar{\omega}$	= loss coefficient

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*Senior Supervisor, Installations, Fans, and Analysis. Member AIAA.
†Supervisor, Installations.

Introduction

RAPIDLY rising fuel costs have placed increased emphasis on the design and development of fuel efficient turbofan engines. The exhaust system is one of the engine components with a large influence on thrust specific fuel consumption (TSFC). It has been proven theoretically and experimentally that engine efficiency can be improved significantly by mixing the core and bypass gases prior to discharging them from the nozzle. Because of the complex three-dimensional flowfield, the design and development of this type of exhaust system has been traditionally dependent upon model rig testing, which is time consuming and very expensive. In contrast, the design and development philosophy utilized on the NASA Quiet, Clean, General Aviation Turbofan (QCGAT) Engine Program was based on integrating advanced three-dimensional viscous numerical methods with current state-of-the-art preliminary design procedures, followed by a minimal rig verification test program. This approach led to significant time and cost savings, yet the design objectives and performance goals were exceeded.

The purpose of this paper is to present the NASA QCGAT mixer compound nozzle design and development procedures. The advanced analytical tools and empirical correlations are described and compared to the rig and full-scale engine test data which were extracted from Ref. 1. The paper describes how these empirical and advanced analytical design methods were integrated into an overall design system to produce program time and cost savings.

Design System Summary

During the NASA QCGAT Program, the mixer compound nozzle design system shown in Fig. 1 was used to achieve the

