Rapid Calculation of Propulsion System Installation Corrections

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A calculation procedure has been developed to help evaluate installed propulsion system performance during preliminary studies of advanced military aircraft. The method is based on experimental and theoretical data relating geometric and aerodynamic variables to spillage drag, pressure recovery, boundary-layer bleed drag, boattail drag, and nozzle interference effects. The procedure accounts for throttle-dependent effects on total pressure recovery and drag. Maps of standardized format, consistent with an acceptable force accounting system, are used to provide recovery and drag as a function of engine-corrected airflow. A description is presented of the computer program that uses the calculation procedure to correct uninstalled engine data for installation effects. Results are presented to show the agreement obtained between calculated and measured installation corrections.

Nomenclature

A_c	= inlet capture area
A_0	= freestream tube area
A_9	= total nozzle exit area
A_{10}	= fuselage maximum cross-sectional area
$C_{D_{add}}$	= additive drag coefficient, $C_{D_{add}} = D_{add}/q_0 A_c$
C_{DP}	= pressure drag coefficient based on projected area $(A_{10} - A_9)$
$C_{D_{spill}}$	= spillage drag coefficient, $C_{D_{spill}} = D_{spill}/q_0 A_c$
C_p	= pressure coefficient, $C_p = (P - P_0)/q_0$
ΔC_D	= incremental drag coefficient
D	= drag
D_{eq}	= equivalent diameter, $D_{eq} = (4A_{10}/\pi)^{1/2}$
IMS	= integral mean slope parameter
IMS_T	= truncated integral mean slope parameter
K_{add}	= additive drag correction factor
M	= Mach number
N	= number of shocks in shock system, including normal shock
P	= static pressure
P_{T_1}/P_{T_0}	= total pressure recovery at inlet throat
P_{T_2}/P_{T_0}	= total pressure recovery at compressor entrance station
q_0	= freestream dynamic pressure, $q_0 = \rho_0 v_0^2/2$
S/D_{eq}	= nondimensionalized nozzle spacing
$W_2(\theta_2)^{1/2}/\delta_2$	= corrected airflow
X	= axial coordinate
δ	= ratio of total pressure to standard pressure
θ	= ratio of total temperature to standard temperature

Subscripts

0	= freestream station
1	= inlet throat station
2	= compressor entrance station
8	= nozzle throat station
9	= nozzle exit station
add	= additive
BLC	= boundary-layer control
BP	= bypass
lip	= cowl lip
spill	= spillage
T/O	= takeoff

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Introduction

ACCURATE propulsion system performance predictions are necessary to evaluate advanced technology components applicable to military aircraft and to determine overall aircraft mission performance. Engine performance can be degraded seriously due to installing the engine in an aircraft. The effect on aircraft performance due to interactions of the engine installation with the aerodynamics of the aircraft also can be significant. Because of the potentially large impact of these installation effects, every effort should be made to account for them as early as possible in the aircraft development cycle. This paper reports the results of a work effort accomplished to develop an improved method for use in configuration research studies that will correct uninstalled propulsion data for installation effects on advanced military flight vehicles capable of flight speeds from Mach 0 to 4.5. With this method, more reliable estimates can be made of the performance characteristics of conceptual flight vehicles, and the method can be applied quickly, allowing a rapid, complete evaluation of propulsion system performance. The level of detail of the calculation methods is consistent with the type of data now available for preliminary studies of advanced aircraft concepts.

In developing the calculation method, experimental results were used as much as possible, with theoretical calculations used to fill gaps in existing test data. The approach followed in generating this method was to survey calculation procedures and correlate data relating geometric and aerodynamic variables to spillage drag, inlet pressure recovery, inlet boundary-layer bleed, nozzle losses, boattail drag, and other drag or interference effects. A method then was formulated using the most appropriate calculation procedures and data correlations, which is suitable for digital programming. The calculation methods, data correlations, and related information are described in detail in Refs. 1-4.

