Development of a Freejet Capability for Evaluating Inlet-Engine Compatibility*

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ABSTRACT

The Arnold Engineering Development Center (AEDC) is installing a freejet test capability into the Aero- propulsion Systems Test Facility (ASTF). The freejet will provide the capability for ground determination of turbine engine and aircraft inlet compatibility by utilizing full-scale inlets and engines as test articles in a simulated flight environment. The details of the design, installation, and projected testing capability are described for a 57 ft supersonic nozzle and a 77 ft² subsonic nozzle. Support systems for mechanically pitching and yawing the freejet nozzles are also reported as well as the test cell hardware for capturing the freejet nozzle flow. The plans for demonstrating the freejet capability prior to its initial operational date are explained. The technology development efforts to validate and utilize the freejet test capabilities are also described.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>ALPFJ</td>
<td>Freejet angle of attack, deg</td>
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<tr>
<td>ALPL</td>
<td>Local angle of attack at inlet reference plane, deg</td>
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<tr>
<td>ALPHA</td>
<td>Free-stream angle of attack, deg</td>
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<td>BETA</td>
<td>Free-stream angle of sideslip, deg</td>
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<tr>
<td>BETFJ</td>
<td>Freejet angle of sideslip, deg</td>
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<tr>
<td>BETL</td>
<td>Local angle of sideslip at inlet reference plane, deg</td>
</tr>
<tr>
<td>D2</td>
<td>Difference between maximum and minimum engine face total pressure normalized by the average engine face total pressure</td>
</tr>
<tr>
<td>DX1</td>
<td>Fan limiting distortion ratio, KA2/KAZL</td>
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<tr>
<td>KA2</td>
<td>Pratt and Whitney engine face distortion index</td>
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<tr>
<td>MACH</td>
<td>Free-stream Mach number</td>
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<td>MFJ</td>
<td>Freejet nozzle exit Mach number</td>
</tr>
<tr>
<td>ML</td>
<td>Local Mach number at the inlet reference plane</td>
</tr>
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<td>PT</td>
<td>Free-stream total pressure, psia</td>
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<td>PTFJ</td>
<td>Freejet total pressure, psia</td>
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<tr>
<td>PT2</td>
<td>Average total pressure at the aerodynamic interface plane, psia</td>
</tr>
<tr>
<td>RAKE</td>
<td>Reference plane rake position on reference plane, in.</td>
</tr>
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<td>RE</td>
<td>Wind tunnel free-stream unit Reynolds number, 1/ft</td>
</tr>
<tr>
<td>REFJ</td>
<td>Freejet free-stream unit Reynolds number at nozzle exit, 1/ft</td>
</tr>
<tr>
<td>RSME</td>
<td>Distortion map comparison parameter, root-mean-square error between wind tunnel and freejet results</td>
</tr>
<tr>
<td>R2</td>
<td>Inlet average total pressure recovery, PT2/PT or PT2/PTFJ</td>
</tr>
<tr>
<td>T12</td>
<td>Turbulence index, aerodynamic interface plane average root-mean-square total pressure fluctuation normalized by PT2</td>
</tr>
<tr>
<td>WC2</td>
<td>Full-scale inlet airflow corrected to standard-day sea-level conditions, lbm/sec</td>
</tr>
<tr>
<td>ΔD2</td>
<td>D2 (freejet) - D2 (wind tunnel)</td>
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<tr>
<td>ΔKA2</td>
<td>KA2 (freejet) - KA2 (wind tunnel)</td>
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<td>ΔR2</td>
<td>R2 (freejet) - R2 (wind tunnel)</td>
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<tr>
<td>ΔT12</td>
<td>T12 (freejet) - T12 (wind tunnel)</td>
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BACKGROUND

Inlet-engine compatibility has been a primary factor in the design and performance of jet aircraft since their invention. Ideally, the inlet should provide

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the turbine engine with the required amount of airflow having a uniform direction, pressure, and temperature while the engine should operate with far less than a uniform airflow. However, the initial turbine engine challenge was to operate under ideal conditions. The first turbine engine operations were in open-air test stands which provided undisturbed airflow but only at sea-level-static conditions. Since jet engines were required to operate at flight speeds and altitudes, a ground simulation of the flight conditions was required. Direct-connect engine testing was the initial ground simulation method of flight conditions and is still the most widely used. In direct-connect testing, the required air supply is conditioned to the flight pressures and temperatures and piped directly to the engine face while the engine is mounted in an enclosed test cell maintained at the proper static pressure for the simulated altitude. This simulation provides the capability to assure engine operation and performance on the ground and the expectation that performance will exist in flight as long as the inlet airflow is uniform.

