Measurement of Net Thrust in Flight

THERON W. DAVIDSON*
Naval Air Test Center, Patuxent River, Md.

The feasibility and accuracy of the traversing-rake system, which samples pressures and temperatures through the engine exhaust, were compared with the interal General Electric gas-generator method in subsonic flight. Results of the first eight runs show agreement within 1% gross thrust and 5% net thrust with the rake as a standard. A North American Vigilante airplane with J-79 engines, which have convergent-divergent aerodynamic nozzles and large secondary airflows, was used. The rake promises developmental and research application bypassing extensive engine-test cell calibrations. Data reduction procedures are lengthy but conducive to automation. Acceptable results are predicted for supersonic tests to Mach 2.

Introduction

THE problem of measuring inflight net thrust, the one tool that can splice the theory of wind tunnels to the realism of operational flight, has long plagued the aeronautical sciences. Its accurate measurement can easily make the difference between success or failure in a new airplane design. However, up until now work on this component, so vital to the advancement of aeronautical sciences, has been tempered by many assumptions, ground calibrations, and extrapolations.

It should be remembered that propulsive forces and drag forces acting on an aircraft are related and can influence each other. Gross thrust produced by the engine nozzle influences the boat-tail and base drag on some installations. In addition to the ram drag involved in taking engine air aboard the aircraft, there may be other drags, such as incremental drag, spillage drag, cowl forces, boundary-layer removal, and auxiliary air drag, all of which are influenced by the amount of engine airflow. These extra forces are accounted for either by subtracting from the net thrust acting or by adding to the basic aircraft drag. Net thrust is the difference between engine gross thrust and ram drag of the engine airflow.

Net Thrust in Research

Although the bulk of performance tests are analyzed through the use of the gross-thrust parameter, most of the important features of research and design are dependent upon the accurate determination of net thrust. The new engine needs to be properly mated to the airframe. The engine inlet ducts must be suited to the engine. Feedback from developmental and research flying must reach wind-tunnel engineers to provide the necessary stepping stones for the advancement of the science. The following questions may arise: How well did the tunnel tests determine the drag characteristics of Aircraft XX? Can the friction drag in supersonic flight be predicted accurately with present wind-tunnel methods? If so, to what level of accuracy may it be predicted? Can the confidence level of equating model tests to full-scale predictions be improved? Answers to myriad questions like these can be obtained with precise and reliable inflight net-thrust measurements. These inflight net-thrust measurements can establish the level of reliability of many wind-tunnel coefficients and predictions.

Net Thrust in Testing and Development

Measurement of inflight net thrust greatly enhances not only the research field but also the testing and development areas. The system for measuring inflight net propulsive thrust will play a vital role in: 1) isolating causes of performance deficiencies early in an airplane development program; 2) determining responsibility for noncompliance of performance guarantees; 3) reducing the scope of testing required to determine performance throughout the flight envelope, particularly for flight programs requiring tests on many different aircraft loadings; and 4) determining the accuracy of predictions of performance and of flight testing.

For several years the Naval Air Test Center (NATC) at Patuxent River, Md. has been actively engaged in the development of a satisfactory method for measuring inflight net thrust for turbojet airplanes. The two most satisfactory methods under study are the gas-generator method, by General Electric (GE), and the traversing-rake method, by the Grumman Aircraft Engineering Corporation (GAEC). Both methods are presently in use and are being checked against each other. Each method is undergoing continual refinement. The instrumentation for both methods is installed on the same airplane, so that two independent calculations of net thrust are available for any given test.

Gas-Generator Method

The GE gas-generator method was refined and programed for the Datatron Digital Computer by NATC.[1] It is presently in standard use for performance determinations of airplanes powered by J79-GE-8 engines. This is an internal method, utilizing many coefficients and calibration curves. It is restricted to evaluations involving only those engine types for which extremely complex and extensive laboratory calibrations have been made.

The J79 engine calibrations were conducted by GE in the Tullahoma laboratory. The engine was instrumented with pressure rakes, taps, and thermocouples to measure the gasflow profiles at virtually every station. The characteristics of each measured station were then related to single-probe reading for a "calibration." The single probes at the various stations comprise an "instrumented" engine, the performance of which is calculated through the use of the calibration curves, some of which are proprietary.

Along with the standard airplane performance instrumentation of airspeed, altitude, rpm, fuel flow, fuel used, and outside air temperature, the instrumentation of the calibrated engine included: 1) compressor inlet total pressure and temperature, 2) exhaust nozzle position (area), 3) inlet guide vane position, 4) secondary air total pressure, and 5) turbine discharge total pressure and temperature.

Including the enumeration of input data, there are 55 computer data reduction exercises for the nonafterburning operations and 37 for afterburner operations. These computations involve such relationships as: 1) airflow vs engine speed for various inlet guide vane schedules; 2) tailpipe pressure loss, with respect to temperature and pressures, at both the turbine-

Presented at the AIAA/AFFTC/NASA FRC Testing of Manned Flight Systems Conference, Edwards Air Force Base, Calif., December 4–6, 1963 (no preprint number; published in bound volume of preprints of the meeting); revision received March 6, 1964.