Calculation Procedure

The calculation procedure is designated as Propulsion Installation and Table Assembly Program (hereafter called PITAP). PITAP (Fig. 1) consists of a central bookkeeping

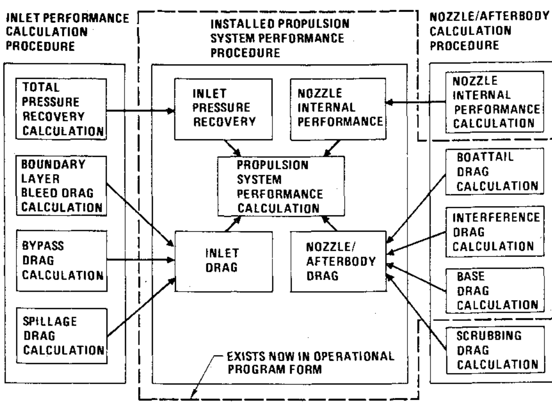

Fig. 1 PITAP procedure.

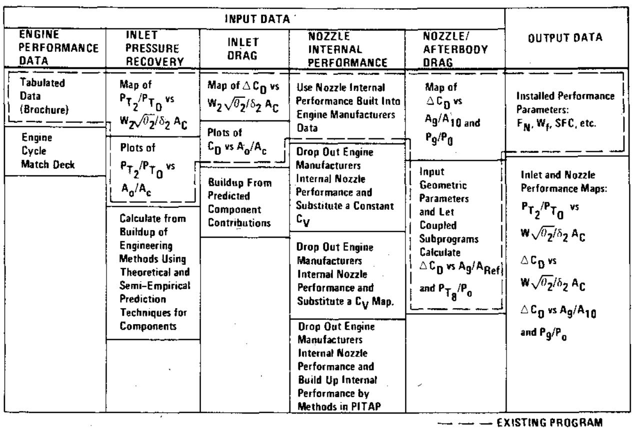

Fig. 2 Calculation procedure options.

and propulsion system performance calculation section, an inlet performance calculation procedure, and a nozzle/afterbody calculation procedure. Portions of the PITAP procedure already have been programmed[2] for the CDC 6600 computer and now are operational on the Air Force Computer System at Wright-Patterson Air Force Base (WPAFB). The calculation procedures contained in the existing computer program (indicated in Fig. 1 by a dashed line) are suitable for calculating installation losses. The remaining procedures exist as documented methods[1] suitable for computer programming. Programming the remaining procedures will improve the flexibility of the program and provide greater capability for making tradeoff studies and more options in the types of input data which can be used (Fig. 2). The discussion of the calculation procedure which follows is divided into two main parts: 1) a description of the computer calculation techniques, and 2) a discussion of input data considerations.

Propulsion System Performance Program

The installed propulsion system performance program is designed to take input data in the form of inlet and nozzle corrections and apply these corrections to the basic engine data. To accomplish this, two major subprograms and a package of several internal subroutines are used. The subprograms, shown in Figs. 3 and 4, are used to obtain the inlet (Fig. 3) and the nozzle/afterbody (Fig. 4) characteristics as a function of throttle-dependent engine airflow, nozzle pressure ratio, and geometry.

Inlet subprogram

The operation of the inlet subprogram is illustrated in Fig. 5 for external and mixed compression inlets. The inlet subprogram accepts the tabulated inlet characteristics and relates

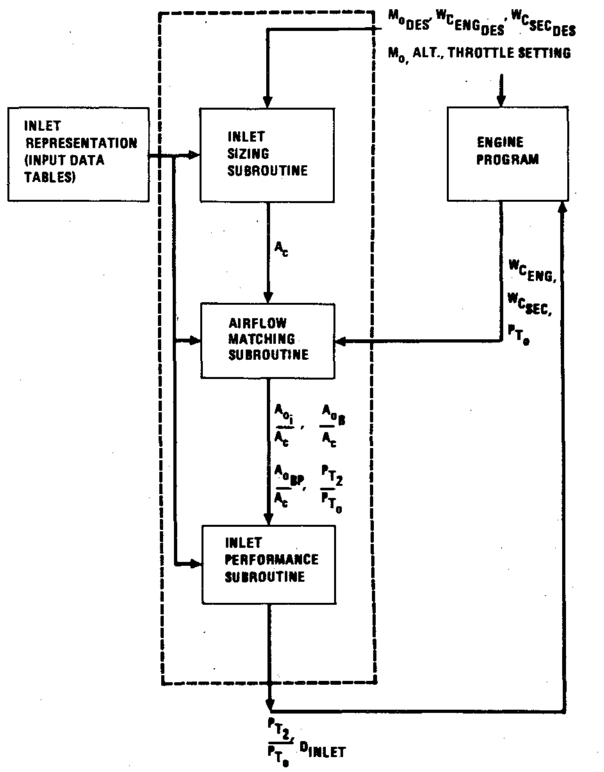

Fig. 3 Inlet subprogram.

