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A Proposal for Integration of Wind Tunnel and Engine Test Programs for the Evaluation of Airframe-Propulsion Compatibility Using Numerical Simulations *

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Abstract

The current high-performance aircraft development programs, and the trends in research and development activities suggest a rapidly increasing level of aircraft subsystem integration, particularly between the airframe/inlet and the propulsion system. Traditionally these subsystems have been designed, analyzed, and tested as isolated systems. The interaction between the subsystems is modeled primarily through evaluating inlet distortion in an inlet test and simulating this distortion in engine tests via screens or similar devices. In the current paper, an overview of current techniques for inlet performance and distortion characterization and engine distortion testing is presented. A review of the current state-of-the-art in inlet analysis is also presented along with a discussion of current engine analysis techniques, from a semi-empirical approach to high-fidelity full Navier-Stokes simulations. Finally, a proposal to coordinate the existing test techniques and analysis capabilities to provide a truly integrated inlet-engine test and evaluation capability is outlined.

Introduction

A primary objective of the Arnold Engineering Development Center (AEDC) test and evaluation (T&E) mission is centered on integrating weapon system airframe and propulsion systems. Airframe-propulsion integration encompasses a number of issues ranging from aircraft stability and control to inlet-engine compatibility. Consequently, the integration involves a wide range of technical disciplines with implications to the T&E environment. Examples include external aerodynamics with the characterization of forces and moments, inlet performance, engine operability, engine performance, controls, and structures. To address the disciplines, the T&E process requires the application of a variety of test resources as well as analytical and computational tools. Testing for airframe-propulsion integration, and in particular inlet-engine compatibility, generally requires the coupling of component tests conducted in wind tunnels and engine altitude facilities.

The advent of technologies for providing controlled flight at extremely high angles of attack and sideslip have enabled weapon system developers to consider supermaneuver and post-stall maneuver capabilities as combat tactics. As a result, future fighter aircraft may be required to execute maneuvers containing drastic and transient changes in flight conditions at the high power settings demanded by combat. Such maneuvers present the issue of the role that the distortion time history might play in the inlet-engine integration task. Large and transient changes in angle of attack can produce hysteresis and therefore deviations from the steady-state condition. As a result, future direct-connect engine or compressor tests may require distortion generators capable of producing a rapid sequence of distortion patterns to provide a time history corresponding to a transient maneuver.

Stealth has produced inlets highly integral with the airframe including blended inlets. Supercruise and stealth have both motivated designers to adopt bay-launched munitions in fighter aircraft designs. Together, these features have increased the proximity between the aircraft inlet and the weapon to be launched in flight. Furthermore, the use of the supermaneuver as a combat tactic in the point-and-shoot concept, will result in weapon launches at angles of attack and sideslip outside current flight envelopes. These factors increase the likelihood that hot weapon exhaust gases will enter the aircraft inlet.

Another type of inlet distortion that may appear in future operability and performance assessments involves flow angularity. The current total-pressure methodology neglects flow angularity as a separate distortion parameter. However, experience with a number of systems showed that flow angularity could affect both operability and performance. In an

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aircraft inlet, flow angularity generally appears in the form of swirling flow. A rotation of the entire flow about the engine or compressor hub constitutes a bulk swirl and either increases or decreases engine performance depending on the direction of rotation with respect to the machine. Localized swirl, in the form of vortices appearing in various regions of the AIP, can affect surge margin. Engines lacking inlet guide vanes have demonstrated the highest sensitivity to inlet swirl. Inlet swirl can originate at the aircraft forebody or it can be generated in s-shaped inlet diffuser ducts. Therefore, the advent of stealth systems, with blended inlets and s-duct, may introduce requirements to address swirl in future inlet-engine compatibility tests.

The AEDC T&E capabilities fulfill an essential role in the verification of the aircraft system performance. However, the need to evaluate the performance of a system often requires a number of separate test facilities. This requirement routinely arises in the integration of the airframe and propulsion system, particularly in the inlet-engine compatibility verification process. Although large propulsion wind tunnels such as AEDC 16T can accommodate complete cruise missile systems, fighter aircraft physical size generally exceeds wind tunnel capabilities. Therefore, fighter aircraft inlet-engine compatibility evaluations generally employ separate subcomponent tests. Subscale inlet model wind tunnel tests characterize inlet performance and distortion characteristics. Subsequently, direct-connect turbine engine tests, using inlet simulators, subject the engine to distorted flow representative of that experienced when coupled to the inlet.

The Inlet-Engine Integration test methodology currently involves two separate processes that are loosely coupled as illustrated in Figure 1. Wind tunnel experts and airframe developers conduct the inlet wind tunnel tests with little insight into the engine tests to follow. The sub-scale inlet tests determine the conditions that must be simulated at the face of a full-scale engine. These conditions although a function of angle-of-attack, side-slip, and flight condition, are characterized by a distortion indexing methodology which may smear out the influences of each individual flight variable.

Similarly, the engine test teams, must wait for an off-site analysis by airframe and engine developers to provide distortion patterns for test. Usually, the engine test team acquires little insight into the inlet distortion measurements and analysis that resulted in the particular selections. The engine test team measures the effect of a series of distortion patterns based upon distortion screens on engine operability and performance. Although efforts are proceeding to improve the inlet simulation devices placed in front of an engine, they presently neglect time history, flow angularity, and certain interactions such as the effect of the compressor face on the inlet characteristics. The true dynamic effect of an aircraft maneuver is not included in this test methodology.

The procedure of separating wind tunnel and engine test cell testing has perpetrated the evolution of separate wind tunnel and engine test cultures, with respect to airframe-propulsion integration, and resulting limitations in overall efficiency and cycle time. The test process limitations stem from the industry approach to test procedures.

Perhaps the latest assessment of the state-of-the-art airframe-engine integration methodologies is best summarized in the 1995 Wright Brothers Lectureship in Aeronautics (Smith, 1995). "In spite of all the improvements cited in this assessment, significant portions of the current state of the art for the airframe-engine integration process are still dependent on empiricism and scaling rules. Such dependencies always contain exposure to risks that the next configuration and/or next mission requirement will lie outside the bounds of applicability of the empiricism and/or scaling rules. These risks portend the possibility of a major negative surprise. The airframe-engine integration process has produced many such surprises in its history."