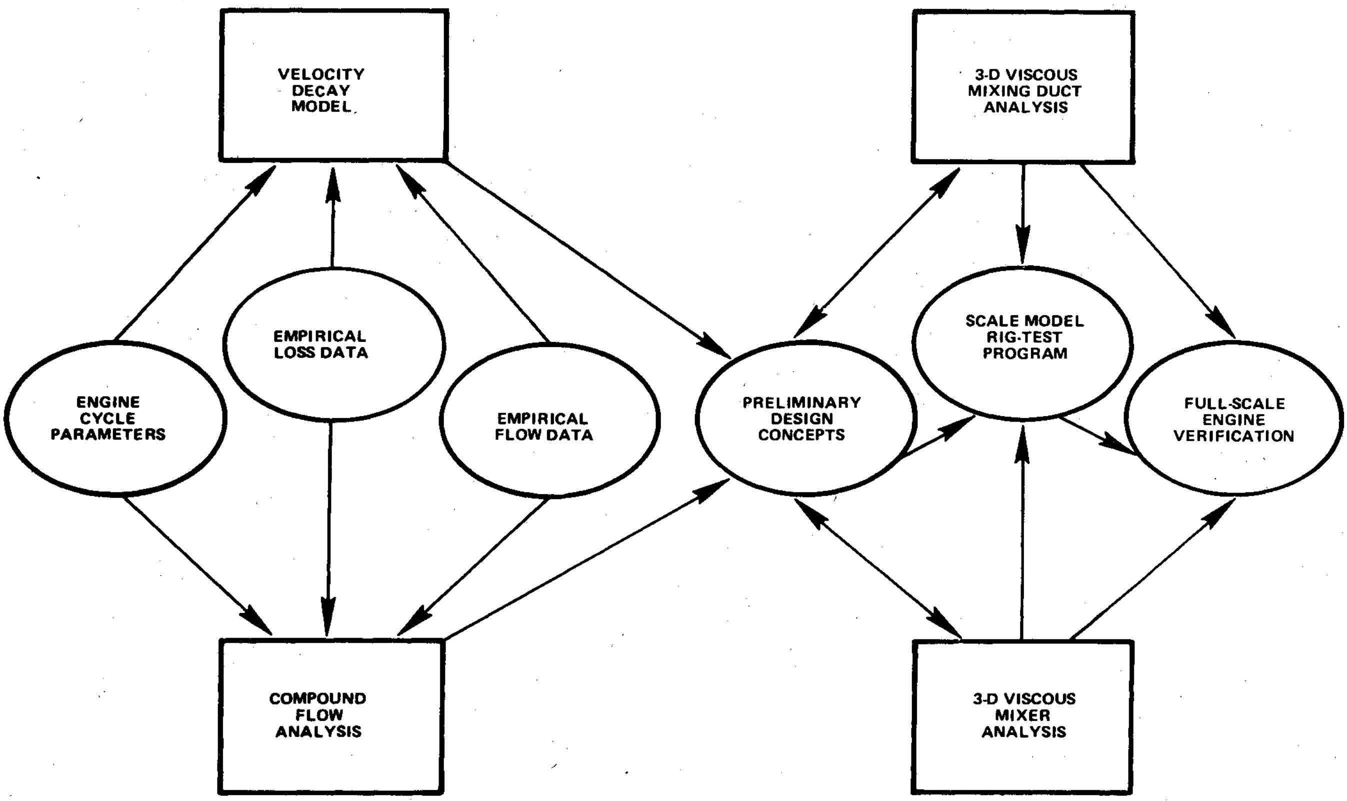

Fig. 1 Mixer-compound nozzle design system.

Table 1 Cost and time comparison of numerical analysis dominated development and test dominated development

Model test[a]			Numerical analysis[b]		
Task	Cost[c]	Elapsed time	Cost[c]	Elapsed time	Task
Geometry definition	8.1	15.4	8.1	15.4	Geometry definition
Model design	7.2	15.4	4.0	7.7	Computer input
Hardware fabrication	38.5	46.2	...	...	...
Test program	38.7	7.7	5.4	7.7	Computer execution
Data analysis	7.5	15.4	3.7	7.7	Data analysis
Total	100.0	100.0	21.2	38.5	Total

[a] Based on one additional configuration in existing model program. [b] Based on one additional configuration in existing analytical study effort. [c] Percent of total experimental program.

program goals instead of a multiphase rig test program. The design system is a unique combination of empirical preliminary design procedures and a detailed design approach based predominantly on numerical analysis. The system includes a single rig verification test prior to full-scale engine test verification.

The preliminary design procedure comprises two modules. The compound flow analysis module provides geometric area sizing, design performance, and off-design performance predictions for engine cycle studies. The velocity decay module is used to optimize the mixer lobe geometry and mixing duct length, as well as to establish the overall mixing efficiency. These preliminary design optimization modules rely heavily on the existing empirical data base that will be discussed in more detail later.

The detailed design procedure has three modular elements. Two 3-D viscous numerical analysis modules are used to analyze the flow in the mixer lobes and the mixing duct, thus providing more design information than is normally available from extensive rig tests. The third detailed design module is the rig verification test. Test data are still required to substantiate the performance predictions; however, the need for extensive parametric testing has been eliminated. For example, the QCGAT rig verification testing consists of one facility entrance with three mixer lobe candidates and two mixing duct variants. A total of only ten performance data points is required to confirm the optimum configuration selection. It should be noted that all five test configurations selected with the numerical methods exceeded the pretest goals.

At the end of the QCGAT test verification phase, a cost and time comparison of 3-D viscous analysis and the rig test was conducted. The purpose of this study was to establish the benefits of the analytically dominated design process relative to the rig test dominated process. The results are presented in Table 1. The study assumed an analysis effort was underway and that a rig test program would be required. Hence the program startup costs or special adapter and survey hardware

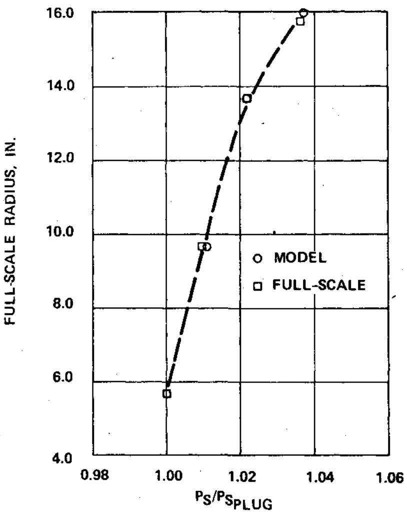

Fig. 2 Static pressure profile at the mixing plane.

