



AEROSPACE INFORMATION REPORT

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Superseding AIR1703

In-Flight Thrust Determination

RATIONALE

AIR1703A has been reaffirmed to comply with the SAE Five-Year Review policy.

FOREWORD

The popularity of SAE AIR1703, In-Flight Thrust Determination, as a resource for guiding and standardizing the approaches to aircraft propulsion system in-flight thrust determination led the E-33 committee in 1996 to assess the validity of the practices set forth in the 1985 document. The committee determined that while the information contained in the document was still valid, there had been sufficient development of technology and changes in practice to warrant a revision to the original document.

While the spirit and intent of the original document have been retained, it has been reorganized by reconvened Subcommittee E-33A to improve the flow of the material for a first-time reader, sections have been rewritten to provide clarity, and the figures have been scrutinized to assure that they support the textual material, are accurate, and are properly labeled. In addition, case studies are included within the appendices to illustrate how the principles and guidelines of this document have been employed.

A brief history of the E-33 committee is given in Appendix A.

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1. SCOPE

In-Flight Thrust Determination, SAE AIR1703 reviews the major aspects of processes that may be used for the determination of in-flight thrust (IFT). It includes discussions of basic definitions, analytical and ground test methods to predict installed thrust of a given propulsion system, and methods to gather data and calculate thrust of the propulsion system during the flight development program of the aircraft. Much of the treatment is necessarily brief due to space limitations. This document and the British Ministry/Industry Drag Analysis Panel (MIDAP) Guide (Reference 1.1¹), which SAE Committee E-33 used as a starting point, can be used to understand the processes and limitations involved in the determination of in-flight thrust. Application to a specific in-flight thrust determination program will require the use of many important assumptions not fully developed in this document, and these assumptions must be evaluated during the conduct of the program.

The determination of in-flight thrust is a complex process. Success depends upon careful planning and meticulous attention to detail throughout the test program. It is important that the participants involved (engine and airframe manufacturers, military service, government agency, etc.) agree at the outset on the definitions and the methods to be used for demonstration. Provisions for flexibility and redundant methods are important to provide for unforeseen difficulties with a particular method.

1.1 Purpose

There are no industry or government standards for determining in-flight thrust or associated uncertainty at present. The purpose of this Aerospace Informational Report (AIR) is to present information and guidance on the selection of methodologies to predict and assess propulsion system thrust during flight development programs of conventional aircraft employing turbofan or turbojet engines. The document is intended to be used as a technical guide, not as a standard or legal document. A companion document, SAE AIR1678 (Reference 1.2), presents procedures for the estimation of uncertainty of in-flight thrust determination. Both documents describe comprehensive procedures and tasks for implementing the methodologies. Each program would select those tasks that are appropriate to meet its particular objectives.

The specific objective of this document is to provide the most current information on:

- a. Test planning considerations and guidelines
- b. Industry practice for the determination of in-flight thrust
- c. Process flow for development
- d. State-of-the-art for instrumentation data systems, modeling, and resulting in-flight thrust capability
- e. Methodology

1.2 Limitations

This document addresses definitions of thrust, force and drag from first principles (when possible). It is limited to fixed-wing and variable swept wing aircraft employing turbojet or turbofan engines.¹ The information in this report is limited to addressing in-flight thrust determination at steady-state conditions with fixed throttle settings (with the exception of a discussion on non-steady-state aircraft test maneuvers).² The scope includes thrust determination for conventional aircraft configurations, excluding the following conditions:

- a. In-flight thrust reverse
- b. Direct lift
- c. Ground effect

Conclusions and recommendations are valid where criteria and data for a specific program application have been identified and measurement uncertainty aspects of the data understood. It is anticipated that this document will be updated periodically as new developments in ground and flight tests occur.

1.3 Overview

This AIR is organized into seven major sections containing the following major topics:

1.3.1 Program Planning Guidelines (Section 3)

The necessity for early involvement of all the participants in the formulation of an integrated test plan is discussed. Specific topics include:

- a. The working group concept is one method suggested for formulating and implementing a plan. The function of this group is described.
- b. The factors to be considered in the selection of method(s) for computing in-flight thrust and the impact which the flight test goals and data validity requirements have on the selection process are presented. Reliance on past experience, judgment, and use of the uncertainty analysis are emphasized.

1.3.2 Definitions and Methodology (Section 4)

This section presents the definitions necessary for the determination of in-flight thrust:

- a. Gross and net thrust are defined along with the justification for the selection of particular reference planes for the definition of inlet and exhaust momentum. Modified gross thrust is introduced and explained in relation to calibration practice. Details of the force derivation and control volume are presented in Section 4.
- b. A thrust/drag bookkeeping procedure, which establishes baseline reference geometry and operating conditions for the throttle-dependent drag terms, is described and terms defined. All aspects of this bookkeeping may not be essential to all applications of in-flight thrust determination, as pointed out in Section 5.
- c. The various nozzle coefficients used for determining flow and thrust in the nozzle option method are defined.

¹ Information on propeller or propfan in-flight thrust measurement can be found in SAE AIR4065 (Reference 1.3).

² In situations where in-flight thrust is being determined at flight conditions that are time variant with either fixed or variable throttle engine conditions, the reader is referred to SAE AIR5020 (Reference 1.4).

1.3.3 Propulsion System Installations (Section 5)

This section discusses the application of thrust/drag bookkeeping for both podded and integrated engine configurations. Inlet and nozzle considerations for variable geometry and unusual installations are addressed briefly.

1.3.4 In-Flight Thrust Methods (Section 6)

This section describes the various options available for determining in-flight thrust:

- a. Overall Performance - This method requires no special engine gas-path instrumentation for implementation. This method is generally the same as the "brochure" option in the MIDAP Guide (Reference 1.1). A special case employs a cycle match computer simulation.
- b. Gas-Path/Nozzle - This method requires special calibrated instrumentation at various engine stations for implementation. A common example is the use of calibrated instrumentation at the nozzle entry station in conjunction with nozzle thrust and flow coefficients. Flow can also be determined from instrumentation at other convenient engine stations. This method is called gas generator options in the MIDAP Guide (Reference 1.1).
- c. Nozzle Exit Traverse - This method uses in-flight measurements of nozzle exit pressures and temperatures to integrate into thrust and airflow. It is not a commonly used method, although there are instances of its successful implementation.
- d. Trunnion - This method involves the utilization of direct in-flight measurement of force at the engine mounts. The force measured at the mounts is a mixture of force terms that present a new set of bookkeeping problems. It has had limited application. It is the only method option which utilizes a direct force measurement in flight.
- e. Examples - Example applications of in-flight thrust methods are presented in the final subsection and carried through this document to show the application of calibration techniques (Section 7) and validation techniques (Section 9).

1.3.5 Calibration Techniques (Section 7)

Methods for calibrating engines and subscale models in ground test facilities are discussed in this section. Subjects included are:

- a. Engine testing in a ground-level test facility (GLTF)
- b. Engine testing in an altitude test facility (ATF)
- c. Scale-model inlet testing to determine throttle-dependent spillage drag
- d. Scale-model nozzle testing relative to facility selection, model design and fabrication
- e. Correction of model data and extrapolation to the full-scale flight vehicle
- f. Scale-model afterbody testing to determine throttle-dependent afterbody forces
- g. Propulsion simulator testing to determine throttle-dependent nozzle, inlet and interference forces

Discussions of facility considerations, test techniques, and examples are included.

1.3.6 Test Data Acquisition Systems (Section 8)

A discussion of general concepts and good practice regarding data acquisition is contained in this section. Sensor and data system requirements for both in-flight testing and testing in ground facilities are discussed for the thrust measurement options described in Section 6. Sensor requirements, signal conditioning, data recording, data processing, datum checks, and calibration are addressed.

1.3.7 Analysis and Validation of Thrust Determination (Section 9)

The use of information from ground and flight test programs to isolate and correct errors and improve confidence in the results is described:

- a. Pre-flight consistency checks are a vital part of the overall performance evaluation. Individual parameters, coefficients and overall performance are compared among model test, full-scale tests and the “math model” using redundant methods. Inconsistencies should be corrected prior to the flight test.
- b. Additional checks of engine operation and performance data are necessary after obtaining engine operating data at static and flight conditions in the aircraft. Comparisons with ground test and math models will continue with particular emphasis on verifying installation assumptions.
- c. Further data verification can be obtained when the aerodynamic drag derived from the propulsion measurements produces a logical drag representation of the aircraft. A more detailed discussion of the fundamentals of this process is given in Appendix C.
- d. Drag determination techniques, which are the basis for the aerodynamic consistency checks are discussed in Section 9.
- e. Examples of test analysis for thrust validation are included in the final subsection.

1.3.8 Appendices

Five appendices are also included:

- a. Appendix A - SAE E-33 Committee Historical Background and Evolution of Documents

This appendix provides a brief history of the E-33 committee and publications.

- b. Appendix B - Bibliography

This appendix provides additional references not cited in the main body of this report.

- c. Appendix C - Thrust and Drag Accounting

This appendix starts from basic fundamentals to outline the principles of thrust, drag, and force accounting which are the foundation for the equations of Section 4. It also provides an overview of the theoretical aspects of air vehicle aerodynamic characteristics and in-flight drag determination techniques, which are the basis for aerodynamic consistency checks discussed in Section 9.

- d. Appendix D - Historical Approach and Fundamental Background to Thrust/Drag Bookkeeping

This appendix provides an alternative formulation of the thrust definition.

- e. Appendix E - Case Studies and Applications

This appendix provides case studies to illustrate the practices and results for determination of in-flight thrust for several modern fighter and commercial aircraft applications.

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2.1 Applicable Documents

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SAE Documents available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

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2.2 Symbols

Roman	Description	U.S. Common Units	SI Units
A	Area	ft ²	m ²
A	Acceleration	ft/s ²	m/s ²
A_0/A_C	Inlet capture ratio = mass flow ratio	-	-
A/B	Afterburner or augmentor	-	-
AEM	Effective area of mixing plane	ft ²	m ²
AIAA	American Institute of Aeronautics and Astronautics	-	-
ATF	Altitude test facility	-	-
C_D	Either discharge coefficient or drag coefficient	-	-
CFA	Compound flow analysis	-	-
C_G	Gross thrust coefficient	-	-
C_L	Lift coefficient	-	-
C_V	Specific thrust coefficient based on ideal flexible convergent-divergent nozzle expansion	-	-
CVV	Compressor variable vane position	deg	deg
C_X	Specific thrust coefficient based on ideal convergent nozzle expansion	-	-
D	Drag force (for subscripts see ϕ)	lbf	N
D_{AFS}	Aircraft system drag at full-scale operating conditions or aircraft reference drag	lbf	N
dt	Derivative with respect to time	s	s
EGT	Exhaust-gas temperature	R	K
f()	Function of argument within ()	-	-
f_s	Stream thrust parameter	-	-
F	Force or absolute stream force	lbf	N
FB	Forebody	-	-
Fc	Surface friction drag on the center body	-	-
Fd	Surface friction drag on the nozzle mixing duct	-	-
F_E	propulsive drag; a combination of ram drag, inlet spillage drag, afterbody and nozzle drag, and other throttle-dependent "drag" forces	lbf	N
F_{EX}	Excess thrust (i.e., thrust minus drag)	lbf	N
F_G	Gross thrust and gauge stream force	lbf	N
F_G^*	Modified gross thrust at core or bypass nozzle exit	lbf	N
FHV	Fuel heating valve	BTU/lbm	J/kg
F_{IPF}	Installed propulsive force	lbf	N
F_M	Measured test stand force	lbf	N
F_N	Net thrust between stations 0 and 9 for single-stream engine	lbf	N
F'_N	Overall net thrust between stations 0 and 00	lbf	N
F_N^*	Modified net thrust	lbf	N
$F_{N,int}$	Intrinsic net thrust between stations 1 and 9	lbf	N
FPC	Fan pressure correlation	-	-
F_R	Ram drag or freestream momentum	lbf	N