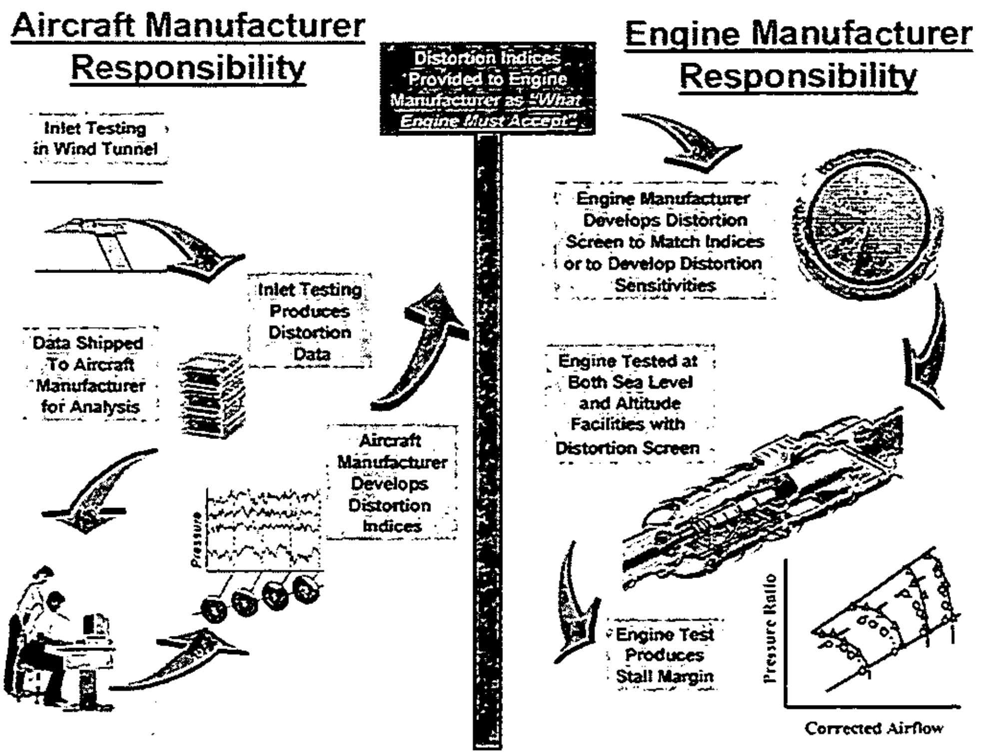

Fig. 1 – Current Inlet-Engine Integration Test Methodology

Through the use of modeling and simulation technology combined with the baseline information provided by the current wind tunnel and test cell test procedures, it is postulated that a virtual coupling of the wind tunnel facility with engine test cell information can be accomplished. The fusion of computational and experimental data will result in an increased level of information available to the design engineer for system development and potentially reduce the risk of a surprise in the next development cycle

This paper reviews what constitutes the current practice for evaluating engine and inlet compatibility issues and highlights the potential for increasing the information available from current testing through the fusing of computational modeling and simulation and experimental data to provide a numerical simulation of the airframe-engine system. This paper also addresses the need and level of simulation technology that will be required for ground test facilities to provide a simulation capability for full inlet-engine compatibility evaluations.

Description of Existing Test Techniques**

Both inlet and engine ground and/or flight testing use a methodology developed by the S-16 committee of the Society of Automotive Engineers (SAE), the Aerospace Recommended Practice, ARP-1420 and its companion document, the Aerospace Information Report, AIR-1419 as guidelines for evaluating inlet and engine performance and operability with non-uniform inlet airflow. These documents are a recommended practice, derived by consensus of industry and government practices during the late 70's and early 80's. Over the last 25 years, these consensus practices have become established methodologies. A review of these methodologies is presented below.

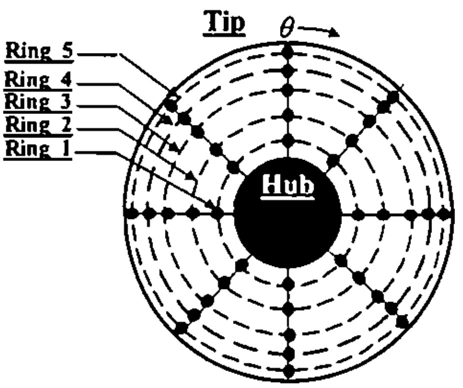

Fig. 2. Standard 40-Probe Rake

The AIR-1419 documents engineering information for use as reference material and for guidance. The document addresses the full spectrum of the methodology including definition of distortion descriptors, distortion test methods, instrumentation, data handling, performance assessments, and stability assessments. Inlet total-pressure and other forms of flow distortion that can influence inlet-engine compatibility require examination to establish their effect on engine stability and performance. The report centers on inlet-generated total-pressure distortion measured at the Aerodynamic Interface Plane (AIP), not because it is necessarily the sole concern, but because characterizing inlet distortion in terms of total-pressure parameters has historically proven adequate for integrating inlet and engine systems. The methodology assumes that total-pressure distributions, which can be readily measured during wind tunnel tests of inlets and direct-connect tests of engines, describes the distorted flow in sufficient detail to allow the aircraft developers to avoid surge problems. The report does not address the procedure for dealing with performance destabilizing influences other than those caused by total-pressure distortion, or with the effects of any distortion on aeroelastic stability.

The report advocates defining spatial total-pressure distortion using an array of steady state and high-response probes distributed over the AIP as illustrated in Figure 2. Standardizing the probe distribution provides a common basis for determining steady state and dynamic distortion in wind tunnel tests, engine ground tests, and flight tests.

The selection of the 40-probe arrangement, shown in Figure 2, is based on providing the spatial fidelity required for inlet-engine compatibility assessment objectives while avoiding excessive blockage. The probes are arranged on eight rakes spaced 45-deg apart to provide measurements of the circumferential distortion component. Each rake contains five probes spaced on five corresponding rings to provide measurements of the radial distortion components. Each ring represents an equal area of the AIP to simplify the data reduction process. Thus each probe measures the pressure of an equal segment of the face area.

The concepts that are fundamental to the AIR-1419 methodology are:

- Inlet flow quality can be characterized, in a form relevant to engine distortion response, with numerical descriptors derived from an array of high-response total-pressure probes;
- Propulsion system stability can be controlled by the aircraft and engine designers,
- Engine stability can be demonstrated by tests using equivalent levels of steady state distortion, and
- The dynamic or time-variant distortion effects on engine stability are limited to events lasting longer than approximately one revolution of the machine and may be represented in test by a fixed peak distortion pattern selected from the distortion time history.