* Technical Consultant, Flight Test Division.

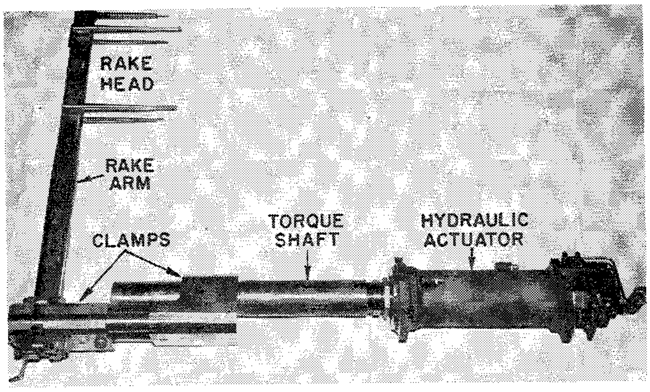

Fig. 1 Assembled traversing-rake system.

out and exhaust stations; 3) compressor discharge static pressure vs turbine-out total pressure with respect to turbine-out Mach number; 4) engine inlet airflow vs engine speed with respect to compressor face total pressure; 5) airflow corrections for Reynolds number effect and variable stator positions; 6) exhaust-system pressure loss vs a turbine discharge-flow function, with respect to effective discharge area and the exhaust-to-turbine absolute temperature ratio; 7) thrust-weight flow-temperature functions vs jet nozzle pressure ratio; 8) secondary-pressure ratio vs primary-pressure ratio, with respect to nozzle area and a function involving secondary and primary weight flow and temperature ratios; and 9) gross-thrust coefficient vs primary-pressure ratio, with respect to nozzle area and a function involving secondary and primary weight flow and temperature ratios.

When the lengthy laboratory tests have been performed for a given engine model, the data reduction procedures can be accomplished rapidly by machinery.

Traversing-Rake Method

Under contract with the Bureau of Naval Weapons, and in consultation with the Naval Air Test Center, GAEC developed a traversing-rake system for inflight thrust measurement.[2,3] When it became apparent that the traversing-rake system was reasonably accurate, NATC procured several complete systems. A complete traversing-rake system was installed, to measure static and total pressures and temperature, behind each of the two J79 engines on a North American Vigilante.

Many concerns, both military and industrial, have attempted to measure thrust with a traversing rake, but most have abandoned the idea. In order to utilize all the experience available on the subject, GAEC, under Navy contract, contacted these concerns for background on problem areas. It was apparent that emphasis should be placed on designing a system from the "ground up," so that the final package could be installed on different airplanes with a minimum of customizing, either of the aircraft or of the system, and that it have as little detriment to aircraft performance as possible.

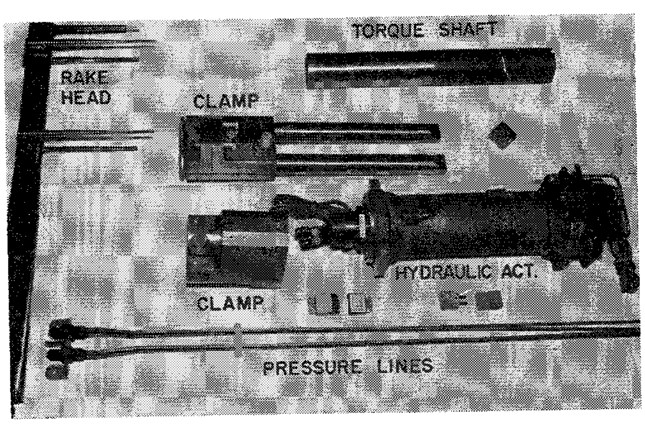

Fig. 2 Unassembled traversing-rake system.

Design Requirements

Some problems of the past generation of rakes had to be overcome in order for the GAEC system to provide: 1) a rake arm that would not bend or warp in the jet from either blast or heat; 2) small enough pressure probes to permit a side-by-side design for the measurement of both total and static pressures, at the same radius and in the same plane; 3) pressure-probe wind-tunnel calibrations for both transonic and supersonic flow; 4) a position-indicating system accurate to within 0.10 in. of nozzle radius; 5) an actuating system that would produce a steady sweep at all times; 6) pressure responses that would produce an accurate indication of exit area in the measurement plane; and 7) reliable temperature readings that would be made simultaneously with the pressure readings throughout the measurement plane.

In addition to these and other design improvements, a low-lag, high-response temperature probe was installed on the rake. The temperature probe makes possible the determination of mass flow at the nozzle exit. The thermocouple in the shielded tip is composed of iridium and 60% iridium-40% rhodium wire. It has consistently measured temperatures up to 3600° R during 6-sec sweeps.