The initial method for simulating inlet distortion was to artificially distort the flow approaching the engine in a direct-connect duct. Distortion screens were used to approximate total pressure patterns which would be produced by the inlet. The first step in distortion screen development is to determine the flow distortion pattern at the engine face. This is accomplished by testing a model of the aircraft with a flow-through inlet in a wind tunnel. Airflow through the model is controlled by a calibrated flow plug, and an array of pressure probes is located in the model at the engine face station. Laminates of various size wire screens are laid in patterns to reproduce the engine face distortion pattern. The screen is then inserted into the direct-connect engine duct to determine the effects of the distorted flow on the engine operation. Each screen represents the distortion pattern of one aircraft flight condition, altitude, airspeed, attitude, and engine mass flow. An aircraft development program’s budget and schedule can only accommodate a finite number of screens, so the most appropriate flight conditions must be selected. As the speed and attitude range of aircraft increased, the selection of appropriate distortion screens became more difficult, and other methods of inlet-engine integration testing were sought.

Airjet distortion generators which inject high-pressure air into the direct-connect stream to create the desired pressure patterns were developed to supplement distortion screens. They permit selection of distortion patterns without the necessity of fabricating and changing distortion screens, thereby increasing the number of distortion patterns available. However, neither screens nor airjets can simulate changing flight conditions and, as the actual inlet is not present, they do not simulate the effects of inlet variable geometry operations.

As aircraft speed and maneuverability increased, the requirement for full-scale inlet-engine system compatibility testing became more acute. Propulsion wind tunnels were built to satisfy this requirement. Since propulsion wind tunnels cannot accommodate a full-scale aircraft, the full-scale inlet, engine, and a forebody simulator which generates the flow field at the inlet representative of the entire aircraft are used. Wind tunnels provide ground simulation of both flight flow conditions and patterns for full-scale inlet-engine compatibility testing within the tunnel operating envelope. Current propulsion wind tunnels cover a very wide range of Mach numbers, but only a limited region where the true temperature for the Mach number and altitude can be achieved. True temperature is especially important to ground simulation of the in-flight engine operation. Additionally, current wind tunnels can only simulate small altitude angles because of test section blockage restrictions. For fighter aircraft, simulation of maneuvers requires rapid changes in both flow conditions and flow patterns.

The freejet test concept provides ground simulation of both flight flow conditions and patterns over a wide range of the aircraft operating envelope and can change those conditions at rates which are representative of aircraft maneuvers. The freejet facility accomplishes the flow condition simulation using an air supply plant to condition the intake air to the pressure and temperature representative of the flight airspeed and altitude, an exhaust plant to maintain the test cell at the proper altitude static pressure, and a nozzle to guide the flow to the desired flight airspeed and aircraft attitude. Figure 1 depicts the freejet test facility concept. The propulsion system is mounted downstream of a variable-attitude, variable Mach number freejet nozzle. The nozzle provides conditioned air at a temperature, pressure, flow angle, and Mach number corresponding to a given flight condition. The freejet nozzle directs the air at the test article which, in comparison to the wind tunnel, is large relative to the size of the jet.

Fig 1. Subsonic freejet installation.

Freejet is a proven technique for ground simulation of the flight environment which has been widely used in the past for small missile-size test articles but which has seen only limited use for large, aircraft-size test articles (Ashwood and Philpott, 1980). For aircraft-size test articles, the freejet requires the use of a forebody simulator just as the propulsion wind tunnel does. The fidelity of the ground simulation to the flight conditions decreases as the size of the airstream relative to the test article decreases. So, relative to the propulsion wind tunnels, the freejet achieves its simulation advantages with some degradation in flow pattern fidelity. To achieve its potential for inlet-engine integration testing for fighter aircraft, a large-scale freejet facility, associated facility freejet technology, and the required distortion fidelity had to be developed.
FREEJET SIMULATION METHOD

The freejet simulation for fighter aircraft inlet-engine integration testing requires a suitable nozzle, an appropriate forebody simulator, and a method of establishing conditions simulating flight. A schematic of the basic features of the freejet simulation is presented in Fig. 2. The freejet technique uses conditions at a reference plane in front of the inlet to characterize the flow approaching the inlet. The simulation of flight conditions in the freejet test is based on establishing the flight reference plane flow field in the freejet test facility. With an adequate simulation of the flight reference plane flow field, the inlet and engine behave as in flight. A reference plane rake provides the flow-field measurements, local Mach number, and local flow angle during the test. Freejet test parameters such as nozzle Mach number, nozzle pitch angle, and nozzle yaw angle are adjusted until the required reference plane conditions are achieved.