Surge margin and loss of surge pressure ratio are major concepts to the ARP-1420 methodology. The ARP-1420 defines surge margin at constant corrected airflow at the inlet of the compression component. Surge margin is the difference between the surge pressure ratio, (PR1), and the operating pressure ratio, (PRO), normalized by the operating pressure ratio as defined in Figure 3 and the following equation.

** Information in this section was taken directly from the AIR-1419, Section 2 — some of it has been paraphrased.

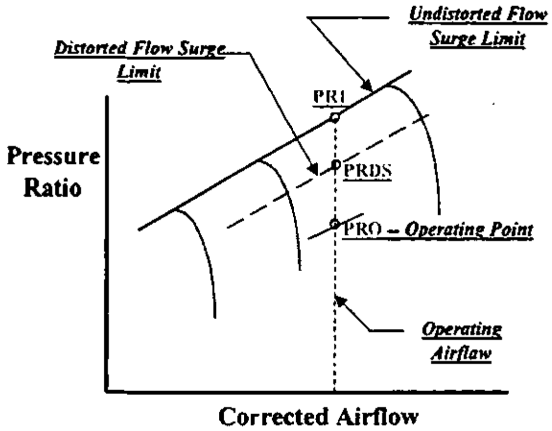

Fig. 3. ARP-1420 Surge Margin Definition

The loss in surge pressure ratio caused by inlet total-pressure distortion is also measured at constant inlet corrected airflow and is defined as follows:

$$\Delta PRS = \frac{(PR1 - PRDS)}{PR1} \times 100$$

The loss in surge pressure ratio is normalized by the undistorted surge pressure ratio rather than by the operating pressure ratio because the operating pressure ratio may not have been defined when compressor rig tests are made to determine the effect of distortion on compression system stability.

Distortion Descriptor Element Definitions

Aerodynamic Interface Plane total-pressure probe data are used to describe inlet distortion directly in terms of the probe readings and numerically in terms of distortion descriptors that are related to the severity of the distortion. Distortion descriptors provide a means of identifying critical distorted inlet-flow conditions and a means of communicating distortion sensitivity during propulsion system development. Inlet spatial distortion is described in terms of circumferential and radial elements that are then linearly combined to provide a single distortion description.

The requirement for a universal Aerodynamic Interface Plane flow distortion descriptor which will:

- Define the quality of the air supplied by the inlet and
- Describe the effect of the severity of the flow field upon engine stability,

is in direct contrast to the requirement for engine-specific information to predict the effect of any distortion pattern upon engine stability. This dichotomy exists, especially when both the inlet and engine development programs start about the same time. Ideally, an inlet development program would be structured such that distortion sensitivity data would be available from engine component tests prior to the start of inlet development testing. The largest impediment to a "universal inlet distortion factor" is that, *a priori*, the engine manufacturer cannot predict how the radial distortion will couple with the circumferential distortion, nor whether a compression component will be hub-or-tip distortion sensitive.

Current Testing Practices

Keeping with one of the fundamental precepts of the recommended practice set forth in the ARP-1420, namely, that engine stability can be demonstrated by tests using equivalent levels of steady state distortion, the aircraft manufacturers, engine manufacturers and testing organizations have implemented testing procedures which reflect that premise. A description of separate inlet and engine testing practices is presented in the sections below.

Wind Tunnel Testing for Inlet Performance

The primary objective of inlet test programs is to determine the suitability of the chosen inlet design for the airframe and engine installation. Primary data obtained for this evaluation are the steady state and dynamic performance and stability data at the compressor face. Depending on the stage of development of the program, different configurations and inlet system operational variables may be tested to aid in the determination of the optimum contours of the inlet duct and configurations of various inlet subsystems (i.e. bleed, bypass, diverter) along with subsystem schedules. For some programs it is important to determine the vehicle (inlet pre-entry) and inlet flow fields (including boundary layer development) using flow-field survey rake assemblies. As the program matures, bleed and bypass configurations for the defined duct are optimized.

Tests involving aircraft with two inlet ducts often investigate cross talk effects of flow variations in one inlet duct on the performance of the other.

Model scale is a significant factor in correctly simulating the inlet performance of the full-scale flight vehicle. Although the scale of the model is quoted as a single number, there are often deliberate variations in scale of various inlet components. Some components are scaled differently because the model test Reynolds number is substantially different from the aircraft full-scale Reynolds number. The difference in Reynolds number causes the boundary layer thickness to be non-proportional from model scale to the actual full-scale. For example, for the inlet duct to see a similar boundary layer from the fuselage, the diverter is sometimes scaled according to the expected boundary layer thickness at the model Reynolds number instead of by the model scale. Variations similar to this may be used as necessary on any inlet component. These scale differences usually will not impact the test program if the boundary layer height analysis is conducted correctly such that the flight vehicle boundary layer conditions are scaled properly on the test model.

Instrumentation

Although most inlet tests have similar instrumentation, there are no universal requirements. The primary instrumentation is usually a compressor face rake with combined steady-state/high-response total-pressure probes (Fig. 1). There are usually static pressure taps near the compressor face station. Tests which use flow plugs to control mass flow through the inlet (most tests) usually have static pressure taps at the flow plugs. Each flow plug also has a potentiometer or LVDT (linear variable differential transformer) to measure its position.

For diagnostic purposes, some test articles have total-pressure rakes on the fuselage. Most models have diagnostic static taps both inside the duct and on the fuselage. Some have high-response pressure transducers mounted internally or externally, especially to monitor wakes from fuselage protuberances forward of the inlet. Models with additional flow passages are often instrumented with steady state, and sometimes dynamic, total and/or static pressure instrumentation in the passages. Occasionally, model temperatures are monitored, especially if the model uses Electronically Scanned Pressure (ESP) modules to measure steady-state pressures.

If separation inside the inlet duct is a concern, total-pressure rakes may be used inside the duct to measure pressure profiles. These rakes are usually removable since their wakes will invalidate pressure measurements at the compressor face station.