F_T	Trunnion thrust	lbf	N
FTB	Flying test bed	-	-
FVV	Fan variable vane position	deg	deg
F/AP	Area-pressure in-flight thrust method	-	-
$F/W\sqrt{T}$	Mass flow-temperature in-flight thrust method	-	-
g	Gravitation constant	ft/s ²	m/s ²
GLTF	Ground-level test facility	-	-
GTP	Gross thrust parameter	-	-
H	Total enthalpy	-	-
HPC	High-pressure compressor	-	-
HPT	High-pressure turbine	-	-
IFT	In-flight thrust	-	-
INS	Inertial navigation system	-	-
LVDT	Linear variable differential transducer	in	in
M	Flight Mach number	-	-
$\bar{m}$	Flow function	-	-
MFR	Mass flow ratio	-	-
MIDAP	Ministry/Industry Drag Analysis Panel	-	-
N	Engine rotational speed	rpm	rpm
NPR	Nozzle pressure ratio	-	-
NPR_A	Area-weighted nozzle pressure ratio	-	-
PCM	Pulse code modulation	-	-
PLA	Power lever angle	deg	deg
P_s	Static pressure	lbf/ft ²	N/m ²
P_{s0}	Freestream static pressure	lbf/ft ²	N/m ²
P_{sB}	Nozzle base static pressure (distinguished from P_{s0})	lbf/ft ²	N/m ²
P_{se}	Mean static pressure over external surface of engine	lbf/ft ²	N/m ²
P_t	Total pressure	lbf/ft ²	N/m ²
q	Freestream dynamic pressure	lbf/ft ²	N/m ²
R	Gas constant	ft-lbf/lbm R	J/kg K
RERR	Residual error procedure	-	-
RNI	Reynolds number index	-	-
rpm	Revolutions per minute	min ⁻¹	min ⁻¹
S	Surface or reference area	ft ²	m ²
STOL	Short takeoff and landing	-	-
SW_1	Airflow scaler	-	-
TSFC	Thrust-specific fuel consumption	-	-
T_t	Total temperature	R	K
V	Velocity	ft/s	m/s
VEN	Variable exhaust nozzle	-	-
VSTOL	Vertical/short takeoff and landing	-	-
V_0	Freestream velocity or flight speed	ft/s	m/s
W	Either mass flow rate or aircraft weight	slug/s lbfm	kg/s N
W_B	Bleed mass flow rate	slug/s	kg/s
W_F	Fuel mass flow rate	slug/s	kg/s
W_{FAB}	Afterburner fuel mass flow rate	slug/s	kg/s

Greek:

α	Angle of attack	deg	deg
γ	Specific heat ratio = C_p/C_v	-	-
δ	Non-dimensional pressure $P/P_{s0,SL,STD}$	-	-
δ_{t2}	Ram-pressure ratio, $P_{t2}/P_{s0,SL,STD}$		
δ_{VF}	Effective-vector force turning angle	deg	deg
Δ	Parameter incremental change	-	-
η_{mix}	Mixing efficiency of core and bypass flow	-	-
η_R	Intake pressure recovery = P_{t2}/P_{t0}	-	-
θ	Non-dimensional temperature = $T/T_{s0,SL,STD}$	-	-
θ_{t2}	Ram-temperature ratio, = $T_{t2}/T_{s0,SL,STD}$	-	-
τ	Thrust incidence angle	deg	deg
ϕ	Axial gauge force on a body or stream tube surface	lbf	N
ϕ_{AB}	Axial gauge force on external surface of core engine afterbody between stations 19 and 00	lbf	N
ϕ_{ADD}	Additive drag force	lbf	N
ϕ_D	Scrubbing force in engine test facility	lbf	N
ϕ_{IC}	Inlet-cowl forebody force	lbf	N
ϕ_{PLUG}	Axial gauge force on plug surface downstream of station 9	lbf	N
ϕ_{POST}	Axial gauge force on post-exit streamtube between stations 9 and ∞	lbf	N
ϕ_{PYLON}	Axial gauge force on pylon surface within bypass streamtube	lbf	N
ϕ_S	Pressure-area and scrubbing forces at ATF slip joint	lbf	N

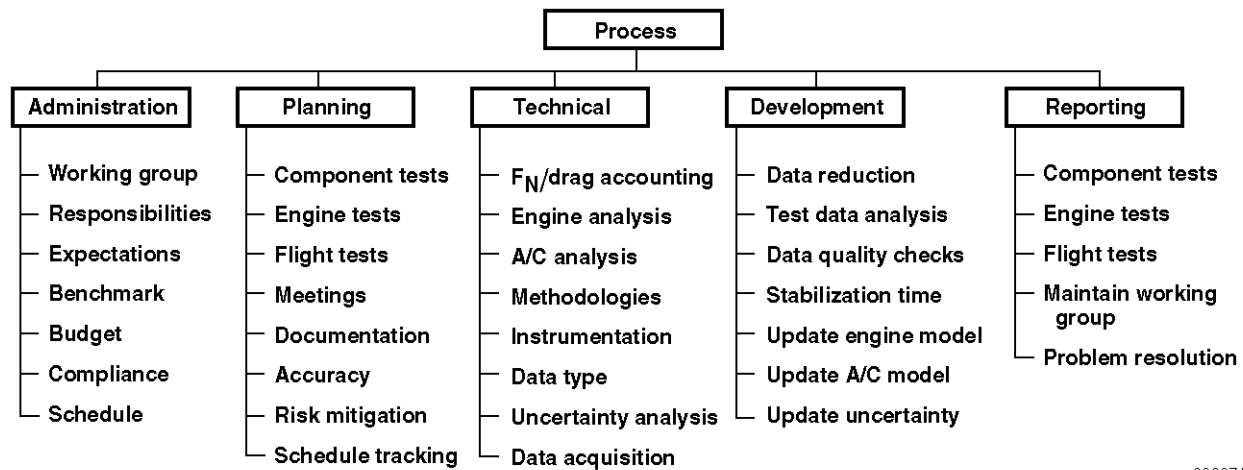
Subscripts:

0,1,2, etc.	Station designations (see Figures 2 and 5)
a and b	Test cell ambient conditions
ACT	Actual value (distinguished from "ideal")
AB	Afterbody (i.e., nozzle/afterbody drag)
AC	Aircraft
AFS	Airframe system
AVG	Average
b	Bypass flow
C	Core flow
calc	Calculated
CCAB	Core-cowl afterbody
con	Convergent ideal nozzle
CON-DI	Convergent-divergent ideal nozzle
EFF	Effective value of V at exit from a con-di nozzle which, when multiplied by W_{ACT} , gives $F_{G,ACT}$, or

	effective flow area
EXH	Exhaust
FCAB	Fan-cowl afterbody
H	High-pressure engine spool
ID	Ideal value (distinguished from “actual”)
INL	Inlet
L	Low-pressure engine spool
max, MAX	Maximum
min, MIN	Minimum
mix	Mixed flow
ref, REF	Reference value of conditions
s, s ϕ	Static conditions
SE	Static equilibrium
SL	Sea level
STD	Standard (temperature or pressure)
T	Total conditions
TRIM	Aircraft trim related
VF	Vector force

3. PROGRAM PLANNING GUIDELINES

The determination of in-flight thrust and subsequently aircraft drag is a five-step process requiring the participation of the customer and all contractors. The five steps are administration, planning, technical, development, and reporting (see Figure 1). A successful program needs to address all aspects of this process. It is imperative to obtain management support early in the process.



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FIGURE 1 - AIRCRAFT IN-FLIGHT THRUST/DRAG DETERMINATION

Typically, the performance of the engine and the performance of the aircraft are sensitive issues to the contractors and the customer. The team of participants needs to recognize these issues and work together to achieve the best technical solution. The success achieved from the flight test performance evaluation is directly related to the degree of attention given to details early in the planning phase of the overall development program.

A properly planned program will necessitate the integration of:

- a. Model, rig, and full-scale propulsion system test programs
- b. Airframe wind tunnel test programs
- c. Airframe and propulsion system test instrumentation
- d. In-flight thrust computational methods
- e. Data handling procedures used for both the propulsion system ground tests and airframe/propulsion system flight tests
- f. Data accuracy requirements and assessment capabilities

Early involvement of both propulsion system ground and flight test propulsion system and external aerodynamics specialists will enhance the potential for successfully accomplishing the desired ground and flight test goals.

3.1 Administration

The program administration needs to be well-executed to provide the proper guidance and direction of the overall processes. The major tasks are: forming a flight test performance working group, identifying responsibilities, setting the overall program expectations and schedule, benchmarking past program failures and successes for lessons learned, identifying and assuring the overall program budget is in line with the expectations, and identifying specification compliance requirements (see Figure 1). The administration of the program may be performed by any of the parties, but it is recommended that the User or Customer take this role.

3.1.1 Working Group

A successful approach for integrating the administration, planning, technical, development, and reporting phases of the overall process, with its various test programs, has been the use of a “flight test performance working group” concept. This team includes specialists of all organizations associated with the development, test, and evaluation of both the propulsion system and the airframe/propulsion system combination. The working group should formulate an integrated planned approach. Periodic meetings of the working group should be held to review progress and update the plan.

3.1.2 Responsibilities

Responsibilities of the aircraft manufacturer, engine manufacturer, and customer, including all partners, should be clearly established very early. The organization responsible for the combined airframe/propulsion system performance would normally be expected to:

- a. Formulate the working group
- b. Provide overall leadership in the formulation of an integrated plan which meets the program objectives with optimum utilization of available resources
- c. Assure all specialists understand how their particular functions fit into the overall plan
- d. Assure there are adequate interfaces between related functions
- e. Assess the success or failure of each phase of the plan

3.1.3 Expectations

A successful aircraft in-flight thrust/drag determination process starts with quantitatively setting the using service's (customer's) expectations. Only then can the proper test program and technical issues be addressed. Any ambiguity in setting goals can result in overexpenditure or even cancellation of the in-flight thrust program. The following items are the minimum that need to be addressed:

- a. Overall program objectives
- b. Test program goals
- c. Data accuracy goals

3.1.4 Benchmark

Any aircraft in-flight thrust/drag determination process should research recent experience and state-of-the-art accuracies obtained with similar propulsion systems and candidate in-flight thrust computational methods. Knowledge of previous program successes and failures can help identify key issues that must be addressed. The case studies presented in Appendix E of this document provide valuable “lessons learned.”

3.1.5 Budget

A proper budget must be established that provides the necessary resources to meet expectations. In general, the accuracy requirements drive the required budget. If budget requirements exceed available resources, then a descope in approach may be required resulting in a “compromise” in meeting objectives, that is, accuracy will be reduced.

3.1.6 Compliance

Specification requirements need to address the in-flight thrust/drag determination process goals and expectations. Reward fees, if any, requirements need to be documented and fully understood by all involved.

3.1.7 Schedule

A viable schedule needs to be established. It should identify key test deliverables and the “critical path” items upon which the schedule is dependent. The schedule should allow time for:

- a. Assessing available resources
- b. Assembling the working group
- c. Devising an integrated, comprehensive program plan
- d. Assigning task responsibility
- e. Conducting uncertainty analysis of candidate instrumentation/data-acquisition systems and in-flight thrust computational methods
- f. Assessing prior success or failure of candidate computational methods with the same or similar propulsion systems
- g. Selecting primary and alternate computational methods
- h. Selecting appropriate instrumentation and data-acquisition systems
- i. Conducting calibrations and installation
- j. Devising integrated detailed test plan matrices for the ground and flight test programs
- k. Updating uncertainty analysis as new information/data become available
- l. Assessing the success or failure of each phase of the program plan
- m. Modifying program plans and individual test plan matrices as required
- n. Assessing the validity of the data generated during the ground and flight test programs, and publishing the results

3.2 Planning

Planning is critical for a successful aircraft in-flight thrust/drag determination program. The overall program plan will likely require periodic updates and contingencies. Tasks required as part of the planning process are identification of test plan requirements, engine test requirements, and flight test requirements; a plan for periodic meetings; a plan for documentation of results; a plan to meet accuracy expectations; risk mitigation; and schedule tracking. An important part of the planning process is the establishment of formally approved test plans for component, engine, ground, and flight tests. Test plans document the goals, requirements, and approach for each test. More information on each of these tasks follows.

3.2.1 Component Test

The component test program for determining coefficients for in-flight thrust determination is usually a subset of the overall wind tunnel test program. A properly planned test sequence might include the following steps:

- a. Conduct wind tunnel tests on aerodynamic scale models at selected reference conditions and adjust data to full-scale conditions
- b. Conduct wind tunnel tests to determine throttle-dependent force increments
- c. Determine inlet spillage drag characteristics from inlet drag model/tests
- d. Determine aft-end/nozzle drag characteristics from jet effects model which permit correcting aerodynamic wind tunnel model for sting and distortion increments
- e. Assess other force increments, if appropriate, from wind tunnel tests
- f. Determine inlet duct total pressure recovery from wind tunnel test data using aerodynamic or inlet drag model
- g. Conduct nozzle tests on scale models to determine momentum losses due to friction and non-axial flow at nozzle exit, static pressure distribution over the nozzle length, and thrust and flow coefficients, and adjust results to full-scale conditions

3.2.2 Engine Test

The engine test program for in-flight thrust determination is usually a subset of the overall engine development and qualification test program. The in-flight thrust program needs to be well-integrated with the overall program. Ground-level test facility (GLTF) and altitude test facility (ATF) testing provides the data necessary to validate models and in-flight thrust (IFT) methodologies. A properly planned test sequence might include the following steps:

- a. Establish flight test and GLTF/ATF test plan matrices
- b. Establish limits for acceptable performance differences between engine runs at different test beds (indoor and outdoor GLTF, ATF) and for the individual engine in-flight thrust calibration where the data can be used without any additional corrections
- c. Conduct engine ground calibrations, including the effects of inlet distortion, ram recovery, and shaft-power and bleed extraction
- d. Analyze GLTF and ATF data, updating in-flight thrust computational routines, and thermodynamic-cycle computer models, as appropriate
- e. Conduct installed engine test to verify function and accuracy of the IFT instrumentation and data-acquisition system

3.2.3 Flight Test

The aircraft flight test program plan needs to establish the flight test program goals, and construct flight test test-plan matrices. Provisions should be made in the flight program to:

- a. Verify the wind tunnel inlet recovery data
- b. Verify the installed engine performance model
- c. Verify the airframe system drag and investigate the throttle-dependent drag increments (inlet spillage and aft-end/nozzle drag)

- d. Verify that the performance models accurately calculate aircraft performance throughout the flight envelope
- e. Provide flexibility and redundancy that will permit the investigation of unanticipated results and the isolation of errors and identification of their causes or error sources
- f. Analyze flight test results for consistency and accuracy; update analytic models as required
- g. Publish flight handbook performance data
- h. Specify aircraft maneuvers that are consistent with the IFT methodology (e.g., quasi-steady-state performance)

3.2.4 Meetings

The periodic working group meetings will require extensive planning to track the program progress and communicate this progress to all stakeholders. Carefully planned agendas are a necessity. Documentation of meeting minutes, decisions, and action items are required.