Fig 2. Freejet test concept.

The design of the forebody simulator and the selection of freejet test parameters require a knowledge of the flight reference plane flow field. Wind tunnel reference plane surveys, computational fluid dynamics (CFD), or a combination of the two are required to quantify the reference plane parameters. A CFD capability development which will decrease reliance on wind tunnel testing, thereby reducing overall test costs is underway and will be detailed later in this discussion.

A validation of the freejet method has been undertaken to define the range of applicability both in terms of test article configuration and flight conditions. The validation is based on comparisons between wind tunnel test results and freejet test results using common subscale test articles. The test articles are flow-through inlet model with complete forebodies in the wind tunnel tests and forebody simulator in the freejet tests. Steady-state and dynamic total pressure distortion parameters defined at the aerodynamic interface plane (AIP) near the engine face station are used as measures of merit for the validation. Validation criteria are established for the measures of merit to determine the useful freejet simulation range.

Initial validation efforts were directed toward fixed-geometry inlets at subsonic high angle-of-attack conditions (Beale, 1986). A 15-percent-scale model of the F-16 inlet served as the test article (Fig. 3). It included the inlet cowl, fuselage boundary-layer flow diverter, inlet duct, and an airflow metering system. The aircraft fuselage from the nose to a station aft of the inlet was included during the wind tunnel tests. For the freejet tests, the fuselage was replaced with a forebody simulator. The model was instrumented with a cone probe rake for measuring inlet reference plane conditions, local flow angle, and Mach number during the freejet tests. An array of 40 total pressure probes located at the aerodynamic interface plane provided steady-state and dynamic distortion measurements. The validation was based on comparisons of inlet distortion between the freejet experiments and an existing wind tunnel database. Reference plane measurements, unique to the freejet test concept, were not part of the existing wind tunnel data set. As a result, CFD was used to estimate reference plane conditions for comparison with limited reference plane measurements obtained in the freejet tests. While the reference plane results were correlated with the aerodynamic interface plane results, the reference plane was not directly used to set the test conditions.

Fig 3. F-16 inlet model installation.
The experiments were conducted at simulated angles of attack of 1 deg and 30 deg. Sideslip angles of 0 and 5 deg were simulated at the high angle-of-attack condition. Mach numbers of 0.3, 0.6, and 0.9 were tested, and inlet flow rate was varied to simulate a range of full-scale corrected engine flows.

Validation results obtained at high angle of attack with sideslip are shown in Fig. 4. The results correspond to the highest of angle of attack, angle of sideslip, and Mach number tested during the experiments: 30 deg, 5 deg, and 0.9, respectively. Freejet measurements of R2, D2, KA2, and DX1 are shown in comparison to wind tunnel results for various inlet flow rates. The results show excellent agreement, even at the extreme flight condition. The comparison of steady-state distortion patterns for maximum flow rate are shown in Fig. 5. The contours represent lines of constant percent deviation from engine face average total pressure. The excellent agreement indicated in the distortion parameters is reflected in the distortion patterns.

A limited number of validation results were analyzed to determine the peak instantaneous distortion. A sample freejet-wind tunnel comparison is shown in Fig. 6 for an angle of attack of 30 deg, an angle of sideslip of 0 deg, and a Mach number of 0.6 with the maximum inlet flow rate. The results correspond to the highest of angle of attack, angle of sideslip, and Mach number tested during the experiments: 30 deg, 0 deg, and 0.9, respectively. Freejet measurements of R2, D2, KA2, and DX1 are shown in comparison to wind tunnel results for various inlet flow rates. The results show excellent agreement, even at the extreme flight condition. The comparison of steady-state distortion patterns for maximum flow rate are shown in Fig. 5. The contours represent lines of constant percent deviation from engine face average total pressure. The excellent agreement indicated in the distortion parameters is reflected in the distortion patterns.

Fig 4. Inlet performance comparisons at ALPHA = 30 deg, BETA = 0 deg.

Fig 5. Inlet steady-state distortion comparisons at MACH = 0.9, ALPHA = 30 deg, BETA = 5 deg, and WC2 = 253.6 lbm/sec.

Fig 6. Peak instantaneous distortion comparisons at MACH = 0.6, ALPHA = 30 deg, BETA = 0 deg, and WC2 = 256 lbm/sec.
flow rate. The results show very good agreement, both in terms of the turbulence index, $T_2$, and the peak instantaneous distortion pattern shapes.