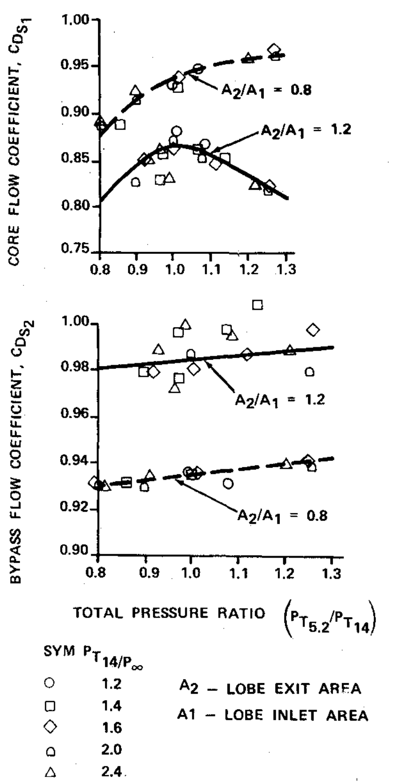

Fig. 3 Mixing plane flow coefficients.

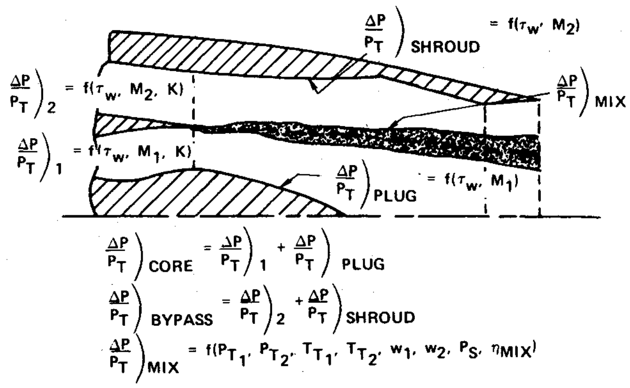

Fig. 4 Compound flow analyses, total pressure losses.

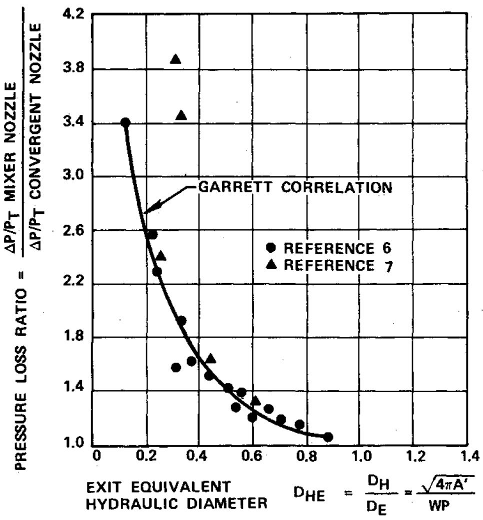

Fig. 5 Mixer lobe minimum loss correlation.

costs were not included. The results show the analytically dominated program costs were approximately 21% of the test dominated program and were completed in 39% of the time—a 79% cost savings and a 61% time savings. The dominant cost and time savings were realized in the hardware cost and fabrication time.