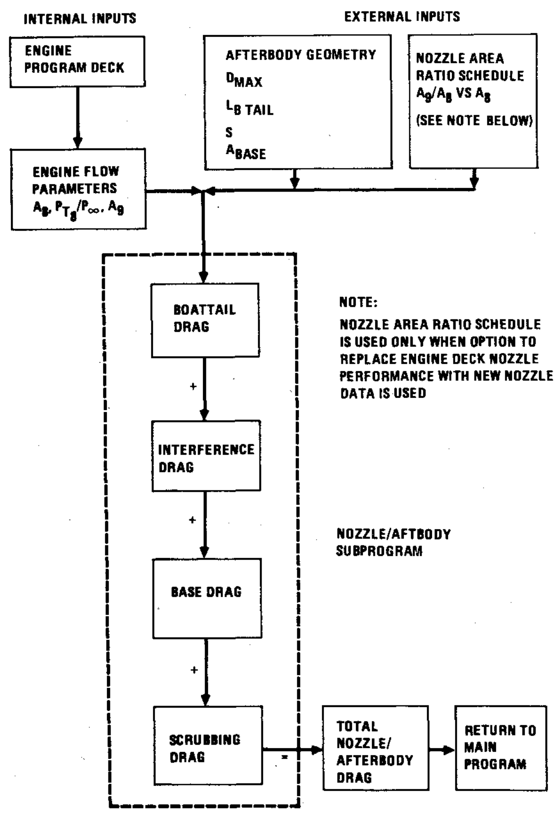

Fig. 4 Nozzle/afterbody subprogram.

them to the proper engine performance by using engine-corrected airflow, $W(\theta)^{1/2}/\delta$, as the matching parameter. Inlet characteristics can be input as either individual performance plots or performance maps, where individual drag and recovery contributions are combined to yield comprehensive maps of recovery and drag as a direct function of engine corrected airflow. This format is often useful in com-