The F-16 results provided the impetus to proceed with the next step of the validation program, a complex side-mounted inlet. The approach was to compare wind tunnel and freejet experimental results using a model of the McDonnell Douglas F-15 inlet (Beale and Collier, 1989). However, unlike the F-16 program, the F-15 validation program included a wind tunnel test dedicated to freejet. As a result, both the instrumentation and the test matrices were tailored to meet the validation needs. Instrumentation for measuring the inlet reference plane flow field was utilized in both the wind tunnel and freejet experiments. The test matrix included a wide range of Mach numbers, angles of attack, angles of sideslip, and inlet flow rates of interest to the validation program. Mach numbers included both the subsonic and supersonic regimes, and sideslip included conditions where the forebody shielded the inlet.

The F-15 inlet model, shown in Fig. 7 included the left inlet, a flow diverter, and a flow metering system. The variable geometry features of the full-scale system were included in the model. The cowl angle, ramp angles, and throat slot bleed rate were remotely variable to permit duplication of the airplane inlet schedules. The model was instrumented with an array of 40 probes at the aerodynamic interface plane for measuring steady-state and dynamic distortion. It was also equipped with an inlet reference plane rake for measuring local flow angle and Mach number. The rake position was remotely variable using a rake traversing mechanism.

One of the objectives of the F-15 validation program was to develop forebody simulator technology. Four forebody simulators, shown in Fig. 8, were tested in the freejet facility. Forebody simulators 1 and 2 were existing experimental designs originally used in a wind tunnel test program. Forebody simulators 3 and 4 were designed using CFD methods under development for freejet applications.

During the validation experiments, the inlet reference plane was used as the control point for the simulation. Freejet test conditions were adjusted until reference plane measurements obtained in the freejet agreed to reference plane measurements obtained in the wind tunnel. The inlet reference plane instrumentation used is shown in Fig. 9. A sample of the results is shown in Fig. 10. The figure includes plots of local angle of attack, local angle of sideslip, and local Mach number for two of the three probes. Probe 3 was inoperative during these tests. On each plot, the vertical axis represents rake position, and the horizontal axis represents one of the flow parameters. The comparison of freejet and wind tunnel inlet reference plane measurements shows very good agreement.
Note that to simulate the wind tunnel reference plane conditions, the freejet parameters were set considerably different from free stream. This is a result of the close proximity of the nozzle exit and reference plane location, as well as the use of the short forebody simulator.

Fig 9. Inlet reference plane instrumentation.

Fig 10. IRP flow-field comparisons at Mach = 0.9, ALPHA = 30 deg, BETA = 5 deg, and WC2 = 197 lbm/sec.
Following the determination of freejet settings using the inlet reference plane measurements, the rake was retracted and the inlet distortion measurements obtained. A sample of the steady-state distortion patterns is presented in Fig. 11. The results simulated the maximum subsonic Mach number of 0.9, the maximum angle of attack of 30 deg, and the maximum sideslip angle of 10 deg, with the forebody shielding the inlet. Despite the extreme conditions, the freejet distortion patterns agreed with the wind tunnel. The comparison of peak instantaneous distortion patterns is underway and will be reported later.

**CFD DEVELOPMENT PROGRAM**

A key element of the freejet test method implementation is the design of forebody simulators. In addition to the requirement for an accurate reproduction of the forebody influence, there is a requirement to cover the flight envelope with the minimal number of forebody simulators. The efficiency of the freejet test program is inversely proportional to the number of configurations which must be tested. Therefore, forebody simulators which are useful over a wide range of conditions are needed. Design methods must be developed which can address the forebody simulator objectives efficiently.

The freejet development program includes a development of forebody simulator technology, particularly in the area of design methodology. The approach is to compress the design cycle through the application of CFD. CFD will be used to advance from previously used experimental design techniques and their associated costs. The forebody simulator design technology development is proceeding in accordance with a 7-generation plan development plan shown in Fig. 12. Each generation builds on the previous generation by including more of the physics in the CFD tools and reducing reliance on design experiments. Generation 1 was the experimental design method used to design forebody simulators for wind tunnel test applications in the early 1970s. Generation 2 uses vortex lattice computations to predict forebody simulator flow fields in the free stream. The method was used to design the F-16 forebody simulator used in the freejet validation. Generation 3 improves the computational accuracy by introducing Euler CFD computations. However, the forebody simulators are computed for the free stream with freejet-confined flow effects ignored. F-15 forebody simulators 3 and 4, shown in Fig. 8, were designed using the generation 3 method. Generation 4 includes confined flow effects by incorporating the nozzle and the freejet boundary in the forebody simulator modelling. However, with the exception of the freejet shear layer, the flow is treated as inviscid. Viscous effects are introduced on the solid boundaries in generation 5. The inverse problem solver is introduced in generation 6. Generation 6 improves the design procedure by optimizing the process of determining a shape which provides a desired flow field. Full 3-D Navier-Stokes computations for the external and internal flow fields are introduced in generation 7. The advancement to each generation includes both the calibration of the required CFD tools and the validation of the total design procedure. The effort is currently at generation 4, with generation 5 under development.