Preliminary Design Procedure

The preliminary design procedure is structured to provide the ability to rapidly optimize design configurations, including off-design performance matching for engine cycle analysis. The compound flow analysis (CFA) module is the first element of the preliminary design process and is used for design and off-design performance prediction as well as geometric area sizing. It is based on the compound choking criterion from Ref. 2,

$$\sum_{\text{throat}} \frac{C_{Di}A_i}{\gamma_i}\left(\frac{1}{M_i^2}-1\right)=0 \tag{1}$$

The static pressure at the mixing plane is also assumed to be constant. Previous test data have shown that the static pressure is constant if there is little or no wall curvature at the mixing plane. The QCGAT rig and engine data indicate that the static pressure gradient for configurations with reasonable curvature is less than 4%, as shown in Fig. 2. Since this pressure is used to compute airflow split, the impact of a nonconstant static pressure is an error in estimating the flow capacity at the mixing plane. Generally, this error is small and can be accounted for in the flow coefficients.

The flow coefficients used in the CFA module are obtained from empirical correlations. The mixing plane flow coefficients are dependent on the flow contraction or diffusion across the lobe. These coefficients collapse to a single-valued curve when correlated against the total pressure split, as shown in Fig. 3. Knowledge of the level and characteristic shape is relatively unimportant for design-point studies. The characteristic shape must be known for off-design performance predictions, and the level must be known for final engine exhaust system sizing. The exit flow coefficients have the same characteristics as unmixed exhaust systems. However, a level adjustment is required due to the thermal mixing process.

Total pressure losses are assigned upstream and downstream of the mixing plane as depicted in Fig. 4. The shroud friction loss is assigned to the bypass stream, and the centerbody loss is assigned to the core stream. The mixing loss is distributed between both streams. The mixer lobe losses are obtained from standard friction loss calculations and the mixer loss correlation presented in Fig. 5. It should be noted that the correlation is a good predictor of the minimum mixer loss.

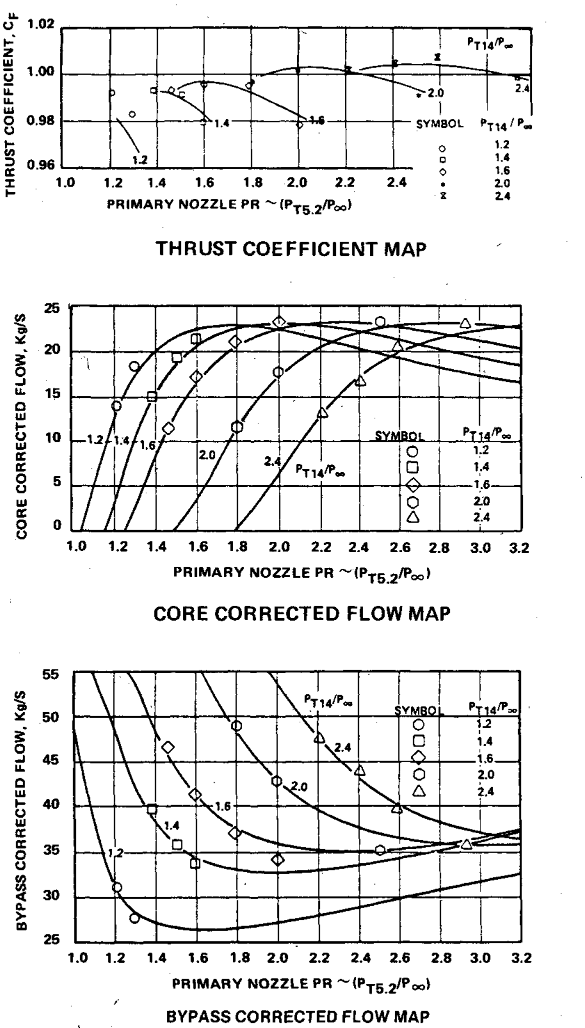

Fig. 6 Test data comparison with predicted off-design performance maps.