3.2.5 Documentation

Timely and accurate documentation of results must be maintained throughout the IFT/drag determination process. Component, engine, and flight test results should be made available to all working group members. Working group members should be invited to witness each other's test to enhance communication, understanding, and awareness.

3.2.6 Accuracy

The program plan needs to address sub-task accuracy requirements and needs so that the overall programs objective accuracy can be achieved. Uncertainty analyses should be initiated early in the program planning process and updated as additional information becomes available.

3.2.7 Risk Mitigation

Risk assessment tools are helpful to identify problem areas early and create an appropriate abatement plan.

3.2.8 Schedule Tracking

Effective meetings and effective communication will enable the progress of the program to be tracked. Schedule modifications must be communicated to all working group participants.

3.3 Technical

At the heart of the aircraft in-flight thrust and drag determination processes are the challenging technical issues that must be solved. The technical tasks are engine thrust-aircraft drag accounting, establishing the engine test analysis process, establishing the aircraft data analysis process, defining the in-flight thrust computational methodologies, selecting instrumentation, identifying required data types (steady-state or transient), conducting a pre-test uncertainty analysis, and defining the data acquisition requirements. More detail on each task is discussed below.

3.3.1 Thrust/Drag Accounting

The first step prior to establishing the methodologies is to clearly define the forces acting on the aircraft. These forces are then assigned to either the aircraft or the propulsion system.

3.3.2 Engine Analysis

The engine test data analysis process should be established prior to the first GLTF or ATF test. This includes:

- a. Establishing the airflow standard methodology and uncertainty
- b. Establishing the thrust standard methodology and uncertainty
- c. Correlating flight-test instrumentation to development instrumentation
- d. Processing test data with proposed in-flight thrust methodologies
- e. Continually refining component correlations

3.3.3 Aircraft Analysis

The aircraft data analysis process should be established early to ensure compatibility with the engine test and analysis process. This process includes establishing:

- a. Redundant methodologies
- b. Time averaging techniques
- c. Data filtering techniques
- d. Time compensation for measurement lags
- e. Process for correcting to desired flight condition
- f. Determination of bleed airflow and horsepower extraction measurement techniques
- g. Determination of secondary airflow

3.3.4 Methodologies

The goals of the flight test program are predominant factors which will influence the selection of a method for computing in-flight thrust. It is paramount that these goals be established prior to any attempt to select a computational method. Factors that should be considered in this selection are:

- a. The scope and nature of the flight test program, as dictated by the applicable flight test goals and program objectives
- b. The economics of the program, as dictated by available resources relative to the desired test goals and program objectives
- c. The state-of-the-art accuracy obtainable from each of the candidate methods which are appropriate to the components of a particular propulsion system.

Any complete in-flight thrust program should include a backup method(s) for thrust determination. Although backup methods may appear to add program cost, having backup-method data can minimize retest and schedule slippage.

3.3.5 Instrumentation

The desired accuracy and the resources available for achieving this accuracy will influence selection of in-flight computational methods and the associated instrumentation/data-acquisition systems. The instrumentation accuracy will be a key input to the uncertainty analysis. Final selection of the instrumentation may be an iterative process to achieve the overall system requirements. Instrumentation response rates must also be evaluated. Flight-test instrumentation should be installed on an engine and checked out, preferably on an ATF engine. Flight-test instrumentation correlations may be required to match the development instrumentation and the measurement standards of the test facility. Some items which need to be addressed include:

- a. Selecting and standardizing instrumentation for GLTF, ATF and flight programs using information developed from method and uncertainty analyses
- b. Establishing instrumentation calibration accuracy requirements
- c. Establishing bleed-duct instrumentation configuration
- d. Calibrating full-scale bleed ducts/instrumentation

3.3.6 Data Type

The flight test programs will likely acquire data during aircraft cruise and dynamic maneuvers. It must be determined if such data can be processed using steady-state or quasi-steady-state methods. Compensation for transient effects such as measurement lag and engine thermal soak may be required.

3.3.7 Uncertainty Analysis

Uncertainty analysis of the proposed instrumentation and computational methods should be conducted early during program planning to establish the predominant parameters which influence accuracy and to highlight areas where the expenditure of resources would be most beneficial (see References 1.1 and 1.5). The uncertainty data can be used to:

- a. Aid in the selection of a preferred in-flight thrust computational method
- b. Assess the necessity for alternate computational methods and aid in their selection
- c. Ensure that the model, rig and full-scale propulsion system ground test programs are adequate to achieve the desired flight test accuracy
- d. Enhance the confidence level associated with the validity of the data obtained during the flight test program

3.3.8 Data Acquisition

The data acquisition system and processing systems need to accommodate a potentially massive amount of data. The data acquisition system should not introduce any significant lag to the measured values. The data acquisition system accuracy should be an integral part of the uncertainty analysis.

3.4 Development

The development phase of the aircraft in-flight thrust/drag determination process deals with the execution of that process. The major tasks are to implement IFT methodologies in a data reduction tool; conduct component, engine, and flight test data analysis; ensure data quality; establish engine stabilization times to ensure consistent and meaningful test data; update engine models or algorithms used to calculate in-flight thrust; update aircraft models or algorithms used to reduce flight test data and determine aircraft performance; and conduct a post-test uncertainty analysis to once again establish accuracy capability. These tasks are discussed below.

3.4.1 Data Reduction

Systematic procedures must be in place to readily process (or reprocess) test data. The data reduction system will typically use an engine cycle model (see 6.3). This model, therefore, must be available for the GLTF, ATF, and flight test program.

3.4.2 Test Data Analysis

An important task in development of IFT/drag methodology is the analysis of engine, component, and aircraft test data. Where appropriate, it should be made possible to analyze the test data during the tests.

3.4.2.1 Engine

General test program goals, applicable to both the ground and flight test programs are to:

- a. Substantiate that the design performance of the propulsion system and propulsion system/airframe combination has been met
- b. Provide information for assessment of departures from design goals and identification of the causes of departures
- c. Provide information to predict performance variations resulting from design changes which may be made during the operational life cycle of the airframe and propulsion system
- d. Provide information to substantiate and enhance theoretical estimation techniques
- e. Provide a database for the improvement of future designs
- f. Establish power extraction relationships based on full-scale rig testing

3.4.2.2 Component

The following should occur:

- a. Conduct analyses to determine anticipated nozzle mass flow variations and/or leakage.
- b. Conduct rig tests to determine frictional blockage and other total pressure losses from the pressure measurement station to the nozzle inlet.
- c. Conduct analyses to determine additional total pressure and momentum losses resulting from leakage and the addition of heat, if applicable.

3.4.2.3 Aircraft

A performance prediction of the propulsion system/airframe design is based on airframe drag estimates and propulsion system thrust estimates. The flight test program can substantiate the predicted overall performance of the aircraft without specific knowledge of propulsion system thrust and airframe drag. This approach requires extensive flight testing to acquire the data for an accurate flight manual. To make more efficient use of flight time, it has been determined that an in-flight thrust computational method, which will provide accurate in-flight thrust information, is required. The in-flight thrust is then used to develop an aerodynamic-thrust model that can be used to generate accurate flight manuals, assess departures from design goals, and assess future modifications or upgrades to the present design (spiral development).

The cost involved in the development and utilization of one particular in-flight method compared to another must be weighed against the fidelity/uncertainty of the data obtainable from each of the methods and related to the accuracy requirement of the desired departure assessment. The necessity of providing highly accurate information for the enhancement of theoretical estimation techniques, and the size and quality of the database to be generated for the assessment of design changes and improvement of future designs, must be considered. If large savings of flight test time are predicated on instituting in-flight thrust procedures, then the necessary up-front support must be provided.

In addition, review of early flight test results to ascertain the necessity for additional ground testing and/or revision to the in-flight thrust computational routine is critical.

3.4.3 Data Quality Checks

A system should be put in place to screen test data. The following need to occur:

- a. Establish instrumentation/data-acquisition system calibration procedures, tolerance limits, and special calibration rig requirements based on uncertainty analysis
- b. Establish the measured parameters that have the greatest impact on the results, using the sensitivity factors derived in the uncertainty prediction
- c. Establish data handling procedures
- d. Establish full-scale flight-test instrumentation requirements and flight-data default and substitution criteria based on uncertainty analyses
- e. Establish flight test maneuver techniques and tolerance limits consistent with meeting data uncertainty goals

3.4.4 Stabilization Time

In-flight thrust methods need to be independent of engine health and thermal state. If calculated thrust reflects these conditions, then the corresponding aircraft drag is also correct. However, if an aircraft performance trait is being evaluated such as specific excess power, then the engine stabilization time procedure needs to be established to assure consistent and meaningful test data. The working group needs to establish this requirement collectively.

3.4.5 Update Engine Models

The following should occur:

- a. Update engine thermodynamic-cycle computer model based on component rig, scale model, and engine test results
- b. Update installed-engine-performance model (thrust, fuel flow, and airflow as a function of altitude, Mach and temperature) based on GLTF, ATF, and inlet pressure recovery, power extraction, and bleed data

3.4.6 Update Aircraft Models

The following efforts need to occur:

- a. Conduct pre-flight performance model updates
- b. Conduct analyses to determine drag increments associated with engine-bay cooling airflow, inlet ramp boundary-layer bleed flow, and other systems
- c. Update airframe-system-drag model with available wind tunnel data
- d. Update throttle-dependent drags

3.4.7 Update Uncertainty

The following efforts need to occur:

- a. Update uncertainty analyses to highlight areas of concern
- b. Initiate uncertainty analyses of candidate in-flight thrust computational methods and instrumentation/data-acquisition systems
- c. Incorporate this information into flight-vehicle uncertainty analyses

3.5 Reporting

The timely reporting of results to all working group participants and their respective management is necessary to ensure the aircraft in-flight thrust/drag determination process is on track. Timely and accurate reporting is critical if the program plan needs to be updated. The reporting of all results and allowing for participation of any working group member during any phase of testing enhances the educational process and builds understanding among participants.

3.5.1 Component Tests

The reporting of component test plan development, execution, and analysis should consider that some working group participants might not be very familiar with such tests. Nothing should be taken for granted. Test results need to be evaluated as to the impact on the overall process. Corrective action may then be necessary. Fundamentals need to be reviewed at team meetings so that the less experienced team members are exposed to the test rationale and procedure.

3.5.2 Engine Tests

The engine test program provides the database for the evaluation of in-flight thrust methods. Again, fundamentals need to be reviewed at team meetings so that the less experienced team members are exposed to the test rationale and procedure. All relevant test data should be used to update model correlations. Test data will frequently be reprocessed to evaluate the capability of the chosen method to match thrust. The results are then presented to the working group for acceptance. Also, these data would be used in updating the uncertainty analysis.

3.5.3 Flight Tests

The flight test reporting begins early with the thrust/drag accounting procedures and flight test plan matrix. Again, fundamentals need to be reviewed at team meetings so that the less experienced team members are exposed to the test rationale and procedure. Once data are obtained, results should be quickly shared with working group participants.

3.5.4 Maintenance of the Working Group

It is essential that the working group be maintained after the engine is qualified in the event an aircraft performance problem arises, and even if the flight test program is proceeding as expected.

3.5.5 Problem Resolution

If a problem is identified or a procedure needs to be changed, the working group can be convened to evaluate and provide the proper direction to resolve the issue. Program management needs to be informed of the problem and the process by which the working group proposes to resolve it. Any management response needs to be provided to the working group so that it can be addressed.

3.5.6 Lessons Learned

Lessons learned should be documented and communicated among the working group members with the goal of continuous improvement.

4. DEFINITIONS AND METHODOLOGY

The in-flight forces acting on the installed propulsion system are sometimes difficult to define and are often more difficult to evaluate. In distinguishing between in-flight thrust and drag forces, it is important that the definition of thrust be well understood by all concerned and that there is a proper accounting of all the forces acting on the propulsion system. The following sections discuss the definitions of thrust, thrust/drag accounting, and other basic terms used for evaluating in-flight thrust.

4.1 Thrust

Prior to discussing thrust and drag force terms, it is necessary to introduce a consistent station numbering system to define flow path locations ahead, within, and aft of the propulsion system. Designations for appropriate stations consistent with SAE ARP755C and AS681H (References 4.1 and 4.2, respectively) are shown in Figure 2.