**ASTF PLANT CAPABILITY**

Until now, the United States has not had a freejet facility large enough for fighter aircraft inlet-engine
compatibility testing, but such a facility is nearing completion at the Arnold Engineering Development Center (AEDC). The Aeropropulsion Systems Test Facility (ASTF) is being modified to provide the freejet test capability. The facility capabilities have been presented in several preceding publications. The need for increased propulsion testing capability was first presented by Mitchell (1972) and more accurately defined by Edwards and Bates (1977). The facility was designed to accommodate both direct-connect and freejet testing. Construction was initiated in 1977 and completed in 1985. The direct-connect checkout operations were initially demonstrated with a production engine in 1986, and testing has continued since. The freejet test capability was deferred in the original design process to allow for additional test technique development studies which are specific to the ASTF. The results of these studies, presented by Beale (1986) and Beale and Collier (1989), have been incorporated in the freejet system currently being developed.

The freejet test capability is currently being implemented in the ASTF Propulsion Test Cell C-2 under a joint program between AEDC and Wright-Patterson AFB Aeronautical Systems Division. Design and fabrication of the subsonic freejet hardware, nozzle, nozzle positioning mechanisms, hydraulic systems, and control systems are complete, and the hardware is currently being installed. Information about those systems was reported during their design phase by Duesterhaus and Maywald (1989). The hardware which is unique to supersonic freejet operations has been designed and is awaiting a funding decision prior to fabrication and installation. This paper will describe freejet simulation potential of the existing ASTF facility, report on the status of the freejet support systems, and detail the plans to demonstrate the freejet operations after completing installations.

The basic test capabilities of an inlet-engine test facility are best described by the amount of air that can be delivered through a test cell at particular pressure and temperature conditions. Edwards and Bates (1977) reported those freejet pressure and temperature conditions for preliminary estimates of ASTF equipment performance and designs of freejet nozzles. The ASTF air plant compressors can compress more than 1,500 lb/sec of atmospheric air up to 40 psia. The air supply is heated or cooled for a temperature range of -100°F to 650°F. The low pressures associated with simulated altitudes in the test cell are maintained by an array of twelve large exhaust compressors which pump the freejet air supply and the engine combustion products up to the atmospheric pressure. When the flight altitude and airspeed conditions result in total pressure lower than atmospheric pressure, air can be drawn from the atmosphere by the exhaust compressors for a maximum airflow of 2,200 lb/sec. These capabilities result in altitude versus Mach number envelopes for a 77 ft² subsonic and a 57 ft² supersonic nozzle in Figs. 13 and 14, respectively, where the freejet can simulate the altitudes, attitudes, and airspeeds typical of fighter aircraft. The supersonic freejet test capability assumes the use of a diffuser to augment the pumping performance of the basic exhaust facilities of ASTF.

**ASTF FREEJET SYSTEMS**

**Attitude Positioning Mechanism**

The C-2 freejet system with the subsonic nozzle installed is shown in Fig. 15. The plenum and test cell are 30 ft and 28 ft in diameter, respectively. The centerline of the test cell is located 2.5 ft above the centerline of the plenum to accommodate freejet nozzle positioning at high attitudes. The freejet bulkhead separates the plenum and the test cell and supports the attitude positioning mechanism. The freejet bulkhead, the plenum, the air supply ducting, the attitude positioning mechanism, and the freejet nozzles are constructed from, or clad with, stainless steel to prevent airflow contamination.