Description

The traversing-rake system is composed of a hydraulic rotary actuator, a torque shaft assembly that is coaxial with the actuator, and a rake. The rake measures total and static pressures, and temperature. Figure 1 shows an assembled traversing-rake system. Figure 2 shows the various components of the system. Note the hollow torque shaft and the pressure lines that run through it. The length of the torque shaft can be altered for any installation, and the position of the rake on the torque shaft is adjustable. This design permits an adjustable sweep, so that the probes can be air cooled in any particular installation. It further provides the flexibility to measure airflow patterns at various distances aft of the nozzle exit.

The sweep rate can be varied by changing the size of certain restrictors in the hydraulic lines. Desirable sweep times are 10–20 sec per sweep in nonafterburning operation and 5–6 sec in afterburner. The successive sweeps, one in each direction, produces an accurate basis for pressure and temperature-lag determinations. The sweep duration for the tests of this paper was about 12 sec.

Figure 3 is a close-up of the traversing-rake head. The temperature probe is the single probe on the end of the rake arm. The total pressure probes are the same length as the temperature probe. The static orifices of the static pressure probes are located so that all readings of temperature and pressure are made in the same plane. The length, size, and spacing of the probes were designed for both subsonic and

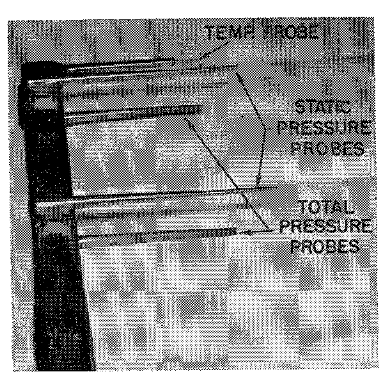

Fig. 3 Traversing-rake head.

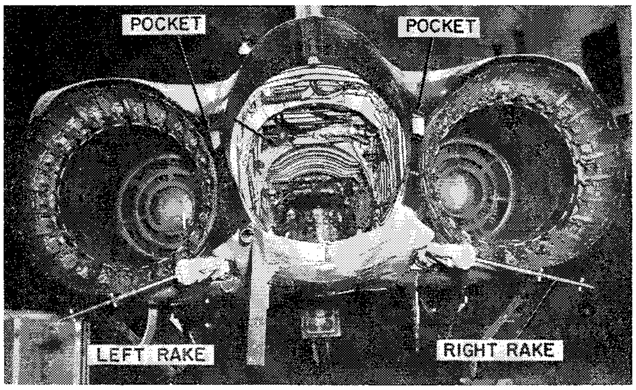

Fig. 4 Left and right traversing rakes in down position.

supersonic flow. The system was calibrated in a wind tunnel.

Figure 4 is a real view of the North American Vigilante (A-5A BuNo 147850), showing the traversing rakes in the down position. Figure 5 is a side view of the right engine with the rake in the down position, showing the clearance of the probes when the engine nozzle is fully extended. The clearance in this case is approximately $2\frac{1}{2}$ in.

Figure 6 shows the left rake in the up position. For any given run, each rake was swept through the exhaust of the respective engine from down to up position and returned through the exhaust to the down position.

Installation

The installation of the traversing-rake system presented no unusual difficulties. The structure of the aircraft was modified by the airframe contractor to withstand the loads imposed by the rake operation. The location of the actuating system on the test vehicle was found to be very important, because the system is subjected to long periods of high temperature and vibration during supersonic flight. Once the rakes were installed and calibrated, there were no major operational difficulties, except for the lack of proper cooling between swings during afterburner operation. The rakes were repositioned to permit better cooling between swings, and $\frac{1}{2}$-in. air lines were routed to the actuator compartments. For extended supersonic testing, it is necessary to position the actuators so that the rake head will be completely clear of the jet exhaust at the end of each swing.

Laboratory Tests

The altitude test chambers of the Trenton Naval Air Turbine Test Station (NATTS) were used to verify the over-all accuracy of the rake system. Figure 7 shows the close agreement between the rake-measured gross thrust and the gross thrust measured by NATTS.[2] Both the Pratt & Whitney J57 and the GE J79 engines were used in the tests with and without afterburning. Only the ambient pressure readings of the test cell were common to both data-reduction programs. The lines on Fig. 7 are for 3% variation. The majority of data agreed within 1 or 2%. The laboratory tests thus proved the rake system on the ground and endorsed it as a basis with which to compare other methods in flight.

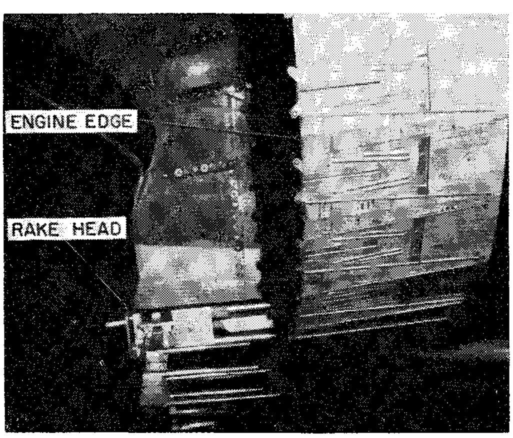

Fig. 5 Side view of right engine with nozzle fully extended and rake in down position.