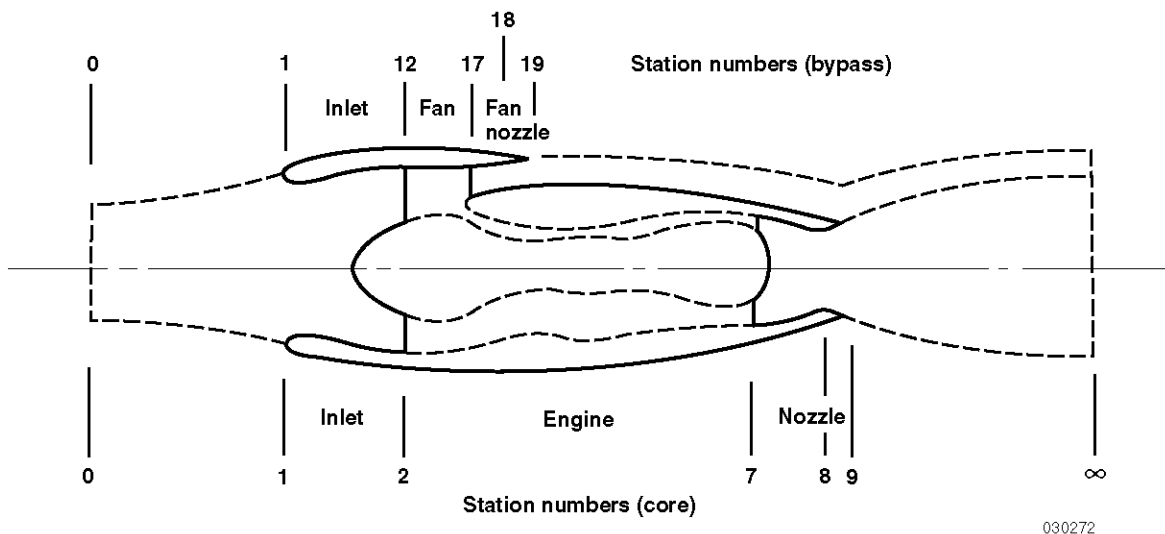


FIGURE 2 - STATION NUMBERING SYSTEM

A useful place to begin the thrust-drag force discussion is with the definition of excess thrust (F_{EX}) which is defined as the difference between the installed propulsive force (F_{IPF}) and the airframe system drag (D_{AFS}):

$$F_{EX} = F_{IPF} - D_{AFS} \quad (\text{Eq. 1})$$

A basic premise in establishing a useful in-flight thrust methodology is to define the propulsion system thrust force and the associated aircraft drag force so they are equal in level, non-accelerating flight. The thrust definition also should facilitate the determination of drag from excess thrust measurements in unsteady flight. To this end, the thrust of a propulsion system is defined as a force attributable to the installed engine. Being a vector quantity, it will generally have components normal to and parallel to the flightpath. For the purpose of the discussion that follows, it will be assumed that the thrust axis is parallel to the flightpath and, therefore, that installed propulsive force is equal to aircraft system drag in steady level flight. Thus, Equation 1 becomes:

$$F_{IPF} = D_{AFS} \quad (\text{Eq. 2})$$

The drag of a non-lifting body is entirely the consequence of energy dissipation in the external flow due to viscous effects resulting from skin friction, flow separation, and the formation of shock waves. In the absence of propulsive flow, drag may be related to the defect in momentum at a station far downstream of the body where static pressures have returned to the freestream ambient value. It is the sum of the drag consistent with this concept and of drag due to the generation of lift that equates to thrust in steady level flight.

Associated with this concept, a mixing process begins at the conjunction of the internal and external flows at the exhaust nozzle exit. Therefore, neither the thrust nor the drag of a propulsion system based on a station far downstream of the nozzle-exit station can be defined mathematically without either the hypothesis of a frictionless slip surface separating the internal and external flows downstream of the nozzle exit, or the involvement of relationships defining the transfer of mass, momentum, and energy between the two flows. With the hypothesis of a slip surface, drag may be equated to a momentum of the exhaust stream(s) at a station far downstream of the nozzle exit station less the momentum of the internal flow at a station far upstream of the engine inlet.

4.1.1 Single-Stream Engine Thrust

The pressure forces and momentum fluxes can be analyzed using the control volumes depicted in Figure 3 for an isolated single-stream, propulsion system in steady flight. Two equivalent control volumes are defined. Both volumes have a common forward control boundary far upstream at station 0. However, the top half of Figure 3 has its exit control surface far downstream at station ∞ while the exit control surface for the bottom half of Figure 3 is at engine exit station 9 and surrounds the exit plug. For the top-half control volume, the streamlines are shown intersecting the leading edge of the cowl or emanating from the trailing edge of the cowl for convenience and clarity. But note that in reality, the dividing streamline is determined by the location of the stagnation streamline wherever it occurs – either at the highlight area or inside it or outside it depending upon the mass flow ratio. In the case of the bottom-half control volume, the same line of thought applies to the forward part of the cowl. However, for the aft portion of the cowl, the exit plane of the nozzle is set at the most downstream physical portion of the nozzle. The station labeled “max” is set at the zero slope portion of the cowl where there are no forward or rearward acting pressure forces. Either control volume can be used to evaluate installed propulsive force, but the terms that must be evaluated will be different.

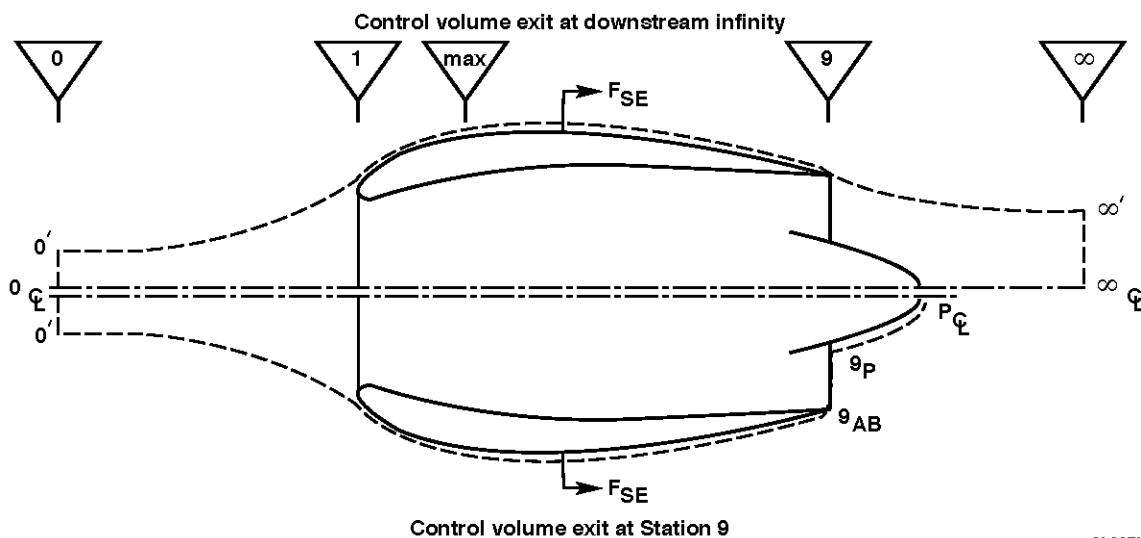


FIGURE 3 - ISOLATED PROPULSION SYSTEM CONTROL VOLUMES

The first step in developing a usable set of equations is to begin with the macroscopic momentum balance for steady flow in the following form:

$$\Delta W V = \sum F \quad (\text{Eq. 3})$$

which states that when applied to a control volume, and neglecting both friction (to simplify the algebra) and body forces, the change in the momentum flux across the control volume is equal to the sum of the forces acting on the control volume where:

$$\Delta WV = W_{\infty} V_{\infty} - W_0 V_0 \quad (\text{Eq. 4})$$

$$\Sigma F = \Sigma \int P dA + F_{SE} \quad (\text{Eq. 5})$$

The sum of the forces is composed of the pressure-area terms and the force F_{SE} that acts to “hold” the control volume in static equilibrium.

Applying Equation 3 to the control volume depicted above the centerline of Figure 3 and carrying out a contour integration in cylindrical coordinates from the upstream centerline to the downstream centerline, the following equation is obtained:

$$W_{\infty} V_{\infty} - W_0 V_0 = \int_{0\zeta}^{0'} P_S dA + \int_{0'}^1 P_S dA + \int_1^{\max} P_S dA + \int_{\max}^9 P_S dA + \int_9^{\infty'} P_S dA + \int_{\infty'}^{\infty\zeta} P_S dA + F_{SE} \quad (\text{Eq. 6})$$

where the elemental area of the pressure integrals dA is normal to the flow direction. The positive direction for the pressure-area forces and F_{SE} is in the stream-wise direction.

Note that

$$\int_{0\zeta}^{0'} P_S dA = P_{S0} A_0 = \text{assuming the static pressure is uniform} \quad (\text{Eq. 7})$$

Thus, Equation 6 can be written as

$$W_{\infty} V_{\infty} - W_0 V_0 = P_{S0} A_0 + \int_{0'}^1 P_S dA + \int_1^{\max} P_S dA + \int_{\max}^9 P_S dA + \int_9^{\infty'} P_S dA + \int_{\infty'}^{\infty\zeta} P_S dA + F_{SE} \quad (\text{Eq. 8})$$

Solving for F_{SE}

$$F_{SE} = -W_0 V_0 - P_{S0} A_0 - \int_{0'}^1 P_S dA - \int_1^{\max} P_S dA - \int_{\max}^9 P_S dA - \int_9^{\infty'} P_S dA - \int_{\infty'}^{\infty\zeta} P_S dA + W_{\infty} V_{\infty} \quad (\text{Eq. 9})$$

This force in steady flight is defined as the aircraft-system-drag reactionary force (D_{AFS}) as shown in Equation 10.

$$D_{AFS} = -W_0 V_0 - P_{S0} A_0 - \int_{0'}^1 P_S dA - \int_1^{\max} P_S dA - \int_{\max}^9 P_S dA - \int_9^{\infty'} P_S dA - \int_{\infty'}^{\infty\zeta} P_S dA + W_{\infty} V_{\infty} \quad (\text{Eq. 10})$$

The pressure forces can be referred to ambient pressure by adding $P_{S0} A_{\max}$ to the right-hand side of Equation 10 in the form

$$P_{S0} A_{\max} = P_{S0} A_0 + \int_{0'}^1 P_{S0} dA + \int_1^{\max} P_{S0} dA \quad (\text{Eq. 11})$$

and subtracting $P_{S0}A_{\max}$ as written in Equation 12 from the right-hand side of Equation 10 noting that $P_{S0}A_{\max}$ acts in the downstream direction and its sign must be changed to act in the upstream direction.

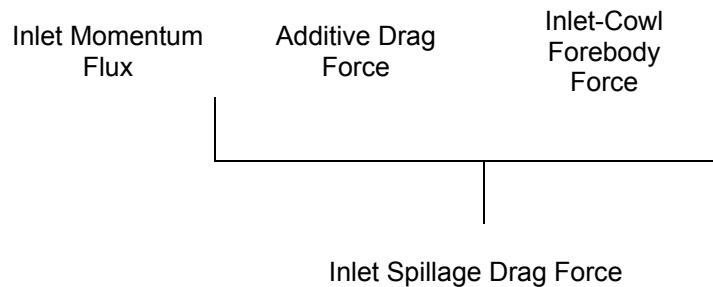
$$-P_{S0}A_{\max} = -\int_{\max}^9 P_{S0}dA - \int_9^{\infty'} P_{S0}dA - \int_{\infty'}^{\infty''} P_{S0}dA \quad (\text{Eq. 12})$$

Combining terms and noting that $D_{AFS} = F_{IPF}$ (Equation 2) yields an equation for the installed propulsive force noting that

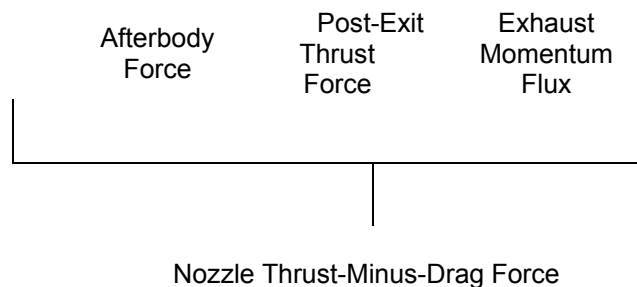
$$\int_{\infty'}^{\infty''} P_S dA = \int_{\infty'}^{\infty''} P_{S0} dA \quad (\text{Eq. 13})$$

since $P_S = P_{S0}$ for the nozzle exit area.

$$F_{IPF} = -(W_0 V_0) - \int_0^1 (P_S - P_{S0}) dA - \int_1^{\max} (P_S - P_{S0}) dA$$



$$-\int_{\max}^9 (P_S - P_{S0}) dA - \int_9^{\infty'} (P_S - P_{S0}) dA + W_{\infty} V_{\infty} \quad (\text{Eq. 14})$$



By grouping the terms as shown in Equation 14, recognizable groupings occur as follows:

- Inlet momentum flux equals “ram drag,”
- Inlet spillage drag force equals the sum of the additive drag force³ and the inlet-cowl forebody force, and
- Nozzle thrust-minus-drag force equals the sum of the afterbody force, the post-exit thrust force, and the exhaust momentum flux.