![Fig 13. ASTF C-2 freejet capability 77-sq-ft subsonic nozzle, standard day.](image)

![Fig 14. ASTF C-2 freejet capability 57-sq-ft variable Mach nozzle, standard day.](image)

![Fig 15. Subsonic freejet installation.](image)
Subsonic Freejet Nozzle

The subsonic nozzle design provides high-quality flow uniformity over the required nozzle exit area and avoids the plenum walls as it gimbals to the pitch and yaw limits. The nozzle is depicted in Fig. 17. As designed, the subsonic nozzle has an exit area of 77 ft², an aspect ratio of 0.72, and a contraction ratio (exit area divided by entrance area) of 2.05 to 1. The upper corners of the nozzles are scarfed at 45-deg angles to provide clearance from the plenum walls. The attitude positioning mechanism pitches the nozzle exit 45 deg up, 10 deg down and yaws the nozzle exit 10 deg to either side. This attitude range provides aerodynamic flow angles of attack and sideslip to the test article as shown in Fig. 18.

Fig. 17. Subsonic freejet nozzle.

Fig. 18. Subsonic freejet nozzle aerodynamic angle envelope.

Extensive water tunnel and subscale experiments were performed to assure good nozzle flow quality because of the unusual hardware geometry. A ramp was installed on the bottom leading edge of the nozzle to prevent the...
formation of vortices at high nozzle pitch angles. As the nozzle inclines to high angles, the ramp is tilted up so that the flow entering the nozzle is more gradually turned. A subscale nozzle of this type was used for freejet simulations reported by Beale (1986) and Beale and Collier (1989).

As the freejet flow approaches sonic conditions, local shock waves will be produced because of the shape of the forebody simulator. These shock waves will cause serious simulation problems when they reflect off the nozzle side walls and freejet boundary. The potential for shock reflections back to the engine inlet make testing in the transonic region somewhat questionable. Therefore, the freejet simulation at subsonic speeds above Mach 0.9 is considered marginal. The exact location of this region of degraded freejet simulation is dependent on the test article geometry and size. Beale (1986) and Beale and Collier (1989) have shown excellent simulation fidelity for F-15 and F-16 models up to Mach 0.9.

The subsonic nozzle was designed by AEDC, delivered to AEDC in December 1990, and is to be installed in 1991.

**Supersonic Freejet Nozzle**

The concept of the supersonic freejet nozzle is depicted in Fig. 19. The nozzle concept has flexible side walls which allow the Mach number to be varied up to 3.0 and down to subsonic conditions. Each side wall is actuated in only two lateral positions. This concept is called a semi-flex wall nozzle as opposed to a fully variable wall nozzle, which requires an array of wall positioning jacks.

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**Fig 19. Supersonic freejet nozzle.**
The nozzle contours vary from subsonic to Mach 3.0 by utilizing a solid block throat for the 6-ft region from the entrance to the throat and a flex plate from the throat to the exit. The throat block is rotated by a hydraulic jack which sets the basic position of the flex plate. The flex plate contour is then refined by trimming jacks. The nozzle performance was analyzed by a method of characteristics solution with a boundary-layer correction described by Varner (1986). The calculated nozzle wall contours are shown in Fig. 20 for several test Mach numbers. The predicted flow quality or Mach number deviation over the usable nozzle flow area is shown in Fig. 21 over the Mach number operating range. A subsonic operating region was also included to provide for engine starting and stabilization at subsonic conditions prior to supersonic transition.

The simulated supersonic flight conditions exist in a test rhombus extending upstream and downstream from the nozzle exit bounded by the Mach waves for the particular simulated Mach number. A test rhombus for a typical test article is shown in Fig. 22. As the Mach number decreases, the size of the supersonic rhombus decreases. Therefore, just as there is an upper limit for subsonic operation, there also exists a low supersonic operating limit where the flight simulation fidelity is compromised.

The nozzle is sized to be less than 25 ft long to fit within current facility hatch limits with an exit area of 57 ft². The nozzle exit area has a width-to-height aspect ratio of 0.78, and the nozzle will weigh approximately 80 tons. The nozzle contours can be adjusted to produce a 0.05 Mach number change in 1 sec. The aero-dynamic and mechanical concept studies were completed in 1988. Final design was completed in 1990. A fabrication funding decision is planned for August 1991. The fabrication of the supersonic nozzle will require 2 years with a projected total cost of $6.0 million. The nozzle installation and supersonic demonstration would then be planned for late 1993 and early 1994.
Hydraulic System

The hydraulic system provides the power for the attitude positioning mechanism to position the freejet nozzles throughout the pitch and yaw ranges. Figure 23 depicts the system. Two 85-gpm hydraulic pumps powered by 175-hp electrical motors charge a bank of 36 accumulators, each with a 15-gal capacity. The system is pressure compensated at 2,950 psig and utilizes metered fluid flow through the hydraulic cylinders to assist in cylinder temperature conditioning. The hydraulic fluid is maintained between 40°F and 200°F by heating or cooling.