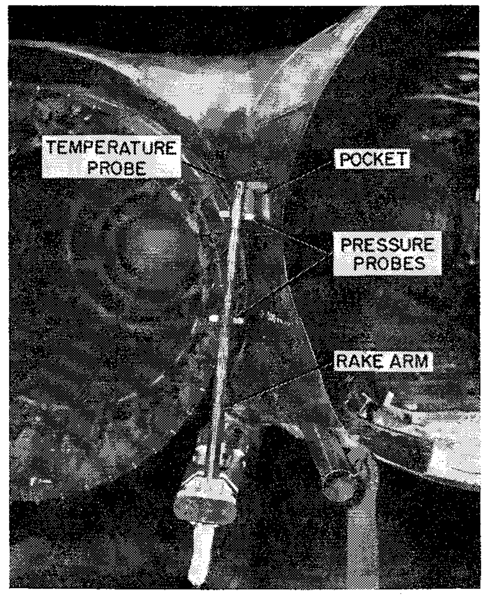

Fig. 6 Left rake in up position.

Flight Tests

Nine stabilized runs at various airspeeds were made at 25,000 ft to provide the data in this first analysis. Each run provided complete data for performance and fuel consumption for both the GE gas-generator method and the GAEC traversing-rake method. The ratio of airplane weight to the pressure ratio (altitude ambient pressure to sea-level standard pressure) was kept relatively constant in order to keep a constant lift coefficient from run to run. Analysis was based on the fact that in stabilized level flight the thrust is equal to drag.

Rake traverses were made on both engines at the same time for each stabilized flight data point. Two sweeps were made on each engine on each run.

The flight Mach numbers ranged from 0.94 to 0.56 in approximately even increments. At no time during the tests

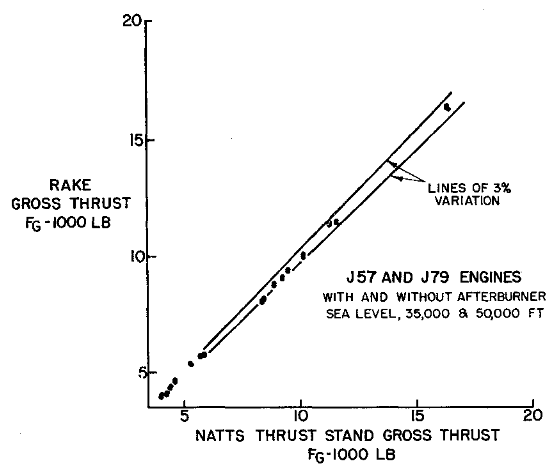

Fig. 7 Comparison of rake-measured gross thrust and the gross thrust measured by NATTS, Trenton Laboratory.

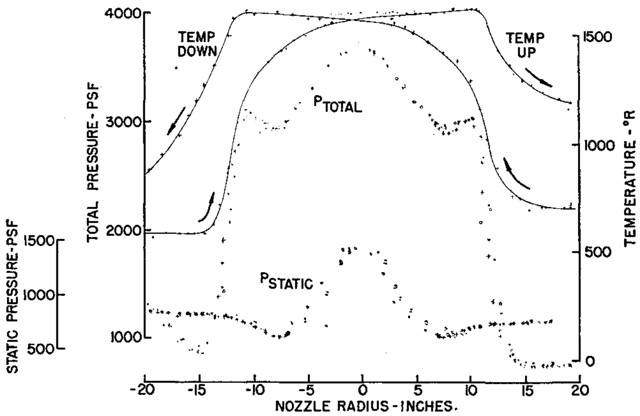

Fig. 8 Sample machine plot of temperature and pressure profiles for the determination of lag corrections.

could the pilot detect any change in the characteristics of the test vehicle while the rakes were being traversed.

Since the original nine runs were made (giving data for 18 rake traverses), over 1200 rake traverses have been successfully completed for many different altitudes and airplane loadings. Tests have been made in both subsonic and supersonic flight with equally acceptable results. Both flight and data-handling techniques are constantly being improved.

Data-Reduction Procedures

A photopanel recorder and an 18-channel oscillograph were used to record the airplane and engine performance parameters. The data reduction of the traversing-rake data is divided into three parts.[2,3]

Part I

Part I input data is made up of the oscillograph and photopanel readings plus the various calibrations. A sample output of part I is shown in Fig. 8. Figure 8 is a machine plot of temperature and pressure vs nozzle radius for the determination of proper lag corrections. This plot is for one engine, and it displays two static pressure, two total pressure, and temperature readings for both sweeps. Sweeps in both directions for the same test run are required accurately to account for lag. Each pressure and temperature measurement is associated with a unique radial distance from the center of the nozzle area.