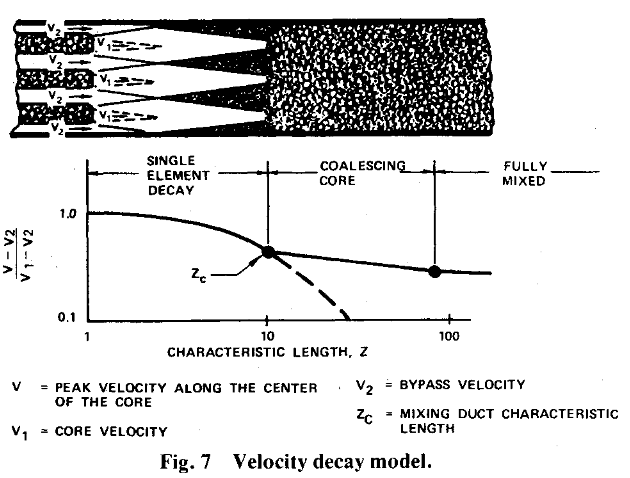

Fig. 7 Velocity decay model.

Once estimates of the losses and flow coefficients have been obtained, the off-design nozzle performance maps can be generated using the compound flow analysis. The predicted maps agree well with the test data shown in Fig. 6. These performance maps are then used to optimize the engine cycle. For many engine cycles, it is easier to represent the mixer-compound exhaust system with performance maps, rather than incorporating the loss and flow coefficient accounting into the cycle deck.

The second element of the preliminary design process is the velocity decay model that is shown in Fig. 7. This velocity

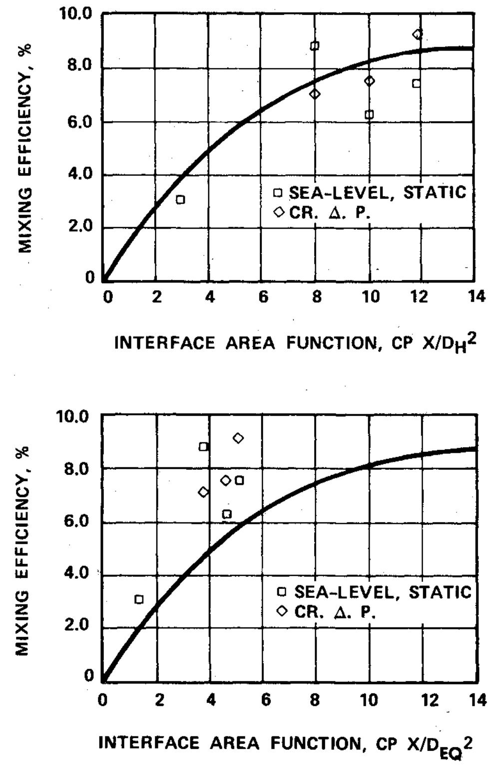

Fig. 8 Comparison of QCGAT-tested mixing efficiencies with modified Frost correlations.

decay concept parallels an external jet wake decay model developed by NASA.[3-5] The mixing process is divided into three distinct zones. The single-element decay zone is where rapid mixing and rapid velocity decay occur. In the second, or coalescing core zone, the mixing process is significantly slower, which yields a much lower rate of peak velocity decay. The third zone is the region of fully mixed flow. The single-element decay zone is the area of practical interest, since designs operating in the coalescing core zone require significant increases in mixing duct length to provide a practical change in mixing or peak velocity decay. The transition point between the single-element decay and coalescing core zone establishes the practical mixing duct length for a given mixer lobe geometry. This point is called the mixing duct characteristic length. This length and its associated velocity decay may be calculated from the mixer lobe geometric parameters:

$$\frac{V-V_2}{V_1-V_2}=[1.0+(0.15Z_c)^a]^{-1/a} \qquad (2)$$

$$Z_c=12\left[1+\frac{1}{4}\frac{S}{W}\right]^{2/3}\left(\frac{S}{W}\right)^{1/3}\left[1+\frac{(8/3)(1/D_{HE})-1}{1+5(1-1/\mathrm{TR})^8}\right]^{-1}$$
$$\times\left[1+\frac{1}{3}\frac{R}{S}\sqrt{\frac{A_1}{A_2}}(\mathrm{BPR})^2\right]^{-1} \qquad (3)$$

where

$$a=4.0\left(2.0-\frac{1.0}{\mathrm{TR}}\right)\left[1+\frac{8.0}{3.0}\left(\frac{1}{D_{HE}}-1.0\right)\right]^{-1.0} \qquad (4)$$