³ This derivation is shown for an inlet mass flow ratio less than one. For low Mach numbers where the mass flow ratio may be greater than one, the “additive drag force” becomes negative in sign and thus, becomes a “thrust.” In traditional bookkeeping for mass flow rates greater than one, usually spillage drag is assumed to be zero, that is, the cowl force offsets the additive drag force since there are no separation losses. Additive drag is considered normally only for mass flow rates less than one.

The definition of “inlet spillage drag force” has been found to be useful in inlet design. It is of interest to note that for a well-designed subsonic inlet at Mach numbers below where there may be shocks in the flow field, the inlet spillage drag will be nearly non-existent since the additive drag will be nearly cancelled by the inlet-cowl forebody force.

We can now introduce the surface friction and combine it with the pressure-area terms using Equation 15.

$$\phi = \int_{\text{surface}} [(P_S - P_{S0}) + \tau(\cot\lambda)] dA \quad (\text{Eq. 15})$$

where:

τ = Shear stress acting on ds

λ = Angle between freestream flow direction and a plane tangent to the surface element ds

$dA = (\sin\lambda) ds$ = area of surface element, ds, projected on a plane normal to the freestream flow direction

The integral in Equation 15 is taken over the surfaces of interest. With the inclusion of the friction force, the inlet-cowl forebody force $\int_1^{\max} (P_S - P_{S0}) dA$ becomes ϕ_{IC} , the afterbody force $\int_{\max}^9 (P_S - P_{S0}) dA$ becomes ϕ_{AB} , and the post-exit thrust force $\int_9^{\infty'} (P_S - P_{S0}) dA$ becomes ϕ_{POST} . Further, $\int_0^1 (P_S - P_{S0}) dA$ is defined as ϕ_{ADD} and $\int_9^{\infty'} (P_S - P_{S0}) dA$ is defined as ϕ_{POST} . Now Equation 14 becomes

$$F_{IPF} = - W_0 V_0 - \phi_{ADD} - \phi_{IC} - \phi_{AB} - \phi_{POST} + W_{\infty} V_{\infty} \quad (\text{Eq. 16})$$

Ram Drag	Additive Drag Force	Inlet- Cowl Forebody Force	Afterbody Force	Post- Exit Thrust Force	Exhaust Momentum Flux
Inlet Spillage Drag Force			Nozzle Thrust-Minus-Drag Force		

The form of the thrust equations shown in Equations 14 and 16 contains an explicit “post-exit thrust” term that is difficult, if not impossible, to mathematically evaluate. For most commercial applications, this term is considered negligible and will be assumed zero for this discussion. Even though small, the effects are accounted in the forces measured during the “wind-on” wind tunnel test of the aircraft afterbody force test (see 4.2.2).

An alternate and equivalent force summation for F_{IPF} based on the control volume in the bottom half of Figure 3 is given by Equation 17. This method has become the general standard, provides the information that goes into F_{IPF} , and leads to the definition of modified gross thrust, F_G^* .

$$W_9 V_9 - W_0 V_0 = \int_{0Q}^{0'} P_S dA + \int_0^1 P_S dA + \int_1^{\max} P_S dA + \int_{\max}^{9AB} P_S dA + \int_{9AB}^{9p} P_S dA + \int_{9p}^P P_S dA + F_{SE} \quad (\text{Eq. 17})$$

Noting

$$\int_{0\mathcal{C}}^{0'} P_S dA = P_{S0} A_0 \text{ assuming the pressure is uniform} \quad (\text{Eq. 18})$$

$$\int_{P\mathcal{C}}^{9P} P_S dA = -P_{S9} A_9 \text{ assuming the pressure is uniform} \quad (\text{Eq. 19})$$

Equation 17 can be rewritten with all appropriate substitutions as:

$$F_{IPF} = -W_0 V_0 - P_{S0} A_0 - \int_{0'}^1 P_S dA - \int_1^{\max} P_S dA - \int_{\max}^{9AB} P_S dA + W_9 V_9 + P_{S9} A_9 - \int_{9P}^{PC} P_S dA \quad (\text{Eq. 20})$$

Adjusted to the ambient pressure reference using Equations 12 and 13 as before:

Inlet Spillage Drag Force

$$F_{IPF} = -W_0 V_0 - \int_0^1 (P_S - P_{S0}) dA - \int_1^{\max} (P_S - P_{S0}) dA - \int_{\max}^9 (P_S - P_{S0}) dA$$

$$+ W_9 V_9 (P_{S9} - P_{S0}) A_9 - \int_{9P}^{PC} (P_S - P_{S0}) dA \quad (\text{Eq. 21})$$

Modified Gross Thrust F_G^*

Equation 21 can be rewritten using Equation 15 to include both pressure and friction terms as follows:

$$F_{IPF} = W_9 V_9 + (P_{S9} - P_{S0}) A_9 - \phi_{PLUG} - W_0 V_0 - \phi_{ADD} - \phi_{IC} - \phi_{AB} \quad (\text{Eq. 21a})$$

The same sign conventions have been used for both Equations 16 and 21. Unfortunately at this point, the signs for ϕ_{AB} and ϕ_{PLUG} are not consistent with standard industry usage. Rewriting Equation 21a to be consistent with industry sign conventions, Equation 21a becomes

$$\begin{array}{c}
 \text{Modified Gross Thrust } F_G^* \quad \text{Ram Drag} \\
 \hline
 F_{IPF} = W_9 V_9 + (P_{S9} - P_{S0}) A_9 + \phi_{PLUG} - W_0 V_0
 \end{array} \quad (\text{Eq. 22})$$

$$\begin{array}{c}
 \text{Inlet Spillage Drag Force} \\
 \hline
 \begin{array}{ccc}
 \text{Additive Drag Force} & \text{Inlet-Cowl Forebody Force} & \text{Afterbody Force} \\
 - \phi_{ADD} & - \phi_{IC} & + \phi_{AB}
 \end{array}
 \end{array}$$

where:

$$\int_0^1 (P_S - P_{S0}) dA = \phi_{ADD} \quad (\text{Eq. 23})$$

$$\int_1^{\max} (P_S - P_{S0}) dA = \phi_{IC} \quad (\text{Eq. 24})$$

The positive signs for ϕ_{AB} and ϕ_{PLUG} were obtained by noting that

$$\int_b^a P dA = - \int_a^b P dA \quad (\text{Eq. 25})$$

While use of this fact was previously used for Equation 8 where P was a constant, it is not immediately obvious that this is true for a generalized integrand. However, if P represents an integrable function, one can show that an average pressure (which is constant) can be defined and thus, Equation 25 can be shown to be true for a function such as pressure. Therefore,

$$- \int_{\max}^9 (P_S - P_{S0}) dA = \phi_{AB} \quad (\text{Eq. 26})$$

$$- \int_{9_p}^{P_C} (P_S - P_{S0}) = \phi_{PLUG} \quad (\text{Eq. 27})$$

It is useful at this point to depict the direction in which each of these forces act as well as the direction of the momentum fluxes. For the purposes of this exercise, we are assuming an inlet mass flow ratio of less than one and a commercial type inlet in subsonic flow. Each force term has been addressed in the following table in order to better elucidate the reasoning.

TABLE 1 - ANALYSIS OF TERMS IN INSTALLED PROPULSIVE FORCE EQUATION
FOR A TYPICAL COMMERCIAL INLET

Force	Symbol	Direction of Force	Reasoning
Additive Drag	ϕ_{ADD}	In direction of flow (a drag force)	The value of the integral is positive since P_S is increasing and is equal to or greater than P_{S0} .
Inlet-Cowl Forebody	ϕ_{IC}	Against direction of flow (a thrust force)	The flow is being accelerated over the cowl surface and P_S is less than P_{S0} , thus, the pressure integral coupled with the friction term is negative.
Afterbody	ϕ_{AB}	Against direction of flow (but, a drag force)	The flow is being decelerated along the cowl surface and P_S is less than P_{S0} . Thus, the pressure integral coupled with the friction term is negative.
$(P_{S9} - P_{S0})A_9$	NS*	Against direction of flow (a thrust force)	$P_{S9} > P_{S0}$
Plug	ϕ_{PLUG}	Against direction of flow (a thrust force)	The flow is being recompressed and results in P_S being greater than P_{S0} . Thus, this force is a thrust even when friction is included.

*NS-No Symbol

These forces are shown in Figure 4 along with the momentum fluxes.

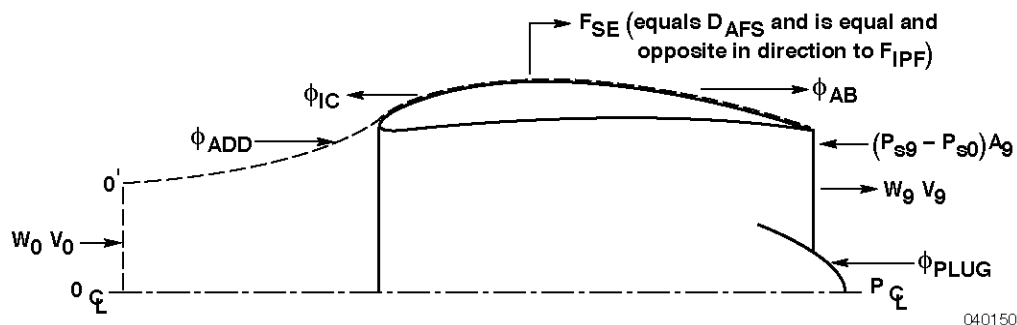


FIGURE 4 - FORCES ON CONTROL VOLUME

Equation 22 defines the inlet drag force, afterbody drag force, and modified gross thrust. The modified gross thrust is defined as

$$F_G^* = W_9 V_9 + (P_{S9} - P_{S0})A_9 + \phi_{PLUG} \quad (\text{Eq. 28})$$

The gross thrust, F_G , is defined as

$$F_G = W_g V_g + (P_{S9} - P_{S0}) A_g \quad (\text{Eq. 29})$$

All the terms in Equation 22 must be evaluated and measured to obtain F_{IPF} . Combining modified gross thrust F_G^* and ram drag ($F_R = W_0 V_0$) results in modified net thrust (F_N^*) such that

$$F_N^* = F_G^* - F_R \quad (\text{Eq. 30})$$

or

$$F_N^* = W_9 V_9 + (P_{S9} - P_{S0}) A_9 + \phi_{\text{PLUG}} - W_0 V_0 \quad (\text{Eq. 31})$$

The inlet force that results from the sum of the integrals between station 0 and “max,” is a function of engine airflow for a turbofan engine. The afterbody force which results from the integrals between station “max” and 9 is a function of nozzle pressure ratio and area. Therefore, these forces are “throttle-dependent” (i.e., they are functions of engine power) and must be accounted for in the thrust/drag bookkeeping process as incremental inlet and exhaust forces with respect to reference conditions. Further, it should be noted that the inlet and exhaust forces can be considered independent only for “uncoupled” configurations. See 4.2 for further details.

4.1.2 Dual-Stream Engine Thrust:

The extension of the above definitions to multiple-flow propulsion systems creates no new problems. If one of the flows totally encloses another, the exhaust thrust term of the enclosed flow is cancelled by an equal and opposite force exerted on the enclosing flow.