For the subsonic nozzle, the hydraulic system is estimated to provide an angular velocity of 20 deg per sec at acceleration/deceleration rates of 50 deg per sec. The accumulators have the capacity to provide maximum velocity motion for 45 deg of pitch and 30 deg of yaw change simultaneously. After a maximum discharge movement, the pumps will recharge the accumulators within 5 min. This provides the capability to simulate rapid in-flight attitude changes to determine their effect on the propulsion system.

All the hydraulic system components have been purchased, and installation of all components exterior to the cell was completed in 1989 and 1990. The piping within the cell to the attitude positioning mechanism and the cylinders is being installed in 1991.

For the supersonic nozzle, the hydraulic system will be common with the subsonic system with the exception of the pitch and yaw cylinders and the servovalves. The hydraulic system is planned to power supersonic nozzle attitude changes up to 1 deg per sec and permit attainment of that velocity within 1 sec. Analysis has been performed to ascertain that the hydraulic system is capable of this performance. The design of the hydraulic cylinders and the servovalves was performed in conjunction with the supersonic nozzle design. The cylinders will be fabricated for installation when the supersonic nozzle is installed. Throughout the life of the system, these subsonic and supersonic components will be interchanged as required.

Supersonic Diffuser

A supersonic diffuser is used to collect the high-velocity freejet nozzle flow and convert the kinetic energy to increased static pressure, thus reducing the exhaust compressor pumping requirements. The need for a diffuser in the freejet test installation is shown in Fig. 14. The diffuser also optimizes the size of the test rhombus by maintaining the test cell pressure at the nozzle discharge pressure.

The freejet supersonic diffuser design problem is unique because of the aerodynamic range for diffuser operation and the diffuser blockage attributable to the test article. An extensive subscale experimental research effort was devoted to the supersonic diffuser design for the ASTF supersonic freejet installation. A variable geometry diffuser could be built to accommodate a range of test article sizes, but would be costly and require further development studies. The ASTF freejet diffuser design process is simplified, however, since the large capacity of the ASTF exhaust plant allows the diffuser to be relatively inefficient. The maximum diffuser rise ratio (the diffuser exit static pressure divided by the nozzle exit static pressure) required for the design range and the extended operation ranges of Fig. 14 is 2.2.

A simple cylindrical diffuser will provide the required exhaust assistance for the ASTF exhaust plant for an F-15 size test article. The resulting cylindrical diffuser would be 12.2 ft in diameter to provide the required diffuser rise ratio. As the test article size and configuration changes, the diffuser size may change. Since a fixed-geometry diffuser is a relatively low-cost item, the current approach is to build the diffuser when specific test articles are defined. For any proposed test program, the performance with existing diffusers and the test article would be estimated for the test conditions and a new diffuser would be built if required. This analysis procedure is based on a viscous three-dimensional calculation design process validated by an experimental freejet diffuser study. Validation results, depicted in Fig. 24, show that for...
future test articles the diffuser performance can be adequately estimated.

The inlet reference plane control system surveys the flow field in front of the inlet at a control plane and compares it to the flow field required to simulate a particular flight condition. The required flow field could have been determined by either subscale inlet testing as done for past programs and/or by computational techniques. The inlet reference plane control system then requests an attitude change from the nozzle control system or a plant condition change from the automatic test control system. The nozzle and automatic test control systems have feedback loops to compare the requested settings to the obtained settings and correct as necessary. The automatic test control system is in place and operating for direct-connect turbine engine testing. The algorithms to accommodate the subsonic freejet modifications were accomplished in 1988. In 1989 the algorithms were coded and tested on an ASTF simulation prior to installation in 1990. The supersonic algorithms were developed in 1990 and will be implemented as required for the supersonic demonstration.

All subsonic components of the NACS are being installed in 1991 and will be fully operational for the subsonic demonstration scheduled to start in September 1991. The components for the supersonic system are similar, but the peculiarities of the supersonic nozzle installation, such as the larger hydraulic cylinders and the new hydraulic servovalves, will require software changes. These will be completed after the supersonic nozzle and hydraulic designs are completed.