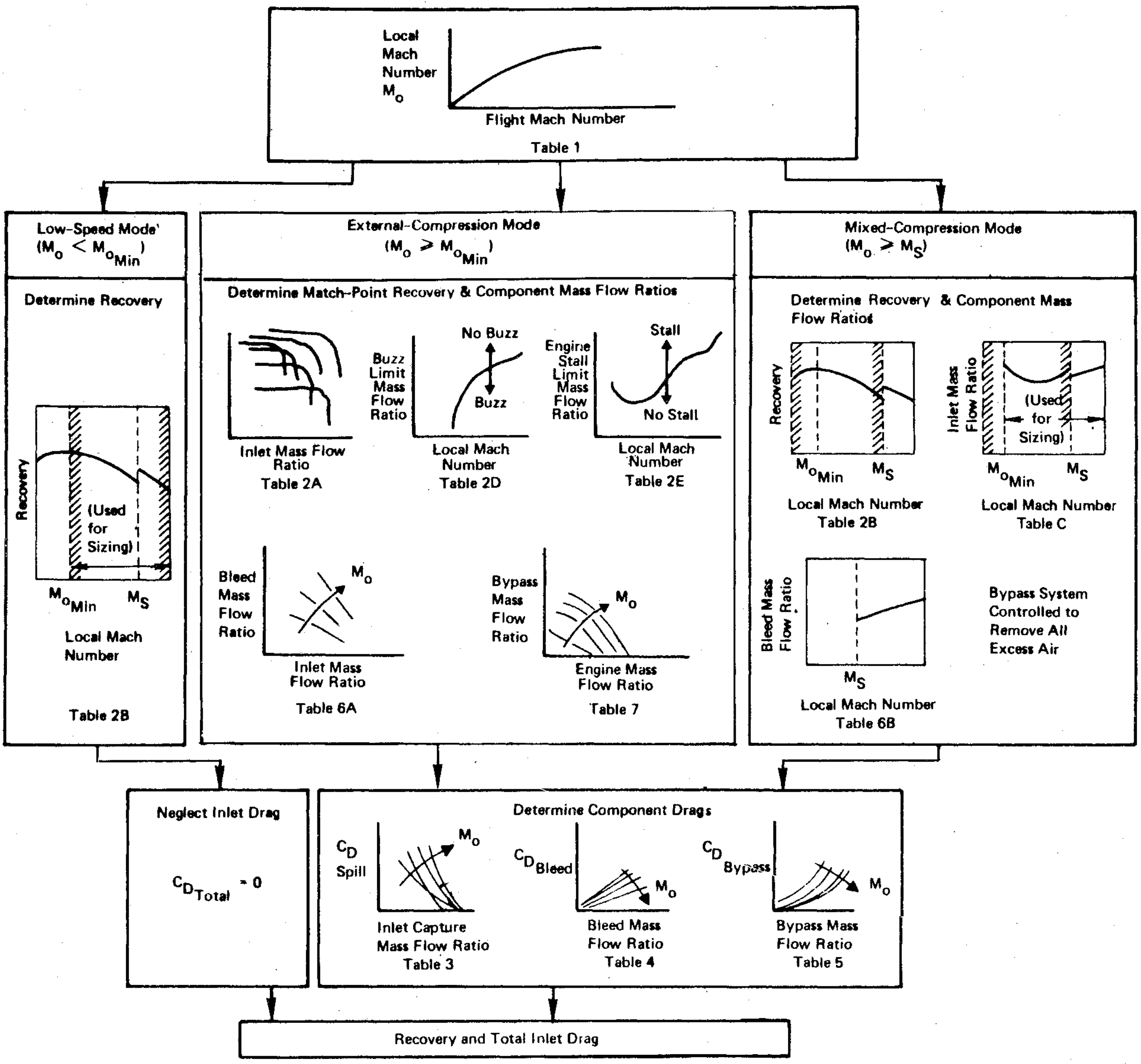

Fig. 5 Performance calculation for external and mixed-compression inlets.

municating between engine and airframe manufacturer. Individual plots are obtained directly from wind-tunnel tests or analytical methods. Either input format may be used. Individual inlet performance maps can be built up from theoretical and semiempirical methods and data if testing has not been accomplished (which is often the situation during preliminary design studies). Engineering calculation methods that can be used to build up inlet performance plots are described in Ref. 1. The changes in engine internal performance due to change in inlet recovery are calculated using the following procedure:

1) Uninstalled engine performance data are input in the form of tables of the following quantities

$$F_N,\ W_F,\ W_2(\theta_2)^{1/2}/\delta_2,\ P_{T_8}/P_0,\ A_8,\ A_9,\ C_{F_G}$$

These quantities are specified as functions of altitude, Mach number, and power setting.

2) Exhaust nozzle flow is calculated by the following equation

$$W_8 = [W_2(\theta_2)^{1/2}/\delta_2]\quad \delta_2/(\theta_2)^{1/2} + W_F - W_{BX}$$

3) The recovery ratio is calculated by

$$\text{ratio} = (P_{T_2}/P_{T_0})_{\text{input}}/(P_{T_2}/P_{T_0})_{\text{MIL 5008B}}$$

4) Using the recovery ratio, corrected values of nozzle flow, fuel flow, airflow, and nozzle pressure ratio are calculated as follows.

$$(W_8)_{RF} = W_8 \times (\text{ratio})$$

$$(W_F)_{RF} = W_F \times (\text{ratio})$$

$$(W_2)_{RF} = W_2 \times (\text{ratio})$$

$$(P_{T_8}/P_0)_{RF} = P_{T_8}/P_0 \times (\text{ratio})$$

Nozzle gross thrust is computed by using the ratio of gross thrusts calculated by program subroutines for 1) MIL 5008B recovery, and 2) recovery from input tables. This ratio is applied as follows. From input quantities

$$F_{G_{\text{old}}} = F_N + W_2 V_0/g$$

Using MIL 5008 recovery

$$F_{G_1} = F_{N_1} + (W_2)_1 V_0/g$$

Using recovery from input tables

$$F_{G_2} = F_{N_2} + (W_2)_2 V_0/g$$

The new gross thrust then is calculated by

$$F_{G_{\text{new}}} = F_{G_{\text{old}}} (F_{G_2}/F_{G_l})$$

Next, the net thrust, corrected for internal losses, is calculated by

$$F_{N_R} = F_{G_{\text{new}}} - (W_2 V_0/g) \ (R_F/R_{F_{\text{MIL}}})$$

$$W_{F_R} = W_F(R_F/R_{F_{\text{MIL}}})$$

The final installed thrust and specific fuel consumption then are calculated by including the effects of external drag