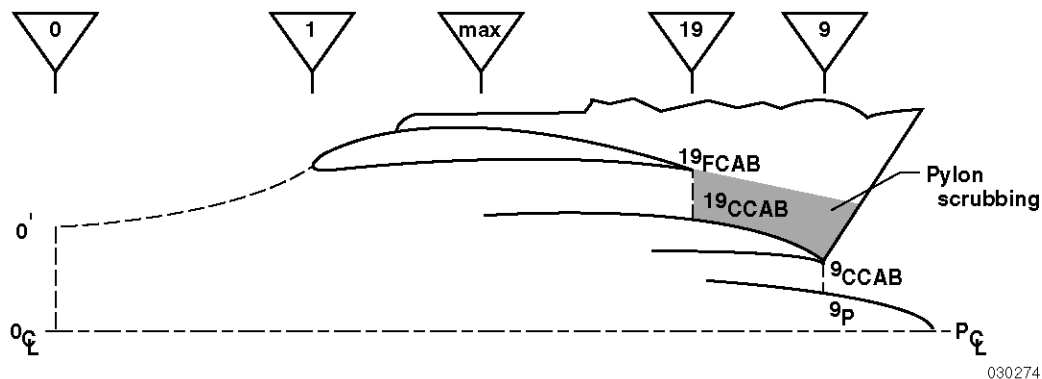


FIGURE 5 - DUAL-STREAM ENGINE CONTROL VOLUME

Thus, with reference to Figure 5 and Equation 3, the momentum-force balance can be written as:

$$W_{19}V_{19} + W_9V_9 - W_0V_0 = \int_{0_{\mathbb{L}}}^{0'} P_S dA + \int_{0'}^1 P_S dA + \int_1^{\max} P_S dA + \int_{\max}^{19_{\text{FCAB}}} P_S dA + \int_{19_{\text{FCAB}}}^{19_{\text{CCAB}}} P_S dA \\ + \int_{19_{\text{CCAB}}}^{9_{\text{CCAB}}} P_S dA + \int_{9_{\text{CCAB}}}^{9_{\text{P}}} P_S dA + \int_{9_{\text{P}}}^{9_{\mathbb{L}}} P_S dA + \int_{9_{\mathbb{L}}}^{\text{PYLONS}} P_S dA + F_{\text{SE}} \quad (\text{Eq. 32})$$

As accomplished for Equation 22, by noting

$$\int_{0_{\mathcal{C}}}^{0'} P_S dA = P_0 A_0 \quad (\text{Eq. 33})$$

$$\int_{19_{\text{FCAB}}}^{19_{\text{CCAB}}} P_S dA = -P_{19} A_{19} \quad (\text{Eq. 34})$$

$$\int_{9_{\text{CCAB}}}^{9_{\text{P}}} P_S dA = -P_9 A_9 \quad (\text{Eq. 35})$$

and making use of Equations 12 and 13 (and equations similar to them), and Equation 15, Equation 32 can be written as:

$$F_{\text{IPF}} = -W_0 V_0 - \phi_{\text{ADD}} - \phi_{\text{IC}} + \phi_{\text{FCAB}} + W_9 V_9 + (P_{S9} - P_{S0}) A_9 + \phi_{\text{PLUG}} + W_{19} V_{19} + (P_{S19} - P_{S0}) A_{19} + \phi_{\text{CCAB}} + \phi_{\text{PYLON}} \quad (\text{Eq. 36})$$

where:

$$\int_{0'}^1 P_S dA = \phi_{\text{ADD}} \quad (\text{Eq. 37})$$

$$\int_1^{\text{max}} P_S dA = \phi_{\text{IC}} \quad (\text{Eq. 38})$$

$$-\int_{\text{max}}^{19_{\text{FCAB}}} P_S dA = \phi_{\text{FCAB}} \quad (\text{Eq. 39})$$

$$-\int_{19_{\text{CCAB}}}^{9_{\text{CCAB}}} P_S dA = \phi_{\text{CCAB}} \quad (\text{Eq. 40})$$

$$-\int_{9_{\text{P}}}^{9_{\mathcal{C}}} P_S dA = \phi_{\text{PLUG}} \quad (\text{Eq. 41})$$

$$-\int_{\text{PYLON}} P_S dA = \phi_{\text{PYLON}} \quad (\text{Eq. 42})$$

ϕ_{FCAB} and ϕ_{CCAB} are the pressure-area and surface friction forces acting on the fan-cowl afterbody (FCAB) and core-cowl afterbody (CCAB), respectively, and ϕ_{PYLON} is the viscous and pressure force on the pylon due to fan stream.

The equivalent formulation of modified net thrust for a two-stream turbofan engine is provided by Equation 43.

$$\begin{aligned}
 F_N^* &= W_9 V_9 + A_9 (P_{S9} - P_{S0}) + \phi_{\text{PLUG}} \\
 &\quad \boxed{\text{Primary (Core) Modified Gross Thrust } F_{G9}^*} \\
 &+ W_{19} V_{19} + A_{19} (P_{S19} - P_{S0}) + \phi_{\text{CCAB}} + \phi_{\text{PYLON}} - W_0 V_0 \\
 &\quad \boxed{\text{Ram Drag}} \\
 &\quad \text{Bypass-Duct Modified Gross Thrust } F_{G19}
 \end{aligned} \tag{Eq. 43}$$

Equation 43 forms the basis for a practical thrust/drag accounting system for a dual-stream engine. The quantity F_N^* includes all the forces measured in an engine test (i.e., core cowl, pylon and primary plug forces induced by primary and bypass stream flow) adjusted for the effects of flight velocity. When thrust is defined this way, model and full-scale engine test results (which measure the forces) may be applied to determine F_{IPF} .

Thus, the modified gross thrust for a dual-stream engine is

$$F_G^* = F_{G9}^* + F_{G19}^* \tag{Eq. 44}$$

$$F_G^* = W_9 V_9 + (P_{S9} - P_{S0}) A_9 + \phi_{\text{PLUG}} + W_{19} V_{19} + (P_{S19} - P_{S0}) A_{19} + \phi_{\text{CCAB}} + \phi_{\text{PYLON}} \tag{Eq. 45}$$

And the gross thrust, F_G , for a dual-stream engine is

$$F_G = W_9 V_9 + (P_{S9} - P_{S0}) A_9 + W_{19} V_{19} + (P_{S19} - P_{S0}) A_{19} \tag{Eq. 46}$$

The foregoing equations are all for steady-state flow conditions. Reference 1.5 presents information to substantiate the validity of this assumption for fixed-throttle engine operation during steady-state and quasi-steady-state aircraft maneuvers.

4.1.3 Selected Equations for Reference

In addition to Equations 22 and 36 for the installed propulsive force for single-stream and dual-stream engines, respectively, the terms and associated equations for gross thrust, modified gross thrust, and modified net thrust are used so often that they warrant being assembled in tabular form as shown in Table 2. Special note should be given to modified net thrust for it is the quantity for which the engine manufacturer is normally responsible.

TABLE 2 - SUMMARY OF KEY TERMS AND EQUATIONS

TERMS	SYMBOL	SYSTEM TYPE ¹⁾	EXPRESSIONS
GROSS THRUST	F_G	SS	$W_9 V_9 + (P_{S9} - P_{S0}) A_9$
		DS	$W_9 V_9 + (P_{S9} - P_{S0}) A_9 + W_{19} V_{19} + (P_{S19} - P_{S0}) A_{19}$
MODIFIED GROSS THRUST	F_G^*	SS	$W_9 V_9 + (P_{S9} - P_{S0}) A_9 + \phi_{\text{PLUG}}$
		DS	$W_9 V_9 + (P_{S9} - P_{S0}) A_9 + \phi_{\text{PLUG}} + W_{19} V_{19} - (P_{S19} - P_{S0}) A_{19} + \phi_{\text{CCAB}} + \phi_{\text{PYLON}}$
MODIFIED NET THRUST	F_N^*	SS	$W_9 V_9 + (P_{S9} - P_{S0}) A_9 + \phi_{\text{PLUG}} - W_0 V_0$
		DS	$W_9 V_9 + A_9 (P_{S9} - P_{S0}) + \phi_{\text{PLUG}} + W_{19} V_{19} + A_{19} (P_{S19} - P_{S0}) + \phi_{\text{CCAB}} + \phi_{\text{PYLON}} - W_0 V_0$

1) SS - SINGLE-STREAM; DS - DUAL-STREAM

4.1.4 Thrust/Drag Bookkeeping System

Definitions and methodology for thrust accounting have been presented in this chapter. However, as indicated by Equations 1 and 2, engine thrust and airplane drag are inextricably linked when the engine and airframe come together.

While the propulsion specialists are busy developing an engine and measuring thrust at static conditions, aerodynamic specialists are busy developing an airframe and measuring drag at wind-on conditions, usually in separate organizations and at different locations. When the engine and airplane components are integrated, however, such a simple and neat separation of component performance is not usually possible. Installed engine thrust will depend on airframe external flow effects and airplane drag will depend on engine exhaust flow effects.

Because of the imprecise “split” between thrust and drag, it is imperative that the parties involved in the determination of installed propulsive thrust, F_{IPF} , and airframe system drag, D_{AFS} , (Equation 2) reach early agreement regarding the definition of “thrust” and “drag” and on a convenient thrust/drag bookkeeping system. The agreed upon bookkeeping system is often driven by practical considerations such as the amount and type of component data available from wind-on testing. The following paragraphs of this section will discuss in more detail, the thrust/drag accounting issues that impact the definition of the thrust/drag bookkeeping system.

4.1.5 Installed Thrust

In order to accurately predict aircraft performance for situations where the “small angle approximation” is appropriate, both the aerodynamic and the propulsive forces are resolved into the flightpath axes, parallel and perpendicular to the freestream velocity vector. Aerodynamic drag is defined as positive acting along the velocity vector. Aerodynamic lift is defined as positive upward through the top of an upright aircraft and perpendicular to the velocity vector (see Appendix C).

It is assumed that propulsive gross thrust acts parallel to the engine axis or the engine exhaust nozzle axis with positive gross thrust pushing the aircraft forward. Gross thrust is broken down into forces in the direction of the velocity vector and perpendicular to the velocity vector (propulsive lift). Propulsive drag acts parallel to the velocity vector and is positive acting aft (same as aerodynamic drag).

The propulsive drag is primarily ram drag, but it also includes incremental throttle-dependent forces defined relative to a reference engine operating condition. The reference condition may include engine or inlet airflow, inlet geometry (if variable), nozzle pressure ratio, and exhaust nozzle geometry (if variable).

For situations where engines are not canted outboard, the installed propulsive force acting along the aircraft flightpath axis is defined to be:

$$F_{IPF} = F_G^* \cos(\alpha + \tau) - F_E \quad (\text{Eq. 47})$$

where:

F_{IPF} = Installed propulsive force

F_G^* = Modified gross thrust

F_E = Installed propulsive drag (see Appendix C)

α = Aircraft angle of attack (generally equal to the angle between the reference line in the body axis and the aircraft velocity vector)

τ = Thrust incidence angle (for an engine with its exhaust nozzle mounted symmetrically on the afterburner or the gas generator, τ is the angle between the engine centerline and the aircraft body axis with τ positive for the centerline of the engine face inclined above the centerline of the exhaust nozzle)

4.2 Thrust/Drag Accounting

The measurement and validation of in-flight thrust requires definition of a thrust/drag accounting system that clearly defines the treatment of all the propulsion-related forces acting on the system (References 4.3 and 4.4). The variety of actual and possible propulsion systems makes it impractical to specify a single rigorous accounting system. Therefore, to obtain the most accurate and efficient bookkeeping system, the accounting methodology is tailored to the requirements of each particular system.

The parties involved in the determination of “thrust” in flight should reach early agreement regarding the definition of “thrust” and corresponding “drag,” and of a convenient thrust/drag accounting procedure. The determination of overall net thrust cannot be accomplished without the estimation of the magnitude of one or more forces that cannot be measured directly.

Thrust will depend on external flow-field effects. Only if the effects of the external flow field are neglected is it possible to define a thrust that can be established by direct force measurement through static testing of the engine and exhaust system in a ground-level or altitude test facility. Recognition of the effects of the external flow on thrust may be achieved through model testing (see 7.2 and 7.3). Force measurements acquired in the presence of an external flow will invariably include elements of drag or exclude elements of thrust that cannot be determined in a direct manner.

In many instances, exhaust thrust and afterbody forces are negligible; in other cases, the relegation of exhaust thrust and/or unaccounted afterbody forces to the drag account may be of no practical consequence. The degree to which external flow-field effects are properly represented in in-flight thrust determination depends entirely on the testing performed to establish installed engine or exhaust system performance characteristics. Precise accounting for external flow-field effects requires “wind-on” testing of the engine installation in a wind tunnel and the application of appropriate accounting methods to break down measured forces into thrust and drag components.

Modified net thrust (Equations 31 and 43) is considered an acceptable starting place for most aircraft propulsion systems. However, modified net thrust does not account for inlet, exhaust, or thrust-moment forces. These significant forces are essential to thrust/drag accounting. They must be accounted for, but are uniquely a function of the installation and the engine/aircraft operating conditions. Figure 6 illustrates forces involved in the thrust/drag accounting of an isolated, axisymmetric propulsion system. The inlet force increment ΔF_{INL} , which results from the difference between ϕ_{ADD} and ϕ_{IC} and their respective reference conditions, is a function of engine airflow. The exhaust force increment ΔF_{EXH} , which results from the difference between ϕ_{PLUG} and ϕ_{AB} and their respective reference conditions, is generally a function of nozzle pressure ratio and nozzle area. Therefore, changes in these forces, ΔF_{INL} and ΔF_{EXH} , are propulsion system dependent and must be accounted in the thrust/drag bookkeeping procedure, along with other forces such as trim forces. The above nacelle/aircraft friction and pressure forces (drags) are impractical to separate from the propulsion system forces. Fortunately, this is not mandatory as long as all forces are included either separately or as differences between forces.

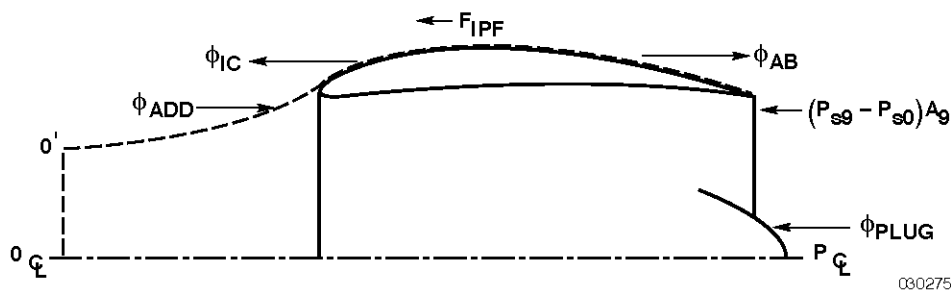


FIGURE 6 - FORCES ACTING ON A PROPULSION SYSTEM

The general approach is to select an aircraft/propulsion-system reference operating condition. Thereby, a reference drag for the aircraft is established that includes reference inlet, exhaust and friction forces. Differences in overall aircraft drag from this reference are established, generally from scale-model testing as a function of the inlet and nozzle operating conditions; and these throttle-dependent forces (drags) are then accounted as changes in propulsive thrust in the thrust/drag accounting procedure. This accounting method permits aircraft performance to be related to engine net thrust and to a reference aircraft drag polar (Appendix C describes aircraft drag polars).