Flow Generation

An associated task of every inlet test is to provide the necessary flow through the inlet. At low Mach numbers there is insufficient pressure ratio across the inlet system to induce the desired airflow. There are two primary methods currently in use to overcome this problem. The more convenient method uses a high-pressure-air-powered ejector (Robinson, 1969). The ejector is mounted at the rear of the test article, behind the flow plug. High-pressure air is piped to the ejector and blows out through small sonic or supersonic nozzles in the ejector body. The high-speed flow exiting the nozzles reduces the ejector body pressure, inducing the flow through the duct.

The other primary system used to reduce the duct backpressure and thus produce airflow uses the suction scoop. The scoop is a tunnel system designed to remove exhaust gases from operating turbine engines or rocket motors. The scoop is directly connected to the aft end of the model and its pressure is reduced enough to induce airflow through the inlet duct. This system can often provide lower backpressure than is possible with an ejector and thus produce higher inlet mass flows which is useful when factors prohibit the use of an ejector system.

The most critical case for sizing any flow generation system is at static and low Mach number, high-pressure conditions. Inlets are tested statically and at low Mach numbers to determine performance for take-off and landing. These conditions often require high mass flow. In addition, the backpressure to which an ejector is exhausting is high and consequently the duct pressure ratio is minimal. This is usually the most challenging situation faced by the mass flow generator.

Flow Metering and Measurement

An important requirement of an inlet test is the accurate setting and measurement of the airflow through the inlet duct. In general, the best results have been obtained by using a device that is operated in a choked condition. (This requires that the throat of the entire inlet duct system be at the device itself rather than at an upstream or downstream location.) When the flow-metering device is choked, the actual corrected airflow is a function of area only. By varying the area, the flow can be varied, and for most devices the area is directly related to a measurable position of the choking device.

The most common device currently employed is a calibrated flow plug. The flow plug is a translating conical body that moves fore and aft in a pipe fitted with a diverging section matching the contours of the plug. As the plug translates within the conical area, the opening area changes. With sufficiently low backpressure, this translates to a change of flow through the duct. Typically, the plug is run with backpressure low enough that the plug remains choked.

An alternate method of mass flow determination involves the integration of the compressor face pressure measurements. The compressor face total-pressure integration uses the average-static-to-total-pressure ratio at each total-pressure probe to calculate a local Mach. Once the Mach number is calculated it is converted to a velocity and used with the local air density and area to obtain a mass flow element. All of the individual mass flow elements are summed. The sum is then multiplied by a discharge coefficient to obtain the total mass flow at the compressor face station.

To use the integration of compressor face pressure method to measure inlet mass flow, there must be static pressure measurements at the station where the compressor face total-pressure probes are located. Integration of the individual total-pressure measurements at the compressor face provides a less accurate calculation that best serves as a check of the flow plug measurement.

Setting Model Attitudes and Plug Positions

There are several types of data variations that may be acquired during an inlet test. The most common variation is a mass flow sweep at constant angles of attack and sideslip. Others include an angle of attack sweep at constant mass flow and sideslip angle, mass flow sweeps of secondary flows, and angle of sideslip sweeps.

It is generally preferable to use computer control whenever possible for any positionable device which will be moved frequently during the test. This will usually result in more accurate and faster settings. Computer control is ideal for digital devices and very good for analog devices.

The usual mode of data acquisition during an inlet test is to first set model angles of attack and sideslip and follow with a mass flow/plug position sweep.

Engine Testing for Total-pressure Distortion Effects

Compression systems can be tested for performance and operability characteristics using any of a number of techniques. These include wind tunnel tests, direct-connect tests, freejet tests, and flight tests. The choice of technique depends on such factors as the size of the vehicle, cost, and stage of development. Each technique employs a method of subjecting the compression system to distorted flows representative of the flight environment.

Smaller vehicles such as cruise missiles may be tested in large propulsion wind tunnels such as the AEDC PWT 16T/S. The complete inlet, airframe, and engine assembly can be evaluated as a system. The wind tunnel flow conditions simulate the uniform far-stream flight environment. The airframe and inlet modify the flow in a manner similar to that in flight subjecting the engine to steady state and dynamic distortion. This method is not limited to cruise missiles. The F-15 fighter aircraft development included full-scale tests of the inlet-engine assembly in both PWT 16T and 16S albeit at only moderate angles of attack. Although physical space prevented inclusion of the complete airframe, the test did include the entire inlet-engine assembly and the portion of the airframe most influential to the inlet flow.

The freejet technique also allows testing of the complete inlet-engine system. Unlike the wind tunnel, the freejet method uses a variable attitude and variable Mach number nozzle to provide a flow enclosing only the inlet opening and influential portions of the external airframe. Rather than change test article attitude, as in the wind tunnel, the technique changes the freejet attitude to simulate flight conditions. As a result, the method can simulate high flight angles of attack with fighter-size aircraft that physical size would prohibit in the wind tunnel.

The flight test method provides an evaluation of the complete inlet, engine, and airframe system. Often, the AIP is instrumented to measure inlet steady state and time-variant distortion to allow correlation with other techniques. Generally, the flight test approach appears as the development of an aircraft system matures.

By virtue of being available early in the air vehicle development cycle, the direct-connect method has become the workhorse for testing compressors or engines in distorted flows. The method can readily be applied to engine components such as individual fans or compressors as well as to complete engines. In the direct-connect test, the component or engine is connected directly to an air supply duct that provides conditioned air at a pressure, temperature, and Mach number commensurate with a given flight condition. Thus, the duct conditions correspond to the flow output by the inlet after the diffusion process. With respect to the freestream, these conditions often include lower Mach numbers, higher static pressure, and higher static temperature. So, in a sense, the supply duct functions as an inlet simulator taking the place of the actual inlet.

In the absence of the inlet and airframe, the direct-connect approach must rely on additional techniques to simulate the distortion produced by the inlet. A number of methods have been applied to simulate steady-state inlet distortion as well as various aspects of time-variant distortion. The two most widely used inlet distortion simulators are the distortion screen and the air jet distortion generator.

The distortion screen (Overall, 1972) generates steady-state total-pressure patterns through flow blockage, a function of screen porosity and approach velocity. The screen consists of an assembly of various wire meshes with shape and porosity tailored according to the particular pattern of interest. When mounted forward of the compressor or engine and normal to the flow, the screen subjects the machine to distortion similar to that produced by the inlet. An example of a distortion screen appears in Figure 4.