$$F_{N_A} = F_{N_R} - D_{\text{inlet}} - D_{\text{noz}} + D_{\text{ref}}$$

$$SFC = W_{F_R}/F_{N_A}$$

The program uses, for thermodynamic properties, curve-fits of Keenan and Kaye data. These thermodynamic properties are used primarily to calculate exhaust nozzle static pressure and jet velocities. An energy balance is used for exhaust gas calculations. This energy balance calculates exhaust gas enthalpy and pressure from a knowledge of compressor face temperature, airflow, nozzle pressure ratio, and fuel flow.

Nozzle gross thrust calculation procedures are incorporated into the program to handle mixed and nonmixed flow nozzles of the following types: 1) convergent (throat-choked), 2) convergent-divergent (fully expanded), and 3) convergent-divergent (not fully expanded). An internal program calculation procedure also is available to calculate nozzle pressure ratio if it is not included as part of the input data. This calculation procedure assumes fully expanded flow and calculates nozzle pressure ratio from thrust, fuel flow, and airflow. (C_{F_G} is assumed equal to 1.0.)

Nozzle/afterbody subprogram

The purpose of the nozzle/afterbody program is to calculate nozzle internal losses and nozzle/afterbody drag. The program currently uses a procedure that includes nozzle internal performance supplied by the engine manufacturer for his engine. The nozzle/afterbody drag includes all drag elements associated with the exhaust system installation which are affected by the engine power setting. Drag associated with skin friction is included in the airplane drag polars. Drag elements identified as contributors to the nozzle/afterbody drag include: 1) nozzle/afterbody boattail drag; 2) interference effects for multiengine installations; 3) afterbody base drag; and 4) scrubbing drag.

The nozzle/afterbody drag is computed using maps that represent the afterbody drag characteristics, external input geometric data, and fundamental engine data obtained internally from the engine subprogram. The external inputs are required constants that describe the nozzle and afterbody geometry: maximum nacelle diameter, boattail length, lateral nozzle spacing, base area, etc. Fundamental engine data obtained internally from the engine subprogram include nozzle throat area, nozzle pressure ratio, freestream conditions, and ideal gross thrust. An essential geometry input is the nozzle exit area, A_9, which is required for boattail drag computation. This parameter is obtained in either of two ways: 1) from the engine subprogram when the existing nozzle data are used; or 2) from a table of A_9/A_8 vs A_8 which is developed when new nozzle data are used.

The program currently has the format to use for base drag calculation the variation of base pressure, P_b/P_0, as a function of freestream Mach number. Although the format for entering the base drag data is in the program, no base drag data have been entered into the program. The logic used to connect the input drag data and the engine subprogram is illustrated in Fig. 4. The nozzle/afterbody subprogram as yet, does not include provisions for calculating the scrubbing drag element.

The nozzle/afterbody subprogram requires much less external input data than the inlet program. This is because the maps used to obtain nozzle/afterbody drags have been generalized to cover a wide range of possible configurations and are built into the program. Thus, it is necessary to supply as external input data only the geometric parameters used to specify the afterbody geometry.

The generalized maps that are now in the program are shown in Figs. 6-8. Figure 6 shows the variation of boattail

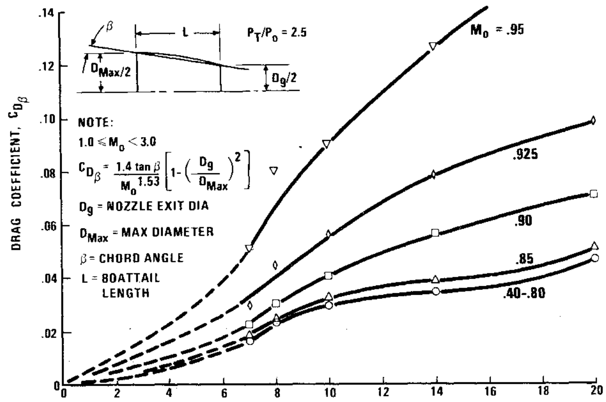

Fig. 6 Nozzle boattail pressure drag coefficients as $f(\beta)$.