The following paragraphs discuss the development of a thrust/drag accounting system for a fully-integrated (buried) propulsion system to illustrate the overall approach. Considering an aircraft in level flight, the simplified force equation (Equation 1 and repeated here) applied in the flight direction takes the form:

$$F_{\text{EX}} = F_{\text{IPF}} - D_{\text{AFS}}$$

where:

F_{EX} = Excess thrust (or total unbalanced force) in the flight direction

F_{IPF} = Installed propulsive force that is obtained from net thrust and throttle-dependent terms with adjustments for deviations from full-scale reference conditions

D_{AFS} = Airframe system drag at full-scale reference conditions as reflected in the aircraft drag polar (see Appendix C)

When excess thrust is zero or can be determined, aerodynamic drag relationships can be used to validate the method for determining in-flight thrust. The airframe system drag has several components that correct the aerodynamic drag to the full-scale reference conditions. Appendix C provides additional information.

The installed propulsive force is defined to be equal to the installed modified net thrust at the full-scale reference conditions and accounts for all propulsive forces acting on the aircraft. Additional forces are included in the airframe system drag. For excursions from the full-scale reference conditions, incremental forces must be considered. These throttle-dependent forces are included as adjustments to develop the installed propulsive force:

$$F_{IPF} = F_N^* - \Delta F_{INL} - \Delta F_{EXH} - \Delta F_{TRIM} \quad (\text{Eq. 48})$$

where:

- F_N^* = Modified net thrust, accounting for installation effects of inlet internal performance, nozzle internal performance, bleed air extractions, and shaft power extractions at the full-scale reference conditions
- ΔF_{INL} = External force increment between full-scale reference and any given operating condition due to the inlet
- ΔF_{EXH} = External force increment between full-scale reference and any given operating condition due to the exhaust system
- ΔF_{TRIM} = External control-surface-trim force increment associated with operating the propulsion system at other than the chosen propulsion system reference conditions

The establishment of the full-scale reference conditions requires the selection of several variables including inlet mass flow ratio, inlet geometry, nozzle pressure ratio, nozzle geometry, secondary airflows, and aircraft trim setting. Since these variables influence the installation drag, a fixed set of reference conditions must be identified. The selection of full-scale reference conditions is influenced by practical considerations, an important factor being the aero-reference model, which is the wind-tunnel scale model used as the basis for determining the aircraft drag polar. The model may be typically 5 to 10% scale and designed to be as representative as possible of the full-scale aircraft. It may have flow-through nacelles, but it cannot altogether simulate the full-scale engine inlet mass flow ratio, inlet geometry, nozzle geometry, and nozzle pressure ratio. To minimize model complexity, secondary airflows are not normally simulated. Aero-reference conditions, therefore, are usually characterized by a nozzle pressure ratio of approximately one, a modified and fixed-inlet or afterbody geometry, a non-representative inlet mass flow ratio, and no secondary airflows.

Additional wind tunnel tests are conducted to determine the incremental drag forces attributed to the inlet and afterbody geometry, inlet mass flow ratio, and nozzle pressure ratio. Three models may be used, as illustrated in Figure 7. A convenient set of full-scale reference conditions are selected, and the aero-reference drags are incremented appropriately to these conditions. The resulting reference drag polar is normally characterized by a fixed geometry for each flight speed, a typical operating inlet mass flow ratio and nozzle pressure ratio, and no allowance for secondary flow.

This general approach to thrust/drag accounting is summarized in Figure 8. The test models and analyses provide a reference aircraft drag and the throttle-dependent drag increments that are used with modified net thrust to determine installed propulsive force at any specific engine/aircraft operating condition.

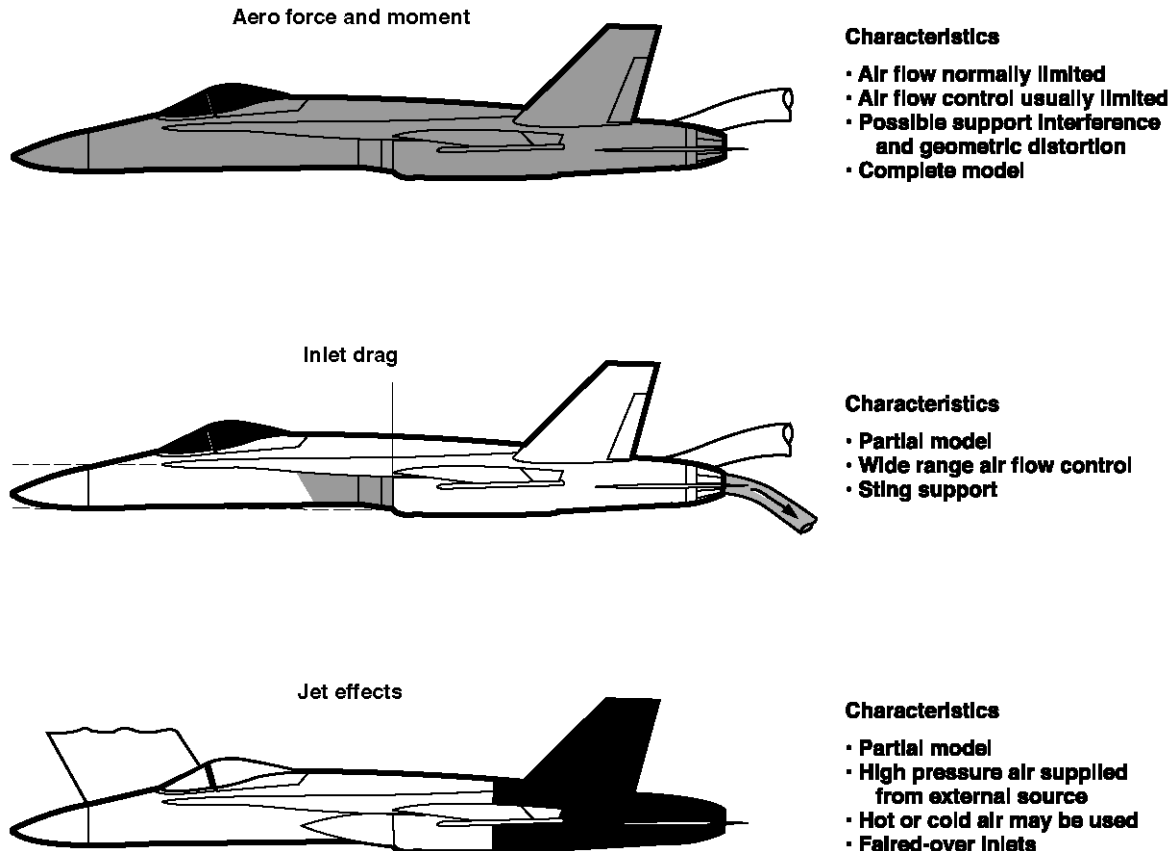
4.2.1 Inlet Force Increment

The inlet force increment can consist of spillage drag, ramp bleed drag, and such secondary flow terms as bypass and ventilation airflow drag. The throttle-dependent inlet spillage drag force increment is defined as the change in aircraft drag force resulting from the difference between operating and full-scale reference inlet mass flow ratios. Spillage drag, which is unrecovered inlet additive drag, varies with inlet mass flow as illustrated in Figure 9.

The drag of the aero-reference-model inlet (Point 1 in Figure 9) is included in the aero-reference drag. The incremental drag between (1) and the full-scale reference condition (2) represents the scale model to full-scale reference correction to be included in the full-scale drag polar, ΔD_{INL} . Drag differences between engine operating conditions (3) and full-scale engine reference condition (2) are accounted for as propulsive-system-related inlet drag force, ΔF_{INL} .

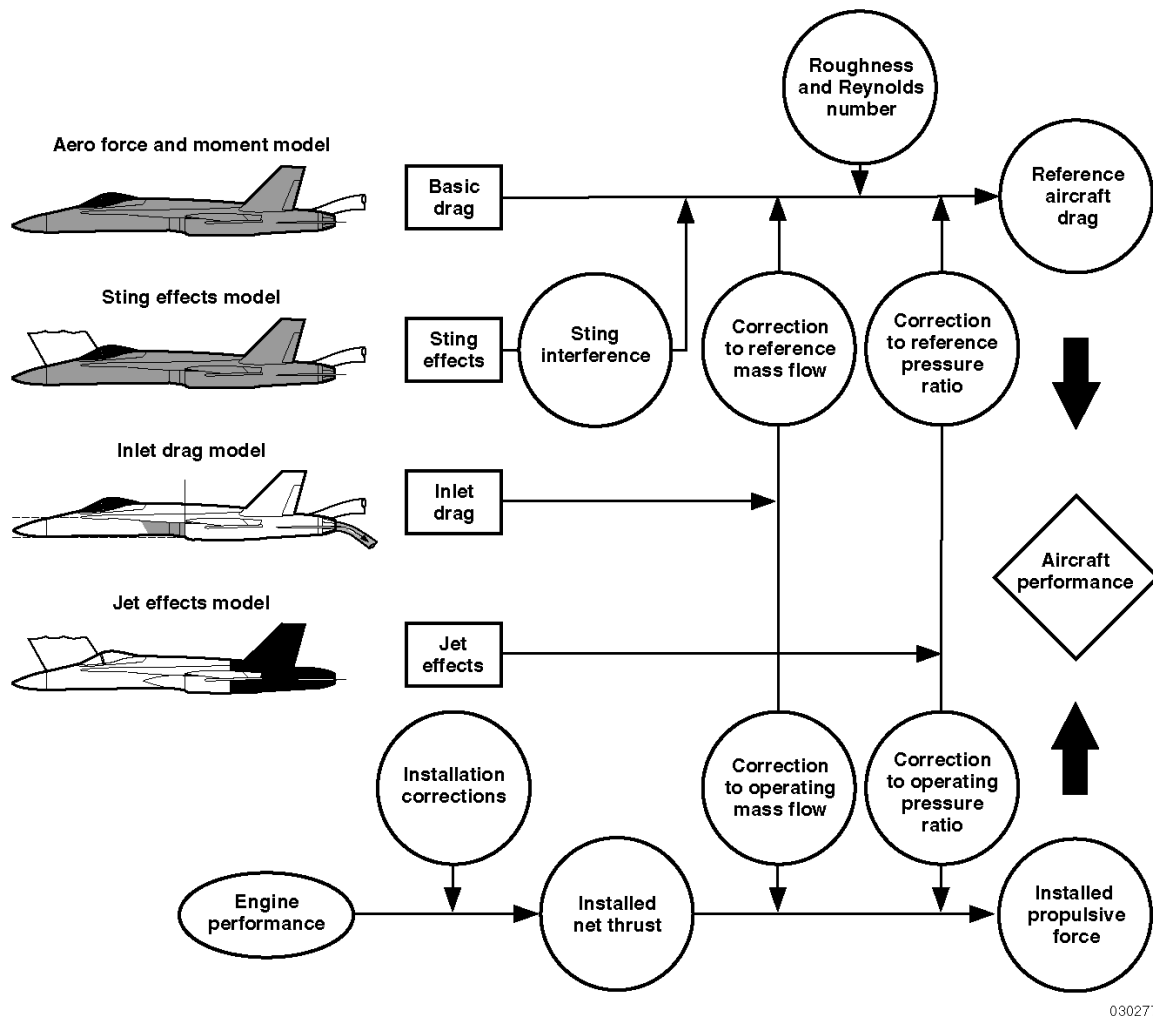
For subsonic podded installations, spillage drag can be investigated by testing isolated flow-through models with internal geometry variations to alter inlet mass flow ratio. Nacelle cowl geometry should be simulated correctly to account for possible inlet/afterbody coupling effects. An isolated nacelle drag test may be used to determine differences in drag due to mass flow ratio.

An inlet spillage drag test is essential for complete thrust/drag accounting of a fully-integrated propulsion system. The inlet and forward fuselage, including any items that might affect inlet flows, should be tested as a unit to assess the spillage drag. A flow-through model with internal duct modifications or an internal flow-metering device could be used to conduct this test. There is generally no requirement to duplicate the afterbody geometry when inlet and afterbody forces are not closely coupled as with podded installations. For inlets on high-speed aircraft, inlet tests must be conducted to determine drag sensitivity to geometry variation as well as inlet mass flow ratio.