The effective mixing duct length is then calculated from the characteristic length:

$$X_c=Z_c^{1/b}D_{E_{\mathrm{lobe}}}C_D\sqrt{1+M_1}\,[1.0+0.2(V_2/V_1)^{1/4}(A_1/A_2)^{1/2}] \qquad (5)$$

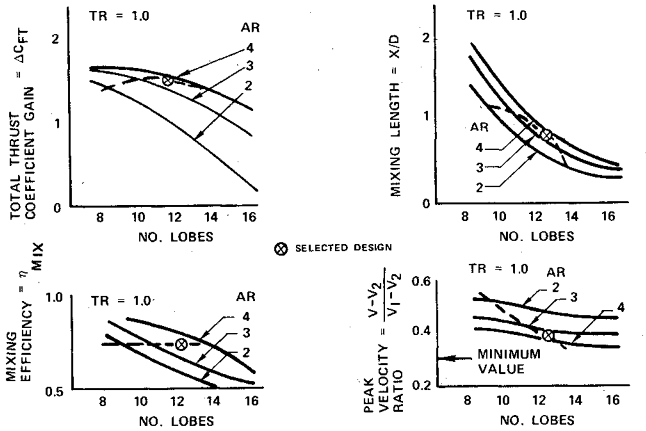

Fig. 9 Effect of lobe number and aspect ratio on performance criteria.

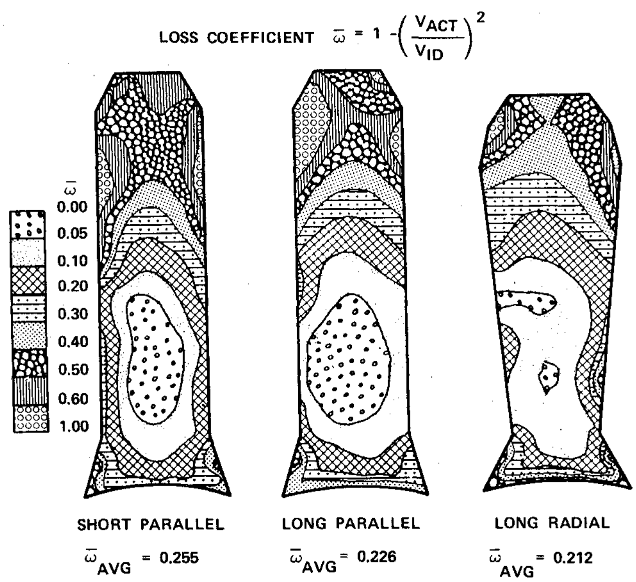

Fig. 10 Comparison of predicted loss coefficients.