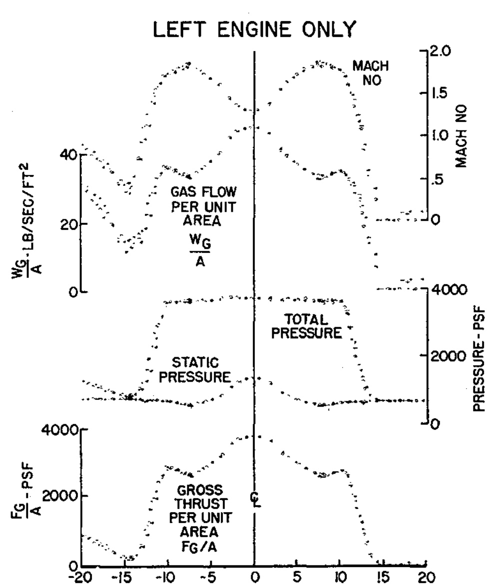

Fig. 9 Automatic machine plot of corrected profiles of various parameters in the jet with respect to engine nozzle radius; only left engine with one complete rake system.

Part II

Part II utilizes the corrected profiles of pressure and temperature of part I, along with weighted area curves and appropriate thrust equations, to compute the following parameters with respect to nozzle radius: 1) Mach number, 2) total gas flow per unit area (mass flow), 3) corrected total-pressure profile, corrected static-pressure profile, and 4) gross thrust per unit area. Figure 9 is machine plot of the part II output for the left engine of run no. 1. The centerline of the nozzle bisects the chart and runs through "zero" on the nozzle radius scale. Note that the minimum values of all the plotted parameters are at approximately 14 in. on either side of the nozzle center. These points mark the edges of the jet, which has a diameter of about 28 in. in the measurement plane. This engine has a variable-area nozzle that changes with engine conditions. Succeeding charts will show how the area of the jet in the measurement plane changes with changing airplane Mach number.

Part III

Part III of the data-reduction process involves integrating the total gas flow per unit area and the gross thrust per unit area curves within the limits of the jet boundaries in the measurement plane.

Data Reduction Manpower Requirement

Although the data-reduction process is largely automatic for most of the work, many man-hours are required to complete the entire process. The first nine runs, for example, required about 20 man-hours each, in order to accomplish organizing the film and traces, making time histories, establishing zeros and resistance calibrations, reading reference pressures, punching computer tapes, operating the computers and automatic plotters, fairing curves, preparing data for each new phase, and performing the final calculations of integration. It is expected that the data-processing time can be shortened by about 50% after more experience is gained.

Repeatability between Systems

Although Fig. 9 is a plot for the left engine only, Fig. 10 shows all the data for both engines on the same plot. Each profile of Fig. 10 is composed of eight superimposed plots; that is, it contains the bottom-to-top and top-to-bottom traverses for each of two engines, with two static- and two total-pressure readings per traverse. During this run the throttle positions of the two engines were closely matched. Since the left and right rake installations are completely separate systems, this particular run displayed two important features of a rake system. First, two separate systems can give identical results with no "juggling" of data. Second, acceptable data for a multiple-engine airplane can be obtained with a single traversing-rake system, provided all engine settings are properly matched.

Interesting Points Giving Confidence in the System

Symmetry

The symmetry of the profiles about the centerline of the jet is worthy of note. It is characteristic of good installation techniques and accurate lag corrections. On the left-hand edge of the plots, the rakes are entering the jet from the local freestream. Here, the Mach number will be in the vicinity of the flight Mach number but not identical to it because of boundary flow. The pressure profiles, consistent with the Mach number profiles, start in the local freestream. The total pressure decreases as the rake approaches the wake and becomes equal to the static pressure at the edge of the jet. The total pressure rises to its greatest value about the first 3 in. inside the jet. As the rake comes out of the jet on the right (top of the swing as shown in Fig. 6), it goes into a static area. Here the Mach number is zero, showing the absence of local airflow. Also, the static pressure is less than ambient, belying the presence of base-area drag.

Mach jump

Several other points of interest helped to increase the confidence in the traversing-rake system. The conspicuous absence of a "Mach jump" in the pressure profile gives credence to the design of the rake head. Such a jump could have appeared at a radius of about 13 in. on Fig. 10, for example, had the design of the rake head been faulty. In this portion of the swing, the rake was sampling data through the regions of subsonic to transonic to supersonic flow. The clear-cut pressure profiles enhance the accuracy of the exit-area measurement because the edges of the jet are so clearly defined.

Total pressure profiles

The total pressure profiles, after the initial increase in pressure, consistently show steady pressures throughout the jet. Compare the total pressure profile of the work plot of Fig. 8 with the corrected profile of Fig. 9. The irregular shape of Fig. 8 has been transformed into the smooth curve of Fig. 9, as a result of corrections for compressibility and total pressure loss across a normal shock. Figure 11 shows the family of pressure profiles for various airplane speeds. The consistency with which the indicated pressure profiles with several inflections are corrected to give constant pressures across the main part of the jet manifests the validity of the wind-tunnel calibrations.

Static pressure profiles

The static pressure profile, even though the magnitude of change is relatively constant, reveals many important flow characteristics. As in Fig. 10, the static pressure is higher in the center of the jet than in any other portion. It reveals that the air is more dense in the center and that a correspondingly high airflow will result. The gas flow per unit area plot exhibits this characteristic, and the gross thrust per unit area curve, of course, follows suit.