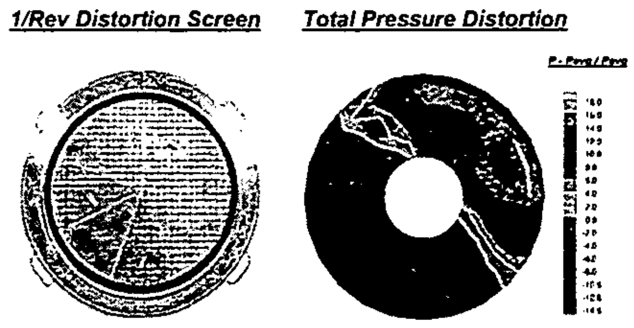

Fig. 4 – Typical Distortion Screen and Corresponding Distortion Pattern

This particular screen produces a one-per-revolution, 180-degree circumferential pattern. As each screen produces a single distortion pattern, a particular test program may require a family of screen assemblies to satisfy inlet-engine compatibility verification objectives.

The air jet distortion generator (Overall, 1976) evolved as an approach to avoiding the cost and cycle time needed to fabricate and install separate screens for each distortion pattern. The device uses the viscous mixing as a means of reducing the momentum in regions of the approaching flow. Forward-facing airjets exchange momentum with the approaching flow to effect pressure losses. An array of such jets, mounted on struts upstream of the test article, provides a means of spatially varying the pressure defects (Figure 5).

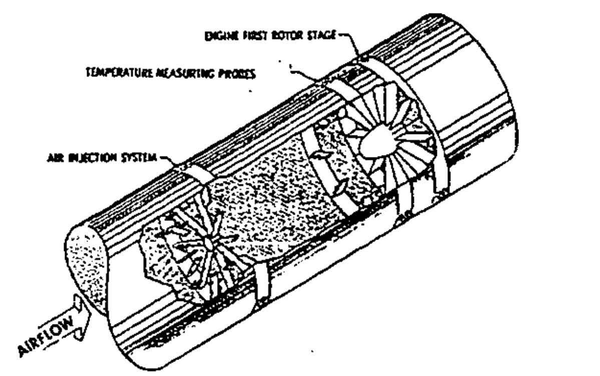

Fig. 5 – Schematic of Airjet Distortion Generator

By remotely adjusting the flow distribution among the jets, the tester can set desired distortion patterns without interrupting the test for hardware changes. Unlike the wind tunnel or flight test methods, the direct-connect method requires *a priori* definition of the flow distortion patterns to set in the inlet simulator whether screen or air jet distortion generator. As the direct-connect approach finds wide application throughout the vehicle development cycle, the patterns fall into two general categories: (1) classical distortion patterns and (2) composite or complex distortion patterns.

The so called classical distortion patterns consist of standardized patterns that provide specific distortion features such as tip radial distortion, hub radial distortion, circumferential distortion with various multiple-per-rev specifications, or combinations. These patterns are generic in the sense that they do not necessarily correspond to a specific vehicle. The classical patterns generally find application earlier in the development cycle to establish the basic sensitivity characteristics of the engine or compression system. A discussion of the classical patterns and sensitivity tests appears in the AIR 1419.

As the vehicle development progresses, the airframe-inlet design will be established. Or, if a specific compression system or engine is to be retrofitted to an existing aircraft, the airframe-inlet design will exist. The direct-connect test may then proceed with composite distortion patterns representing the environment that the engine will experience in the specific vehicle. These patterns are no longer generic. In general, subscale inlet model wind tunnel tests, such as those described in the previous section, provide measurements of the specific patterns expected with the full-scale vehicle in flight. The wind tunnel test must capture the effects of both the inlet itself and the influence of the external airframe on both steady-state and time-variant distortion. The prediction of the distortion patterns produced by the inlet-airframe system represents a key component of the integration of computation and experiment into a distortion evaluation methodology.

The screen and airjet distortion generator devices provide only steady-state distortion patterns. However, historical wind tunnel test results have shown that the time-variant distortion can be significantly higher than steady state. Over the years, a number of devices have been developed in an effort to simulate time-variant distortion in direct-connect tests. Examples of such devices can be found in the random-frequency generator (Brimelow 1976), the discrete-frequency generator (Lazalier 1969), and planar-wave generator (Reynolds 1973). The random frequency generator devices generally used separated flow to produce fluctuations similar in nature to those encountered in an inlet duct. Discrete-frequency generators generally use a periodic pulsing of the flow to develop fluctuations at specific frequencies. These fluctuations may be produced by the air jet distortion generator with pulsed jets or by rotor-stator devices. However, these devices have yet to find general application.

To address time-variant distortion, the current methodology applies the following approach. The time-variant distortion measurements obtained in the wind tunnel, the distortion time history, is screened over the time recorded during the particular test point to identify peak levels of distortion. The wind tunnel data acquisition procedure must include a sufficient data record, typically twenty or thirty seconds, to capture peak distortion events. Experience has shown that turbomachines require a finite time, on the order of one revolution of the compression system, to respond to dynamic distortion events. Therefore, the screening process neglects events lasting less than approximately one revolution. The peak level of distortion is then applied in the direct-connect test using the screen or air jet distortion generator. The peak time-variant pattern becomes a steady-state pattern in the engine or compressor test neglecting the effects of time history. Figure 6 illustrates this approach.

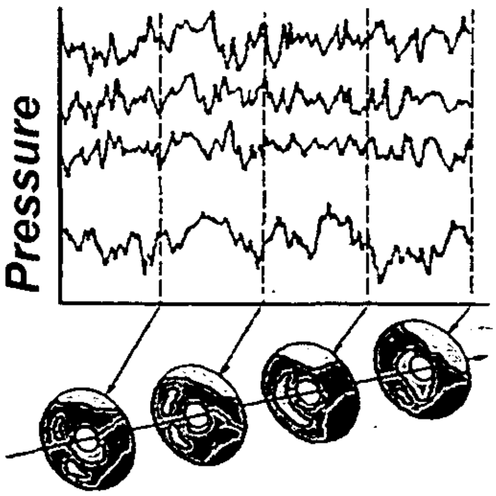

Fig. 6 – Simulation of Time-Variant Distortion with Steady-State Patterns

The SAE methodology described thus far evolved over several decades and has been successfully applied to a number of systems up to current generation fighter aircraft. Recent years have brought forth new aircraft technologies that add new dimensions to the assessment of inlet distortion effects on engine performance and operability. The SAE and others have embarked on the investigation of methodologies necessary to address such technologies in the inlet-engine integration process. These issues will be discussed in the last section of this paper.