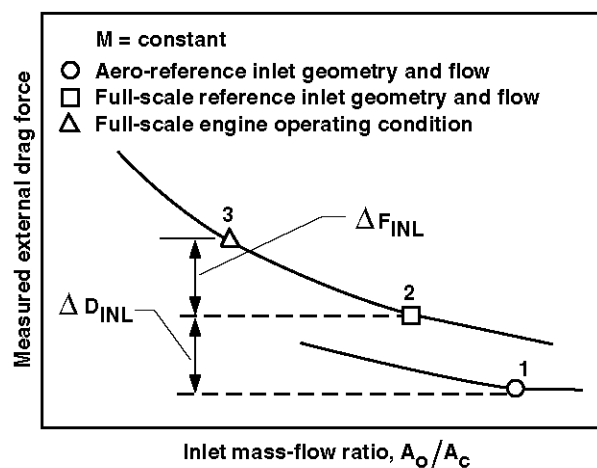
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FIGURE 7 - EXAMPLE TEST MODELS



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FIGURE 8 - TYPICAL THRUST/DRAG ACCOUNTING SYSTEM



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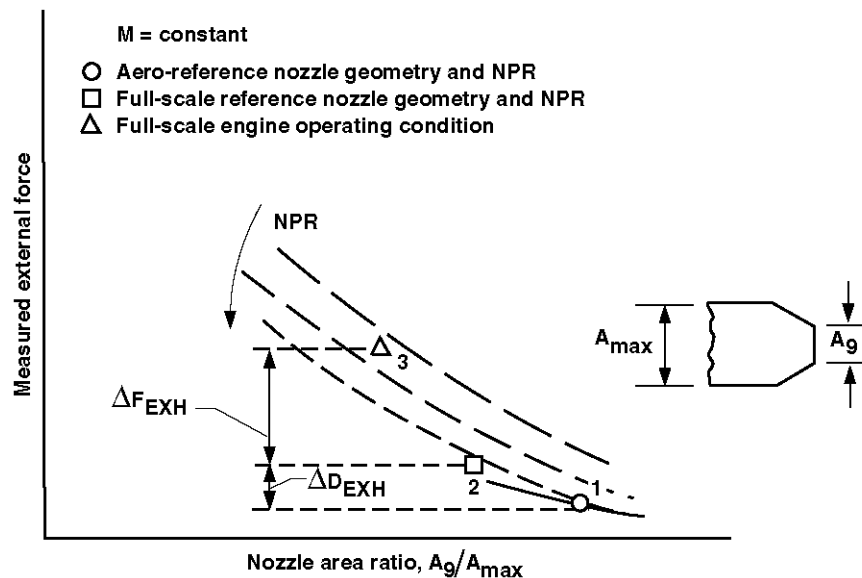
FIGURE 9 - DRAG FORCE VARIATION WITH INLET MASS FLOW RATIO

4.2.2 Exhaust-System Force Increment

The throttle-dependent exhaust system or interference force increment (drag) is defined as the change in aircraft drag force resulting from the difference between operating and full-scale reference nozzle pressure ratio and area. For integrated exhaust systems, nozzle pressure ratio influences the afterbody pressure distribution and drag. A change in nozzle area alters the afterbody closure and pressure distribution that likewise affects aircraft drag. For podded installations, nozzle pressure ratio may influence pressure distributions on the nacelle, pylon, wing, or fuselage. The resulting change in drag is called propulsion-system-related interference drag or jet-effects drag. Typical variations in aircraft drag force with nozzle area and pressure ratio are illustrated in Figure 10.

Afterbody force tests are conducted to evaluate throttle-dependent exhaust-system drag forces. The drag of the aero-reference-model nozzle (Point 1 in Figure 10) is included in the aero-reference drag. The incremental drag between (1) and the full-scale reference condition (2) represents the scale model to full-scale reference correction to be included in the full-scale drag polar, ΔD_{EXH} . Drag force differences between engine operating condition (3) and full-scale engine reference condition (2) are generally accounted for as throttle-dependent exhaust system force, ΔF_{EXH} . Like the throttle-dependent inlet force increment, ΔF_{EXH} represents an adjustment to net thrust to obtain installed propulsive force. Some of the smaller forces (ϕ_{POST}) are impractical to separate between drag and propulsion forces. Fortunately this is not mandatory as long as all forces are measured and included either separately or as differences between forces.

Throttle-dependent exhaust-system forces can be investigated using a blown afterbody model or a blown aircraft model. The term “blown” refers to the use of a high-pressure external source to vary nozzle pressure ratio. The airplane model inlets are faired over. The afterbody model simulates only the aft geometry and, therefore, has no air intake system. The variation in drag due to nozzle pressure ratio, nozzle area, and vector angle is measured and used to account for throttle-dependent drag. More recently, CFD has been used to complement the wind tunnel increment to minimize tunnel time and cost.



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FIGURE 10 - DRAG FORCE VARIATION WITH NOZZLE AREA AND NOZZLE PRESSURE RATIO

Afterbody or interference drag force tests are conducted to determine ΔD_{EXH} to establish a baseline drag level at full-scale reference nozzle area and pressure ratio, which is included in the full-scale drag polar. Incremental changes from this baseline level, ΔF_{EXH} , define the throttle-dependent exhaust system force adjustments to installed propulsive force.

4.2.3 Trim Force Increment

Aircraft weight, balance, and maneuver conditions can require changes in the trim surface positions that affect aircraft drag. These drag differences are normally included in the aero-reference drag. Changes in the propulsion system throttle setting or geometry may also affect aircraft control-surface-trim positions. The drag increment for these items, from the aero-reference condition, is normally charged to the propulsion system and included in the installed propulsion force, F_{IPF} , but not in engine thrust, F_G .

4.3 Ideal Thrust and Normalized Groups

Since the gross thrust, F_G , applies at the nozzle exit plane (station 9) while practical considerations often dictate that nozzle conditions be measured at the nozzle entry plane (station 7), a convention with several unique definitions has been developed to provide in-flight evaluations of thrust and mass flow. The general procedure is to relate real nozzle performance to that of an ideal nozzle through the use of empirically established coefficients.

4.3.1 Ideal Nozzle

For the ideal nozzle definitions, one-dimensional, isentropic flow is considered to exist within the nozzle downstream of the nozzle entry plane (station 7). In the past, the additional constraint of constant specific heat ratio, γ , has often been assumed. However, with the widespread use of digital computers, the substitution of real gas properties does not present undue complications and is the preferred procedure (Reference 4.5). The use of constant specific heat ratio serves a useful purpose in illustrating relationships. In either case, consistency in the use of gas properties should be maintained.

The ideal flow calculations may assume an ideal convergent nozzle where the expansion is limited to sonic (or choked) conditions at the nozzle exit plane. At the critical operating condition, the entry-total-pressure to exit-static-pressure ratio (P_{T7}/P_{S9}) is just sufficient to produce sonic flow at the exit plane via the one-dimensional isentropic flow assumption. At subcritical operating conditions, P_{S9} equals the ambient static pressure, P_{S0} , and the exit Mach number is less than 1.0. At supercritical operating conditions, P_{S9} exceeds P_{S0} due to unity Mach number at the exit plane.

An ideal convergent-divergent nozzle is defined as having a conceptual geometry, which is infinitely variable or flexible such that the exit static pressure, P_{S9} , remains equal to P_{S0} . At subcritical and critical nozzle operating conditions, the ideal convergent and ideal convergent-divergent nozzles are conceptually identical and have the same ideal thrust performance. At supercritical conditions the ideal convergent-divergent thrust exceeds the ideal convergent thrust by virtue of complete isentropic expansion resulting in higher exit velocity.

Ideal-nozzle total temperature, total pressure, and mass flow are assumed to remain constant and equal to the entry values (T_{T7}, P_{T7}, W_7) between the nozzle entry and exit stations. Static temperature, velocity and area (or static pressure) are calculated based on the one-dimensional isentropic-expansion assumption. The minimum area (throat) is designated station 8 and will be coincident with the exit plane (station 9) for the convergent nozzle.

4.3.2 Non-dimensional Groups

Three non-dimensional ideal-nozzle groups are in common use to express the ideal flow and thrust. These are:

$$\left[W \sqrt{RT_T / AP_T} \right]_{ID} = \text{Flow Function} \quad (\text{Eq. 49})$$

$$\left[F_G / AP_{S0} \right]_{ID} = \text{Thrust Function} \quad (\text{Eq. 50})$$

$$\left[F_G / W \sqrt{RT_T} \right]_{ID} = \text{Specific Thrust Function} \quad (\text{Eq. 51})$$

The nozzle area used in forming the thrust function, whether for ideal or actual nozzle performance, is usually the throat area A_8 . This convention is adopted for this report. Freestream static pressure, P_{S0} , is used in the thrust function. Alternate derivations using the exit area, A_9 , and the total pressure, P_T , may be substituted, where needed. The ideal groups are related by the expression:

$$[F_G / AP_{S0}]_{ID} = [F_G / W\sqrt{RT_T}]_{ID} [W\sqrt{RT_T} / AP_T]_{ID} [P_T / P_{S0}] \quad (\text{Eq. 52})$$

In ideal one-dimensional flow, the ideal thrust expressions are functions of nozzle pressure ratio, P_{T7} / P_{S0} , and specific heat ratio, γ , as summarized in Table 3.

When using constant specific heat ratio calculations, these ideal thrust expressions are helpful in reducing the calculation efforts and lead to the $F / W\sqrt{T}$ and F / AP thrust calculations (Reference 4.6). The use of the ideal groups has diminished with the direct calculation of real gas properties using digital computers. The $F / W\sqrt{T}$ and F / AP options provide a choice in the definition of nozzle coefficients.

4.4 Nozzle Coefficients

It is essential that a consistent set of coefficients be defined to relate actual nozzle performance to ideal nozzle performance in a manner that is practical for in-flight thrust determination.

A useful place to start when defining nozzle coefficients is to begin with the definition of ideal airflow. The ideal airflow that would pass through a nozzle with a physical throat area of A_8 can be shown to be

$$W_{8,ID} = \frac{P_{T7} A_8 \bar{m}_8}{\sqrt{T_{T7}}} \quad (\text{Eq. 53})$$

$W_{8,ID}$ is the airflow that would pass through the nozzle throat, A_8 , for a given P_{T7} and T_{T7} if the flow field at the throat was perfectly uniform.

$\bar{m}$ is the flow function (Equation 49) and can be derived from the continuity equation, the definition of Mach number, and the isentropic Mach number relationships, as:

$$\bar{m} = \sqrt{\frac{\gamma}{R}} M \left(1 + \frac{\gamma-1}{2} M^2 \right)^{-\frac{(\gamma+1)}{2(\gamma-1)}} \left(\frac{P_S}{P_T} \right)^{1/\gamma} \sqrt{\frac{1}{R} \left(\frac{2\gamma}{\gamma-1} \right) \left[1 - \left(\frac{P_S}{P_T} \right) \right]^{\frac{\gamma-1}{\gamma}}} \quad (\text{Eq. 54})$$

The throat flow function ($\bar{m}_8$) is defined by limiting the throat Mach number (M_8) to one to account for choked flow.

For convergent nozzles, P_{S8} is approximated by the freestream static pressure ($P_{S8}=P_{S0}$). This approximation is also commonly used for convergent-divergent nozzles. However, it should be noted that applying P_{S0} at the throat neglects the divergent section expansion to A_9 and for unchoked conditions the throat static pressure will be below ambient, the throat Mach number higher than at the exit and the ideal mass flow below what would occur with uniform flow expanding isentropically to the exit area. This difficulty can be overcome by including the area ratio in the definition of $\bar{m}_8$, but at the expense of complexity and making the choking pressure ratio a function of the area ratio.

4.4.1 Flow Coefficient, C_D

It is convenient to define the flow (or discharge) coefficient such that it applies to both the convergent (con) and the flexible-convergent-divergent (flex con-di) nozzles. The coefficient is based on the throat area (station 8) in the case of the convergent-divergent nozzle. The notation is such that P_T and T_T represent suitable mean values of nozzle entry total pressure and temperature, defined at a reference plane located upstream of the nozzle, and that W_{ACT} denotes the actual mass flow passing through the nozzle of actual (geometric) area, A_8 .

The flow (or discharge) coefficient, C_{D_8} , is defined as the ratio of actual mass flow to ideal mass flow for a given nozzle geometry and pressure ratio.

$$C_{D_8} = \frac{W_{8,ACT}}{W_{8,ID}} = \frac{W_{8,ACT}}{\left(\frac{P_{T_7} A_8 \bar{m}_8}{\sqrt{T_{T_7}}} \right)} \quad (\text{Eq. 55})$$

The flow coefficient can also be interpreted as the ratio of the effective throat area $A_{8,EFF}$ to the physical throat area A_8 in the following manner. If an equation similar to Equation 53 is written for the actual flow $W_{8,ACT}$ passing through an effective $A_{8,EFF}$, Equation 56 is obtained.

$$W_{8,ACT} = \frac{P_{T_7} A_{8,EFF} \bar{m}_8}{\sqrt{T_{T_7}}} \quad (\text{Eq. 56})$$

Then Equation 55 can be written as

$$C_{D_8} = \frac{W_{8,ACT}}{W_{8,ID}} = \frac{\frac{P_{T_7} A_{8,EFF} \bar{m}_8}{\sqrt{T_{T_7}}}}{\left(\frac{P_{T_7} A_8 \bar{m}_8}{\sqrt{T_{T_7}}} \right)} = \frac{A_{8,EFF}}{A_8} \quad (\text{Eq. 57})$$

Thus, the flow coefficient can be defined equivalently as the ratio of the effective area to the physical area when the Mach numbers passing through each area are equal.