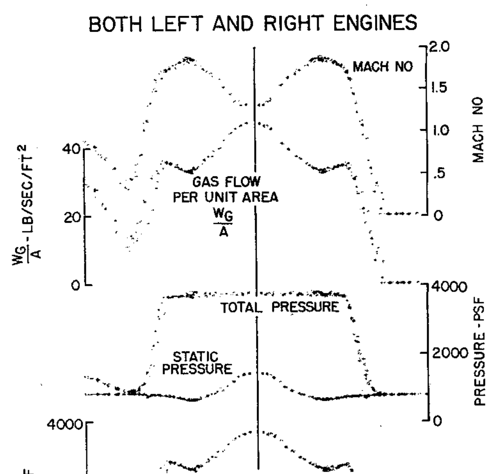

Fig. 10 Automatic machine plot of corrected profiles of various parameters in the jet with respect to engine nozzle radius; both left and right engine data superimposed, utilizing separate rake systems.

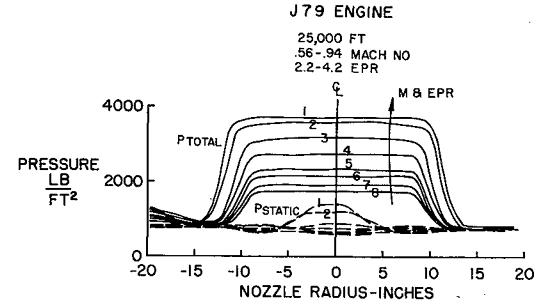

Fig. 11 Pressure profiles across the jet for eight airplane Mach numbers.

From the highest static pressure to the lowest static pressure there is expansion of the gases. In Fig. 10, expansion occurs from the center of the jet out to a radius of about 8 in. From this point to the edge of the jet, however, the pressure rises again, indicating that the jet was overexpanded in the measurement plane. This can be a useful tool, indeed, to the engineer responsible for nozzle and ejector design.

Base-Area Drag

Static pressure to the right of the wake is somewhat less than ambient pressure. This is an important measurement for the computation of base-area drag. Most internal methods assume that the exhaust expands to ambient pressure. This is a safe assumption for a measurement plane far behind the engine exit, but it can have no place in precise net-thrust determinations. Of course, the base-area pressures can be measured by static pressure taps and applied to any method. The traversing rake provides a convenient way to measure the base pressure without additional instrumentation. To indicate the importance of base-area drag in the over-all engine-airplane performance analysis, it is sufficient to say that base-area drag for the test vehicle reached magnitudes in the order of 500–1000 lb. Therefore, accurate determination of base-area drag of the airplane in flight is necessary to evaluate aircraft performance and to check with wind-tunnel results.

Flow Characteristics

Figures 11–14 show the flow characteristics for a series of eight runs, at 25,000 ft, for Mach numbers of 0.56–0.94. The engine pressure ratio (EPR) ranged from about 2.2–4.2 for the tests presented. The figures are tracings of the machine plots. The numbers on the curves show the chronological order of the runs from high to low airplane Mach numbers.

The pressure curves, of course, are the backbone of the analysis, for these data, along with the temperature inputs, form the basis of the other profiles. Note that the edges of the jet show how the area of the exhaust in the measurement

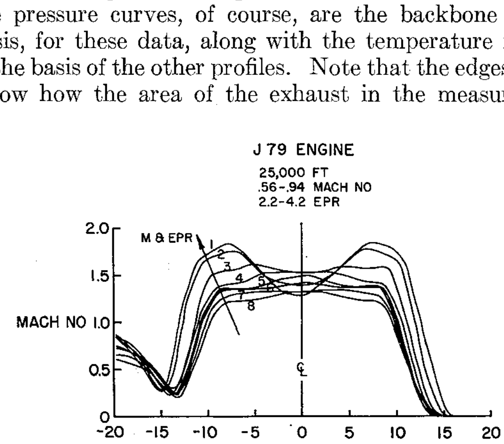

Fig. 12 Mach number profiles across the jet for eight airplane Mach numbers.

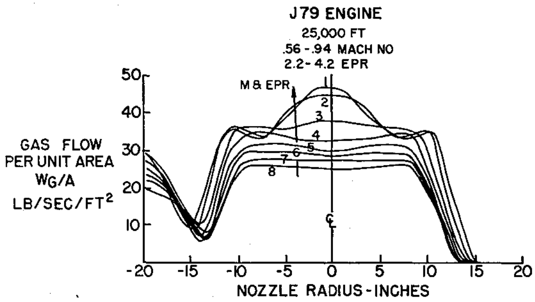

Fig. 13 Gas-flow profiles across the jet for eight airplane Mach numbers.

plan changes with respect to flight Mach number and EPR. To explain the area changes of the pressure profiles, the distance between the nozzle and the rake must be considered.