FREEJET DEMONSTRATION

During 1991, ASTF Test Cell C-2 is committed for the freejet system installation and demonstration.
January through August is required for systems installation. A subsonic airflow demonstration will begin in September 1991. The demonstration configuration has all freejet systems installed, but does not include a test article. The configuration is shown in Fig. 26. The demonstration will be conducted in four phases: the nozzle attitude envelope verification, the nozzle attitude sweep rate determination, the nozzle exit flow field evaluation, and the inlet reference plane control demonstration. Flight conditions throughout the freejet subsonic regime will be utilized as shown in Fig. 27.

The nozzle attitude envelope verification will determine the installed nozzle pitch and yaw envelope and the nozzle ramp/nozzle relative positioning. The nozzle will be systematically moved to its limits, first air off and then air on. The air-on movement will start at a relatively benign load condition, Mach 0.5 at 45,000 ft, and progress to the highest load condition in the test regime, Mach 0.9 at 30,000 ft. The demonstration will begin at ambient temperatures and then progress to the low true temperature associated with the Mach 0.5 at 45,000 ft standard-day test condition to determine the thermal response of the test cell systems. These movements will be made at slow, deliberate rates to verify the nozzle attitude control system capability to position the nozzle as commanded and the plant automatic test control system ability to provide the required freejet flow conditions.

The nozzle flow quality will be determined by a pressure and temperature probe rake which is shown in Fig. 28. The rake extends across the nozzle laterally and traverses vertically to cover the full nozzle exit flow region. The flow angularity and Mach number of the flow will be determined by calibrated conical pressure probes while the flow turbulence is measured by high-response total pressure probes. The rake can be positioned axially from 2 in. downstream of the nozzle exit to 40 in. downstream to investigate the downstream shear boundaries of the freejet. The flow quality will be determined at conditions ranging from Mach 0.3 to 0.9 and altitudes from 14,000 to 56,000 ft. In addition,
boundary-layer profiles will be measured at various points around the nozzle exit.

The inlet reference plane control demonstration will demonstrate the NACS and ATCS integrated performance to set and change selected IRP flow conditions. The simulated flight conditions will be changed throughout the freejet regime at rapid rates accompanied by nozzle attitude movement to produce IRP flow fields representative of aircraft maneuvers such as constant altitude accelerations, altitude changes at a constant airspeed, and altitude changes with increasing angle of attack and decreasing airspeed. For this demonstration, the IRP control probe response does not permit the determination of the IRP flow-field changes during the simulated maneuver, just the flow field at the start and end of the maneuver. The maneuver itself is controlled by ramps in the ATCS and NACS. The supersonic demonstration will be conducted when the nozzle is available in the configuration shown in Fig. 29. The supersonic demonstration will be conducted at the flight conditions shown in Fig. 30. The supersonic demonstration will use a currently available 10.75-ft-diam diffuser.

FREEJET UTILIZATION

Utilization of the freejet for inlet-engine compatibility testing requires prior planning to assure maximum benefit. During aircraft design, the flow field over the aircraft structure at the inlet should be provided to the forebody simulator designer to match with the required freejet geometric constraints. During the normal subscale inlet wind tunnel testing, the flow field at the IRP should be determined to provide the full-scale freejet test control parameters. Additionally, the structural aspects of the freejet inlet-engine installation need to be considered, which parts of the installation are air craft hardware and which are test installation only. AEDC has available a freejet interface document to assist in design for the test cell mounting and the service system interfaces. The forebody simulator, the test cell mounting, and the service system interfaces will require extensive integration and coordination among the engine manufacturer, the airframe manufacturer, AEDC, and other government or industry agencies as applicable. While the freejet system simulates aircraft maneuvers, the inlet-engine system compatibility can be determined with engine transients, stall and recoverability exercises, and inlet and engine geometry variations. The engine controls can be integrated with the freejet control systems as required.

In addition to inlet-engine compatibility testing, the C-2 freejet has the potential of inlet-engine operability determinations in simulated icing conditions with the addition of controlled water sprays at appropriate locations in or upstream of the nozzle. It should also be noted that the C-2 freejet system is appropriately sized for full-scale air-launched missile testing of engine starting and mission profiles at true temperatures for the launch and flight conditions.

CONCLUSIONS

The ASTF freejet development is nearing completion, and the subsonic test capability is scheduled to be operational in 1991. Freejet testing techniques, developed during the full-scale hardware implementation, have great potential for improving aircraft inlet-engine compatibility development. The freejet systems are currently being installed and checked out for the subsonic systems demonstration to start in September 1991. Upon conclusion of this demonstration program, freejet simulation of full-scale aircraft inlets with operating engines will be available for subsonic flight conditions. The supersonic system to increase the Mach range to 3.0 is being developed.

REFERENCES