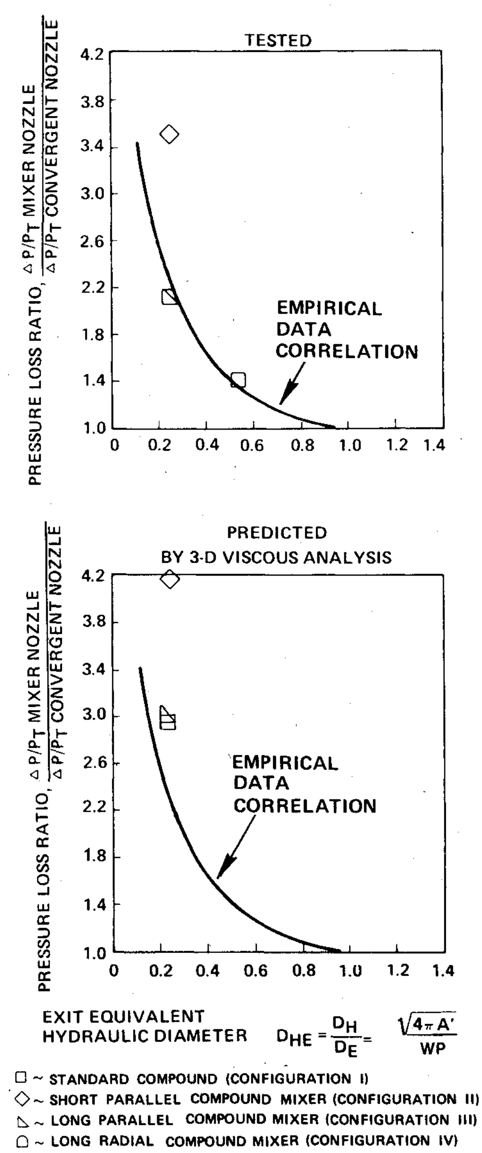

Fig. 11 Mixer pressure losses.

where

$$b = 1 + [3((V_1/V_2)^2 - 1)]^{-1} \tag{6}$$

The effective mixing efficiency is obtained from the Frost correlation[7] using the effective mixing duct length. Care must be taken when applying the Frost correlation to annular mixers or mixing ducts with a centerbody, since it was derived from mixing data in a plain, straight pipe. Correlation studies of annular mixer data (Fig. 8) have confirmed that the Frost curve is a valid predictor if the hydraulic diameter at the mixing plane is used in computing the interface function. Use of other diameter definitions makes the Frost correlation appear overly conservative.

The velocity decay module is combined with the CFA module and the loss correlations to conduct mixer optimization studies. Typical results from the QCGAT design-point studies are summarized in Fig. 9. The results provide an assessment of the influence of mixer lobe geometric parameters on thrust gain, required mixing duct length, and mixing efficiency, and other parameters such as the peak velocity decay ratio. These parametric studies are used to identify preliminary design concepts for detailed design evaluation.

Detailed Design Procedure

The core of the detailed design procedure is two advanced 3-D viscous analysis techniques. The method used to analyze the mixer lobes is a numerical solution of the 3-D compressible Navier-Stokes equations consisting of an equation-splitting technique applied to the momentum equation.[8] This method provides predictions of velocity, pressure, and loss contours, and also provides the designer with excellent flowfield visibility, including insight into the loss generation mechanisms. For example, the QCGAT lobe losses were dominated by the secondary flows in the corners; but a lobe length change, which changed the radial rate of diffusion, significantly improved the loss distribution and reduced the integrated losses as shown in Fig. 10. Test data and empirical correlation comparisons have confirmed that this method is capable of distinguishing between high- and low-loss mixers, as shown in Fig. 11. In addition, the predicted absolute loss coefficient levels are within 8% ($\Delta\bar{\omega}/\bar{\omega} \leq 0.08$) of test data levels (as reported in Ref. 8).

The core and bypass velocity, pressure, and temperature contours exiting the mixer are combined to form the input for the second 3-D viscous analysis tool. The mixing duct is analyzed using a modified Spalding-Patankar 3-D elliptic numerical solution. This method also provides predicted contour plots of pressure, velocity, and temperature for the mixing duct flowfield. This analysis method is known to predict overmixing of the flow in accelerating regions, as demonstrated by the temperature profiles presented in Fig. 12. However, good guidance is provided in ranking candidate mixing duct systems. The comparison of predicted ranking

Table 2 Comparison of 3-D viscous mixing efficiency ranking with test data

Configuration	Predicted 3-D viscous numerical analysis mixing efficiency ranking	Tested mixing efficiency η_{mix} % Takeoff power	Cruise power
Short parallel	1	89.0	72.1
Long radial	2	51.4	65.5
Long parallel	3	37.1	60.8