The measurement plane is about $10\frac{1}{2}$ in. aft of the secondary nozzle flaps in nonafterburning flight and about $2\frac{1}{2}$ in. in afterburner. In either case, the measurement plane is in the divergent portion of the convergent-divergent aerodynamic nozzle. Therefore, the area in the measurement plane increases with flight Mach number, while the actual engine nozzle decreases in size. This continues until maximum thrust without afterburner is reached. When afterburner is selected, the nozzle extends toward the full open position shown in Fig. 5. The maximum extension is about 8 in.

The Mach number profiles of Fig. 12 display interesting patterns of supersonic flow in the jet. For the higher flight speeds, the Mach number in the center of the jet is considerably lower than in the area a few inches inside the edge. The corresponding increase in static pressure, as previoulsy explained, shows that the air is more dense near the center. Even though the Mach number is lower in the center, the increased density more than compensates for the lower gas velocity, with the result that there is a substantial rise in total gas flow (mass flow) in the center of the jet.

Net Thrust from Gross Thrust and Airflow

Figures 13 and 14 show the total gas flow and gross thrust per unit area as a family of curves; the marked similarity between the two families is obvious. Each of these profiles is integrated within the limits of the area in the measurement plane. The result is gross-thrust and exit airflow for each engine for any given flight run. From the airflow, the ram drag of the airplane for the appropriate flight speed is computed and inflight net thrust is defined.

Airplane Performance

Gross thrust

The gross-thrust data, as determined for each engine by integration of the gross thrust per unit area profiles, are presented in terms of the airplane performance parameter F_G/δ_{t_2} in Fig. 15. F_G is the gross thrust, and δ_{t_2} is the ratio of total pressure at the compressor inlet to standard sea-level static pressure. F_G/δ_{t_2} for both the GE gas-generator and traversing-rake methods is plotted vs Mach number in Fig. 15 to show the exceptional agreement in terms of standard performance parameters. (This is before the GE data were corrected to the rake-measured base-area pressures.)

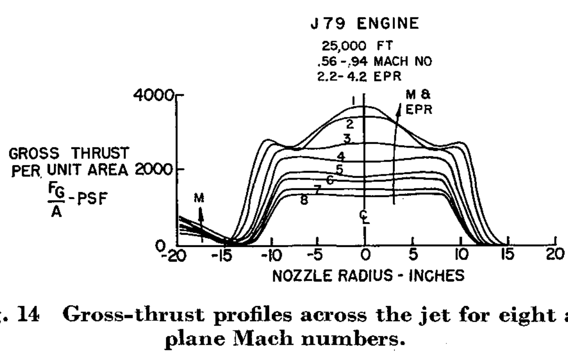

Fig. 14 Gross-thrust profiles across the jet for eight airplane Mach numbers.

Figure 16 shows the agreement of gross thrust for each engine after the GE data were corrected to measured base-area pressures. The majority of the points are on the line of perfect agreement. Thus, knowing the laboratory accuracy of the traversing-rake system, it becomes immediately apparent that the gross-thrust determination of the GE gas-generator method has been checked in flight and found near perfect.

It should be remembered that the data presented are for two widely different methods. The GE data were calculated from measured parameters from the compressor through to the turbine and were based on assumptions and calibrations from the turbine to the nozzle. On the other hand, the rake actually sampled the jet exhaust several inches downstream of the engine nozzle. The approach, concepts, and measurement planes were in no way similar, and yet the end results in terms of gross thrust were, for all practical purposes, identical.

Airflow

The validity of inflight net thrust is proportional to the preciseness of the airflow measurement. Obtaining an accurate indication of airflow has been a problem for years. The traversing rake, with its precise area, pressure, and temperature measurements, can now define the exit mass flow with acceptable accuracy.

The first calculations showed that the GE method was giving airflows that were 3–13% less than the traversing rake. When the GE airflow was corrected to the rake measured base

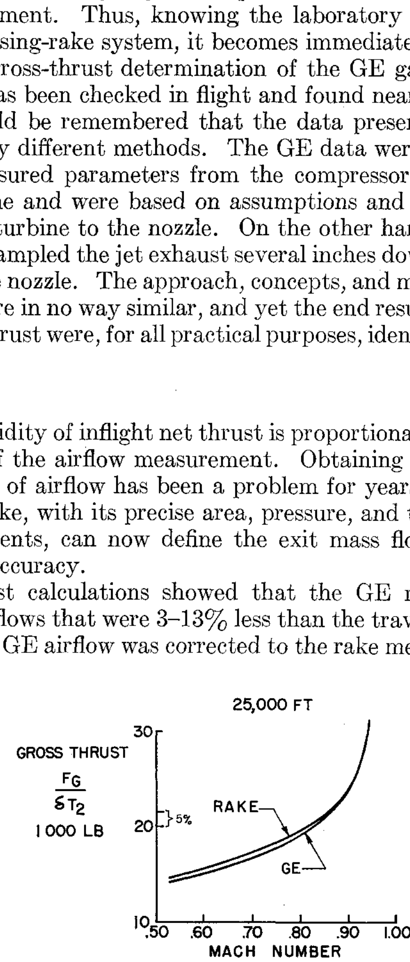

Fig. 15 Airplane gross-thrust parameters for both the traversing rake and the GE methods.