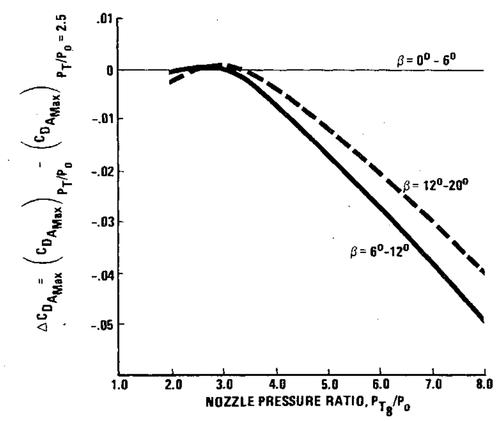

Fig. 7 Boattail drag correction for nozzle pressure ratios greater than 2.5.

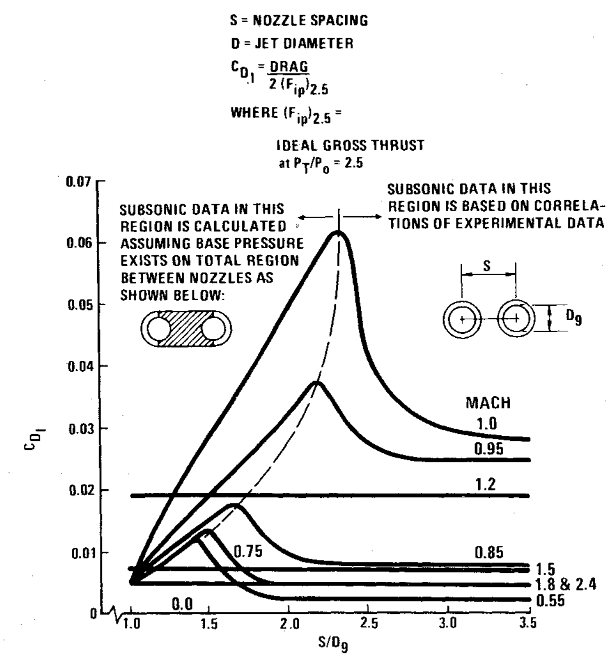

Fig. 8 Nozzle interference drag coefficient.

drag as a function of boattail angle and Mach number for freestream Mach numbers up to 0.95. From Mach 1.0 to 3.0, the equation shown in Fig. 6 is used. These drag data are based on isolated wind-tunnel data for circular arc boattails at nozzle pressure ratios P_T/P_0 of 2.5. For nozzle pressure ratios greater than 2.5, an additional correction is applied to the basic boattails drag coefficient obtained from Fig. 6. This added correction, shown in Fig. 7, is a function of nozzle pressure ratio and boattail angle. This added correction procedure is included in the existing nozzle/afterbody subprogram. Figure 8 shows the data in the nozzle/afterbody subprogram which are used to obtain interference drag for

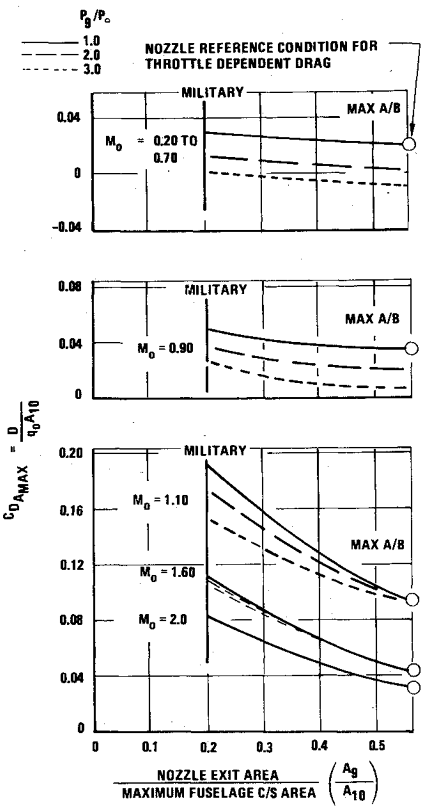

Fig. 9 Nozzle/afterbody drag coefficients as $f(A_9/A_{10})$.

twin-nozzle installations. These data are applicable strictly to installations using convergent-divergent nozzles operating at $P_T/P_0 = 2.5$.

The option is available in the computer program to calculate complete afterbody drag as a function of the ratio of nozzle exit area to maximum fuselage cross-sectional area, A_9/A_{10}. Examples of the drag maps used by the program for the caluclation are shown in Fig. 9.