Table 3 Scale model test performance summary

Model No.	Compound mixer	Configuration, X/D	Sea-level static 298 K (77°F) C_{FT}	η_{mix} %	Cruise, $M=0.8$ alt = 12,192 m (40,000 ft) C_{FT}	η_{mix} %
Design goals	...	...	0.957	75.0	0.9940	75.0
Test goals	...	0.750	0.9782	75.0	1.0005	75.0
I	Compound	0.752	0.9897	30.5	0.9940	...
II	Short parallel	0.752	0.9932	89.0	1.0050	72.1
III	Long parallel	0.752	0.9902	37.1	1.0032	60.8
IV	Long radial	0.752	0.9918	51.4	1.0075	65.5
V	Short parallel	0.501	0.9902	62.6	1.0068	76.2
VI	Short parallel	0.626	0.9908	75.6	1.0066	92.2

Table 4 Comparison of QCGAT engine test results with predicted performance improvements; sea-level static, ISA; F_n = 17512.64 N (3937.00 lb)

	Cycle[a] model	Engine test[b]
Δ TSFC/TSFC	−2.7%	−3.1%
ΔT_{T5}	−7°C (−13°F)	−10°C (−19°F)
$\Delta N_2/N_2$	−0.3%	−0.4%
$\Delta N_1/N_1$	−0.9%	−1.6%
$\Delta WAT/WAT$	+1.5%	+1.5%

[a](Mixer-coannular × 100)/coannular. [b]Test date, Oct. 31, 1978.

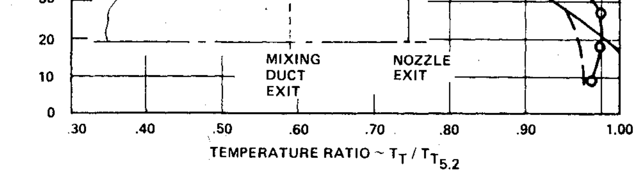

Fig. 12 Exit temperature profiles.

order with tested mixing efficiency levels is in excellent agreement with the test data shown in Table 2.

The 3-D viscous numerical methods used in the detail design procedure provide the engineer with the capability of conducting computer experiments. These numerical experiments provide more flowfield design information than can be reasonably obtained in a test rig. The information is obtained faster and at a lower cost. As a result, the rig test Program is reduced to a single-facility entry verification performance test. The number of test configurations is reduced significantly, and each configuration can be expected to perform well. For example, during the QCGAT Program, three mixer lobe geometries were selected for testing in the rig verification phase. In addition to the mixer lobes, two mixing duct variants and a baseline compound configuration were also selected for testing. A performance summary of all six test configurations is presented in Table 3. All the mixer configurations exceeded the thrust coefficient goals, but only the short parallel lobe design met the mixing efficiency objectives.

Full-Scale Engine Verification

The final proof of any component design system is the full-scale engine verification test. The preliminary and detailed design procedures yield a final configuration for engine test evaluation. The rig verification test results are used to update the off-design performance maps generated from the CFA module. The maps are incorporated into the engine computer analysis deck, and the predicted performance gains are compared to the test results. In the QCGAT Program, the short parallel mixer configuration was tested on the engine, and the overall performance gains exceeded the pretest predictions, as shown in Table 4, thus demonstrating the capability of the design system to develop full-scale engine hardware.

Conclusion

Based on the experience gained in the QCGAT Program, a mixer-compound exhaust system can be designed and developed using a numerically dominated design procedure. This procedure provides a more detailed understanding of the flowfield and mixing process than is normally obtained in a rig test. This directly results in an increased ability to model program goals and objectives, as demonstrated on the QCGAT Program. In addition to providing an exhaust system that meets or exceeds rig and full-scale engine test goals, the design procedure is capable of realizing a substantial savings in program cost and time.

Acknowledgments

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