Computational Capability

For a numerical technique to become viable as a complementary test analysis tool, it must be able to provide solutions both quickly and accurately. Computational fluid dynamic (CFD) solutions for the inlets have been routinely done for many years, even with time-variant events. However, the complexity of the gas turbine engine makes CFD solutions of the full engine impractical at this time. At best, several blade rows of a turbomachinery component can be calculated in an "over-night" time frame. Thus, computational techniques must be used that use reduced grid complexity and levels of computer parallelization must be employed.

The computational simulation of inlets, especially for advanced fighter aircraft, requires modeling of complex geometries and physical phenomena. Inlets are often essentially part of the aircraft fuselage leading to highly non-uniform flow at the inlet entrance. The inlet duct transitions in cross-sectional area from a nearly oval or rectangular geometry to the required circular cross-section at the engine face resulting in significant cross-flow velocities. Inlets for these advanced fighters are also highly curved to hide engine hot parts from infrared and radar detection. These highly curved ducts can results in flow non-uniformities, including flow separation. A fairly simple inlet configuration is shown for a F/A 18A High Alpha Research Vehicle (HARV) in Figure 7.

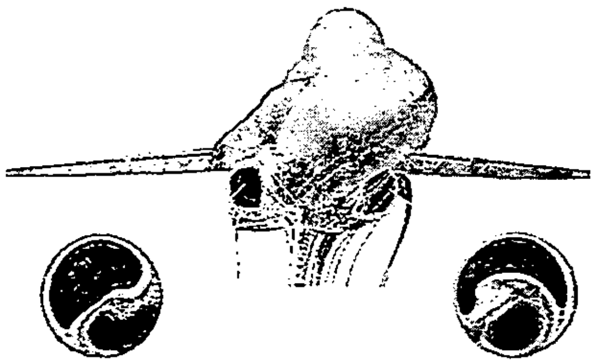

Fig. 7 – Inlet Flow Distortions at High Angle of Attack on F/A 18A

This flow field was computed by Smith and Podelski (1994) using the NPARC Code (Power, et al., 1995) at a Mach number of 0.2 and a 30 degree angle of attack. The Mach number contours shown in the figure indicate significant flow distortion at the AIP. Simulations of more complex inlets can be found in the recent papers by Mayer, et al. (1998) and Philhower, et al. (1998).

These advanced aircraft fly at speeds from low subsonic to supersonic, often at high angles of attack, resulting in complex flow structures in the vicinity and within the inlet, especially at transonic and supersonic conditions. Bleed systems and other mechanical devices are often employed to control shock location and flow conditions within the inlet. The engines are also subjected to other external influences, including rocket plume ingestion from air-launched missiles. Other phenomena, which are of concern, and thus must be adequately modeled, include inlet buzz and inlet unstart. Most, if not all, of these complex phenomena are at least partially influenced by the interaction between the inlet flow field and the propulsion system.

Simulating these complex geometries and the associated complex physical phenomena of engine inlets require simulation tools capable of capturing unsteady, three-dimensional, turbulent flow fields. Because of the highly three-dimensional nature of the flow and the potential for significant flow separation, full Reynold's averaged, Navier-Stokes equations with sophisticated turbulence models must be solved. The Navier-Stokes solver must have the capability to model unsteady phenomena, such as unstart and buzz. Finally, the simulation tool must have the capability to solve for or model the effects of the engine, in particular the first stages of the compressor, on the inlet flow field.

Most Navier-Stokes codes in use today have the capability to model a majority of the flow phenomena required to adequately simulate the inlet flow field. The most challenging requirements are turbulence modeling, fast time-accurate simulation, and the modeling of the effects of rotating turbomachinery.

Current turbulence models that are based on the transport, production and diffusion of turbulence quantities are capable of predicting flow separation in many situations. The most common models are k-ε models, such as the Chien low Re model (Chien 1982), the k-ω model (Wilcox 1992), hybrid models, such as the SST model (Menter 1993) and one equation models, such as the Spalart-Allmaras model (Spalart and Allmaras 1992). Each of these has been shown to provide reasonable results in predicting separation, but none can be considered universally applicable.

Time accurate simulations of fluid dynamic processes are becoming more prevalent as computer power increases and algorithms improve both the speed and accuracy of these simulations. Recent algorithmic advances in other fields of flow simulation, such as store separation (Tramel and Nichols, 1997), can be applied directly to simulation of the unsteady phenomena in inlet flow fields to allow larger physical time steps and, thus, faster simulations. The major limiting factor on speed is now the frequency of the unsteadiness that must be resolved, where significant computer resources are required for resolution of higher frequencies.

One approach to computationally modeling the effect of the engine on the inlet is to modify the flow at the compressor face through specialized boundary conditions. If a flow rate is known, this value can be set, allowing the static pressure to adjust at the compressor face to maintain this flow rate. The pressure may be a constant or may vary circumferentially and radially. If the pressure is known at the AIP, either at a point or over a region, this may be set directly. This technique would be applicable when modeling an inlet without an engine, where the pressure has been measured at various locations at the AIP.

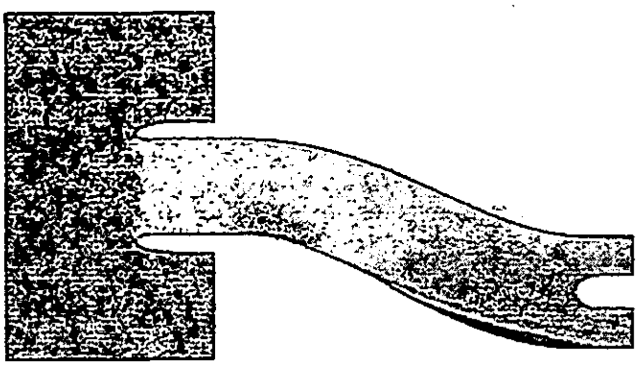

Fig. 8 – Mach Number in an S-duct Inlet

Figure 8 shows the calculated Mach number through an S-duct inlet in a freestream flow at M= 0.21, p_0 = 14.68 psi, and T_0 = 527° R. This configuration is the RAE Model 2129 inlet referred to as Test Case 3 by the AGARD FDP Working Group and was previously analyzed by Nichols (1991). The low speed flow in the region of adverse pressure gradient is shown as blue on the lower part of the duct.