Input Data Considerations

Experience acquired in applying the PITAP calculation procedure to a variety of military aircraft study configurations (for example, Table 1) has shown that it provides several distinct advantages:

1) By using a standardized format for input data, all personnel who are involved with generating and using the propulsion data know in advance what parameters they will have to work with. This helps communication by saving time and eliminating the chance for misunderstanding.

2) Use of a standardized format for inlet input maps has helped in accumulating a library of inlet performance characteristics for a wide variety of aircraft configurations. This library has made it possible to make quick calculations of installed performance for propulsion systems with similar inlet configurations.

3) The input data format has focused increased attention on inlet/engine compatibility by providing buzz and distortion limits that give early indication of possible incompatibility problems. These limits are determined from test data, analysis, or engineering judgment, depending on what information is available. Although they do not represent absolute limits (at least prior to testing), gross mismatching problems and errors in input data have been detected by using these limits.

4) The accuracy of installed propulsion data is improved easily by substituting more accurate data maps as they become available during the design evolution.

The PITAP procedure generally has been very satisfactory for calculating the installed propulsion system performance for the advanced aircraft configurations to which it has been applied. All of the important inlet parameters can be considered in preliminary design studies, and drag and recovery are varied with throttle setting. This requires that an extensive set of inlet data be prepared for each configuration. For gross preliminary studies, where little is known about the inlet and

Table 1 Applications of PITAP

Configuration designation	Max design Mach number	Inlet configuration	Nozzle/Afterbody configuration	Remarks
Lightweight fighter	2.0	Two-dimensional ramp inlet, normal shock inlet (both fixed geometry)	Single nozzle	Underfuselage-mounted inlet
Air superiority fighter	2.5	Two-dimensional, variable ramp inlets, horizontal ramps, external compression	Twin nozzles, twin vertical tails, horizontal interfairing	Fuselage side-mounted inlets
Fighter/bomber	2.5	Two-dimensional, horizontal ramp, mixed compression inlets	Twin nozzles, single vertical tail	...
Interceptor	3.0	Two-dimensional, vertical ramp, mixed compression underfuselage-mounted inlets	Twin nozzles, closely spaced	
V/STOL	1.6	Half-round, external compression, fuselage side-mounted inlets	Single engine, four swiveling exhaust nozzles	...
VTOL	2.0	Half-round, external compression, underfuselage nose inlet	Twin nozzles, exhausting under fuselage	...

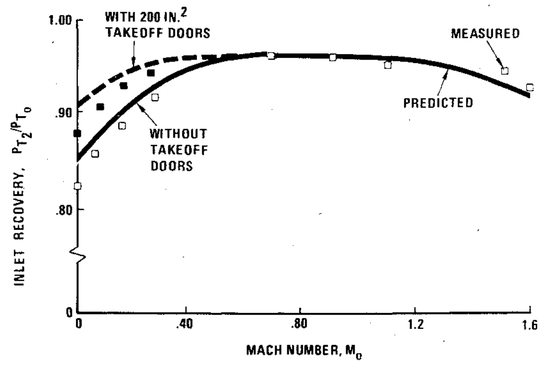

Fig. 10 Comparison of predicted and measured total pressure recovery.

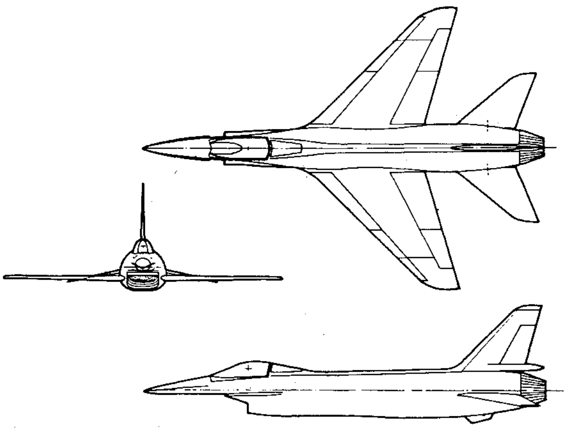

Fig. 11 General arrangement drawing of lightweight fighter study configuration.