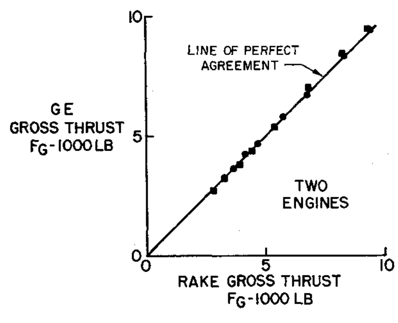

Fig. 16 Comparison of GE and rake gross thrust after GE data are corrected to a measured base-area pressure.

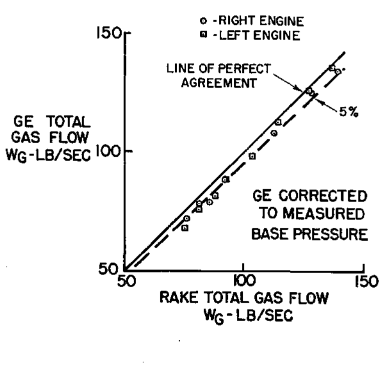

Fig. 17 Comparison of GE and rake gas flow after GE data are corrected to a measured base-area pressure.

pressure, much better agreement was obtained. Figure 17 shows the data from the GE method to be about 5% lower than the rake method after base-pressure corrections.

Bleed and leakage airflow

The fuel flow is, of course, additional mass flow, injected into the system after the intake of air is measured. It is assumed in the GE method that the leakage airflow is equal to the fuel flow that is added to the system. This assumption is fairly valid and has little effect on the over-all result. Both the fuel flow or leakage airflow are in the order of $\frac{1}{2}$ to $1\frac{1}{2}$% of the total gas flow. Bleed airflow, that is, the airflow taken rom the engine system to do other work, is estimated by the airframe contractor to be in the order of $\frac{1}{2}$% of total airflow. With the traversing-rake refinements, it has been assumed that the leakage air plus bleed air for the test vehicle was the same as the fuel flow. Extra measurements of any bleed airflow or leakage and pressures in the base area will permit an even more precise determination of inflight net thrust.

Net thrust

Figure 18 compares the GE internal method with the rake method in terms of the net thrust parameter, F_N/δ_{t_2}. Figure 19 shows that the net thrust of the GE method, consistent with the airflow, is approximately 5% higher than the rake-measured net thrust. Good agreement is seen even though some refinements have not yet been incorporated. Although precise net-thrust values are urgently needed to assist in the design of new airplanes, the values as presented are of sufficient accuracy to establish drag increments for the performance evaluations of airplanes with many different loadings.

Summary

The traversing-rake concept of measuring net thrust in flight has been evaluated for feasibility and accuracy, utilizing a North American Vigilante airplane in subsonic flight. The system provided exceptional accuracy of thrust measurement for the test engines. J79-GE-8 engines, which have convergent-divergent aerodynamic nozzles with large secondary airflows, were used. The system can aid greatly in the establishment of a firm basis for the verification of other concepts, such as ground calibrations and internal methods.

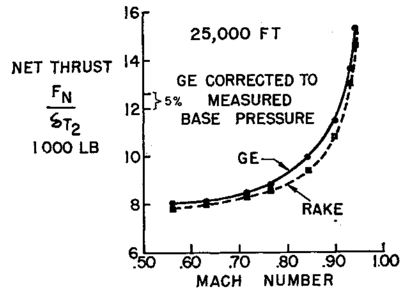

Fig. 18 Airplane net-thrust parameters for both traversing rake and GE methods.

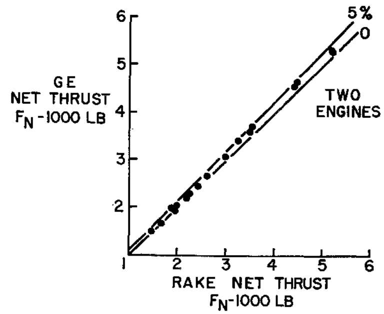

Fig. 19 Comparison of GE and rake net thrust after GE data are corrected to a measured base - area pressure.

It has potential for noteworthy developmental and research applications that need not resort to lengthy engine test cell calibrations. Its main drawback is the stringent requirements for exacting and time-consuming data-reduction procedures. Studies are under way to automate completely the data acquisition and reduction procedures. Supersonic flight data are being analyzed, and the outlook is promising.

References

[1] Davidson, T. W., "Development of a satisfactory method for measuring in-flight thrust of turbojet aircraft-gas generator method," Flight Test T. M. 1-61, Naval Air Test Center (March 8, 1961).

[2] Haines, D. W. and Monsko, R. P., "Development of a traversing rake system for measuring in-flight thrust of a turbojet powered aircraft," Phase II, Rept. FA-B7-111-1-007, Grumman Aircraft Engineering Corp. (October 1961).

[3] Brovetto, R. L. and Haines, D. W., "Development of a traversing rake system for measuring in-flight thrust of a turbojet powered aircraft," Phase III, Rept. FA-B7-111-1-008, Grumman Aircraft Engineering Corp. (March 1962).