In figure 9 the measured wall pressure distribution (symbols) along four circumferential stations is compared to the results of the WIND code (Bush, et al. 1998). In this case, the static pressure at the exit of a straight duct extension of the S-duct was set to a constant value of 13.525 psi. The results compare very well with the data, indicating excellent prediction of the losses in the adverse pressure gradient region of the flowfield.

An even more physical approach to modeling the compressor through boundary conditions has been developed by Paynter (1997) and Paynter, et al. (1998) which models the effect of unsteady pressure or temperature distortions at the engine face as it affects the inlet flow field. This characteristic boundary condition is based on the small disturbance response to a time varying acoustic or convected disturbance.

A more physically realistic approach to modeling the effects of the engine on the inlet flow field is to model simultaneously the flow as it passes through the compressor stages as well as the inlet. This can be accomplished at various levels of empiricism. The most rigorous technique for simulating the effects of the rotating turbomachinery on the inlet flow is to simulate the engine hardware itself. This can be done by modeling the unsteady flow through the rotating blades for each row simultaneously using tools such as ADPAC (Hall and Delaney, 1992) or to model each blade row, but approximate the interaction between the rows using an average-passage procedure, as outlined by Adamczyk (1985.). While the average-passage approach is more efficient than modeling the complete hardware and removes the time-dependency, both of these techniques require significant computer resources.

The choice of which approach to use to model the effects of the engine on the inlet flow field depends on the phenomena of

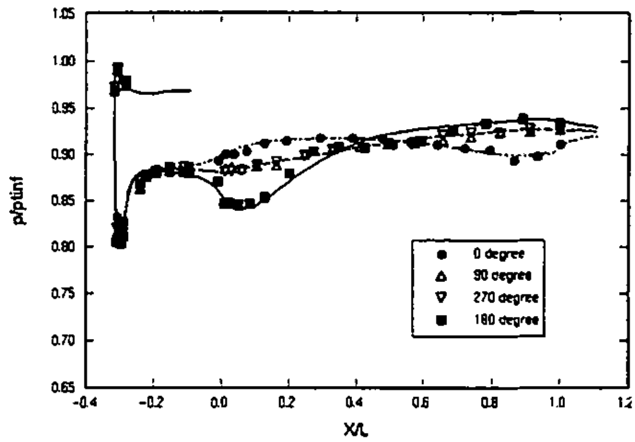

Fig. 9 – Axial Pressure Distribution – S-Duct

interest, the required accuracy of the simulation, the turn-around requirements, and the computational resources available. Integrating a three-dimensional Navier-Stokes CFD inlet model with a corresponding complex 3D CFD engine model for the study of inlet distortion is often not feasible for the required turn-around with the computational hardware of the 1990's, even with parallelization taken into account. Therefore, in order to compute time-dependent complex inlet distortion effects on the compressor flow field and vise versa, one must accept more empiricism in the modeling approach. One such approach is being developed by AEDC and is known as **TEACC** (Turbine Engine Analysis Compressor Code, Hale, A. A., 1998), Figure 10.

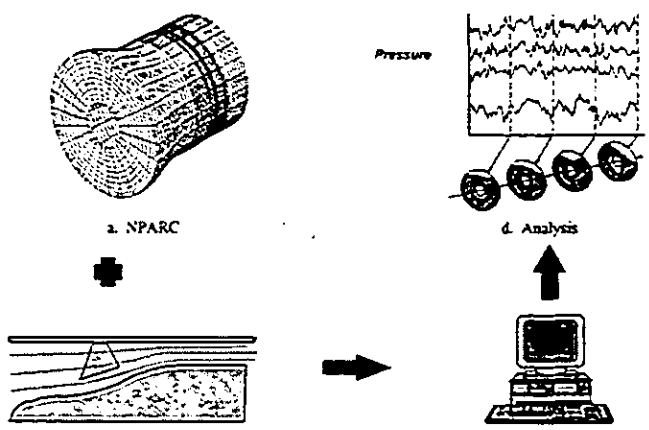

Fig. 10 – Overall TEACC Methodology

A general-purpose 3D flow simulation computer code (NPARC, Power, et al. 1995) has been modified to accept turbomachinery source terms based upon semi-actuator disk theory. The governing equations used in TEACC were developed by applying the conservation of mass, momentum, and energy. TEACC allows for circumferential and radial control volumes to interact directly with each other via the three-dimensional Euler equations with source terms representing a blade row. These source terms representing mass bleed, blade forces and shaft work are supplied by a streamline curvature code (a derivative of HTO300, Hearsey, 1994).

TEACC was developed with complex patterns and dynamic capabilities in mind. Currently, TEACC has been operationally verified for steady operation with and without distortion present for compression systems up to three stages. Future versions of TEACC will be able to address applications of complex dynamic distortion and their effects on compression system operability and ultimately expanded to the full turbine engine.

Integration of Numerical Simulations Into the Test Environment

Clearly the volume of issues facing future integrations of inlet and engine into viable aircraft systems demands the development of new test and evaluation techniques along with numerical simulations capable of dynamic behavior. The techniques must couple experimental and numerical simulations to provide the most cost effective acquisition of information. Both experimental and the corresponding numerical simulations require the development of methods for simulating inlet dynamic pressure distortion, swirl, and temperature distortion. It is the intent of this paper to suggest some ways that evolving numerical simulation capabilities can be utilized in conjunction with existing and new test techniques to address the issues outlined above.

We will examine each of the separate testing processes and suggest improvements that could be made using computational techniques. A schematic of the inlet testing process as it exists today is presented in Figure 11. The aircraft manufacturer develops and designs the aircraft inlet based upon his experience and CFD calculations. The aircraft manufacturer decides on a primary inlet design and requirements for further wind tunnel testing. The aircraft manufacturer decides on what needs to be tested and how much test time will be required. This process is primarily driven by the experience of both the aircraft manufacturer and the ground test provider. A matrix of test conditions is developed which includes flight conditions (altitude and mach number), angle of attack, side-slip, and roll. The wind tunnel test is conducted following the pre-described matrix. The data are stored and shipped back to the manufacturer for analysis. Very little interaction with the data is conducted during the testing process. If something was omitted in the process, the ommission would persist until another test is conducted in the future to get that information.