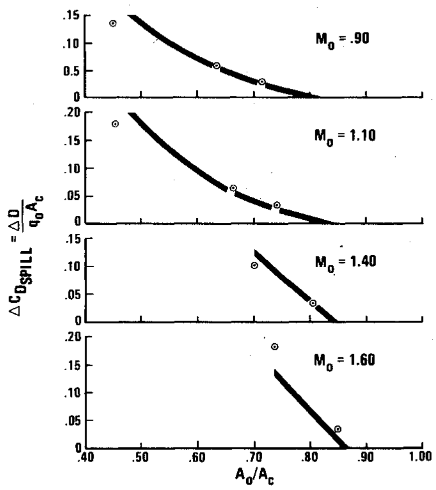

Fig. 12 Comparison of predicted and test data for LWF spillage drag.

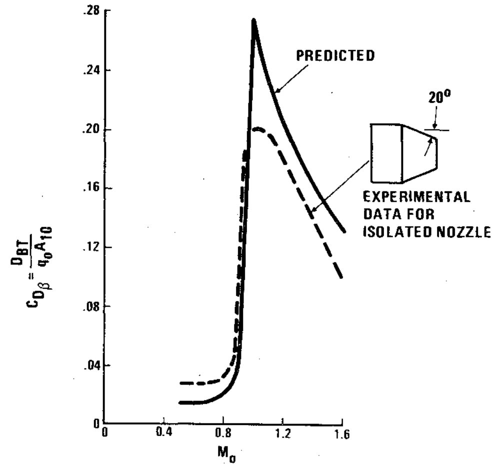

Fig. 13 Comparison of predicted and test data for nozzle/afterbody drag.

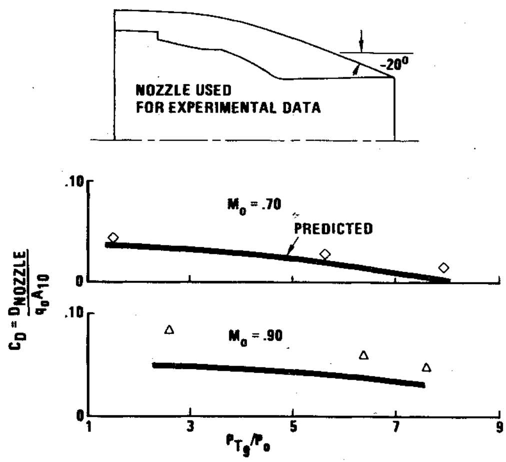

Fig. 14 Comparison of predicted and test data for subsonic nozzle/afterbody drag as $f(P_{T_9}/P_0)$.

nozzle/afterbody, and where mission performance is not extremely sensitive to propulsion system performance, it would be helpful to develop a "limited input" version of the PITAP procedure which requires a minimum of input data. This could be done readily with the existing data base developed for PITAP.

The existing version of the PITAP computer program uses built-in parametric data for obtaining nozzle/afterbody boattail and interference drag. Use of these data makes it necessary to input only a few geometric parameters to calculate nozzle/afterbody drag corrections. Since the programming of the PITAP program, a considerable amount of analytical and experimental work has been accomplished to investigate nozzle/afterbody drag. For example, the Exhaust System Interaction Program[5] has produced a more sophisticated (IMS_T) procedure for predicting nozzle/afterbody drag for single- and twin-engine aircraft. The incorporation of this procedure into PITAP may offer the potential for improved accuracy in drag calculations.

Sample Calculation

To illustrate the results from applying the PITAP installation correction procedure, Fig. 10 presents a comparison of the predicted and measured total pressure recovery for a lightweight fighter (LWF) study configuration (Fig. 11) at flight Mach numbers from 0 to 1.60.[6] Predicted and measured inlet spillage drags are compared in Fig. 12.[7] The predicted nozzle/afterbody drag is compared with test data for the LWF in Figs. 13 and 14.

The predictions of inlet total pressure recovery and spillage drag provide good agreement with experimental values. The nozzle/afterbody drag procedure predicts the trend of drag variations well, and in most cases adequate agreement with experimental data is obtained for preliminary studies.

Conclusions

The PITAP procedure provides a useful tool to calculate the propulsion system installation corrections for preliminary studies of advanced aircraft designs. Input data formats have been developed which make it easy to accommodate either component test data or theoretical data. Additional capability can be obtained by 1) further programming of existing calculation procedures; 2) incorporating results of recent experimental programs and methods developments; and 3) developing a limited input version of PITAP for use when time is not available for preparation of detailed input and/or less accuracy is acceptable.

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