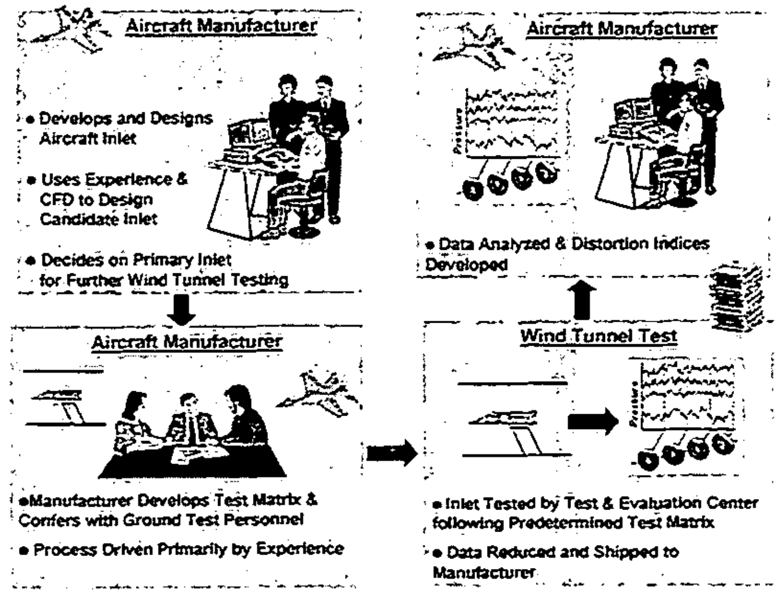

Fig. 11.—Schematic of Current Process for Inlet Testing and Analysis

One way to improve this process is to compute/predict inlet performance prior to testing. Such predictions would provide the means to optimize the test matrix and reduce the risk of a serious ommission. The proposed new process is presented in Figure 12.

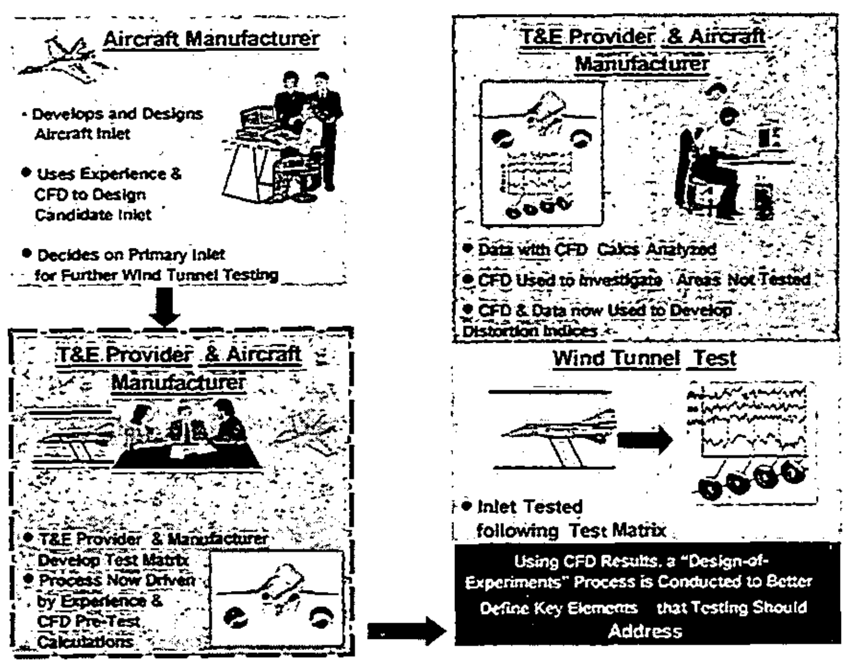

Fig. 12.—Schematic of Proposed Improved Process for Inlet Testing and Analysis

In the improved process, the aircraft manufacturer and the ground test provider decide on the matrix of flight conditions not only based upon experience but on CFD calculations of the proposed test article. These calculations can be used in a "Design of Experiments" process to better define key elements that testing should address. In the improved process, both the test data and CFD calculations are used to develop the distortion indices. The experimental data provide a very coarse description of the flow at the AIP, while the CFD solutions provide the details of the flow between the data points. Validated computations provide the mechanism to fill in the data matrix for benign test condtions. Validated computations also allow the diagnostics of test conditions that result in high levels of distortion so that changes to the test article during the test can be made in an informed manner. When combined, the test data and computational simulations provide the needed information at the lowest cost.

The ultimate capability for inlet testing in the future will be to combine the fused data and CFD solutions for the inlet with a full 3D engine model so that, while the inlet test is being conducted in the wind tunnel, the performance of the inlet can be determined as a function of the engine performance and stall margin changes rather than the nebulus values of distortion indicies.

Looking at current engine testing, we see a process, as illustrated in Figure 13, in place similar to the inlet process. The engine manufacturer uses whatever information that the aircraft manufacturer has provided about the nature of inlet distortion. Generally, the engine manufacturer plans distortion tests based upon previous experience and develops a test matrix using classical or baseline distortion patterns (180 degree circumferential distortion, hub radial and tip radial distortion patterns). The engine manufacturer coordinates with ground test personnel and defines a specific test program and the length of testing required. The engine is tested to map out the compression system sensitivity to the prescribed classical distortion patterns. The data are shipped to the manufacturer who then analyzes the data and determines if the engine can tolerate the distortion patterns produced by the inlet based solely upon the classical distortion patterns.

In the improved engine test process, Figure 14, the process is similar but by using a three-dimensional engine or compression system model, a prediction of the stability limit is obtained prior to test. This prediction is used to streamline the test matrix by emphasizing critical regions of the flight envelope and omitting test conditions that contribute little to the evaluation. Again using a "Design of Experiments" approach, the test matrix is further refined to better define the key elements that testing should address. The engine is tested in the engine test cell based upon the test matrix defined previously. If something abnormal occurs, engine model calculations can be conducted to determine what is the most efficient way of obtaining additional test information. Once the data are obtained, analysis engineers can pool both the engine data and the model calculations to provide a better definition of the stability limit.

New engine test techniques are under development that, in the future, will replace the old distortion screen methods. The new techniques will allow a more realistic representation of both the static and dynamic pressure distortion patterns as well as the flow angles and temperature distributions at the face of the engine. Coupled with the new inlet test techniques that fully define the flow entering the engine, the new distortion devices will be able to accurately simulate the flight conditions seen by the engine.

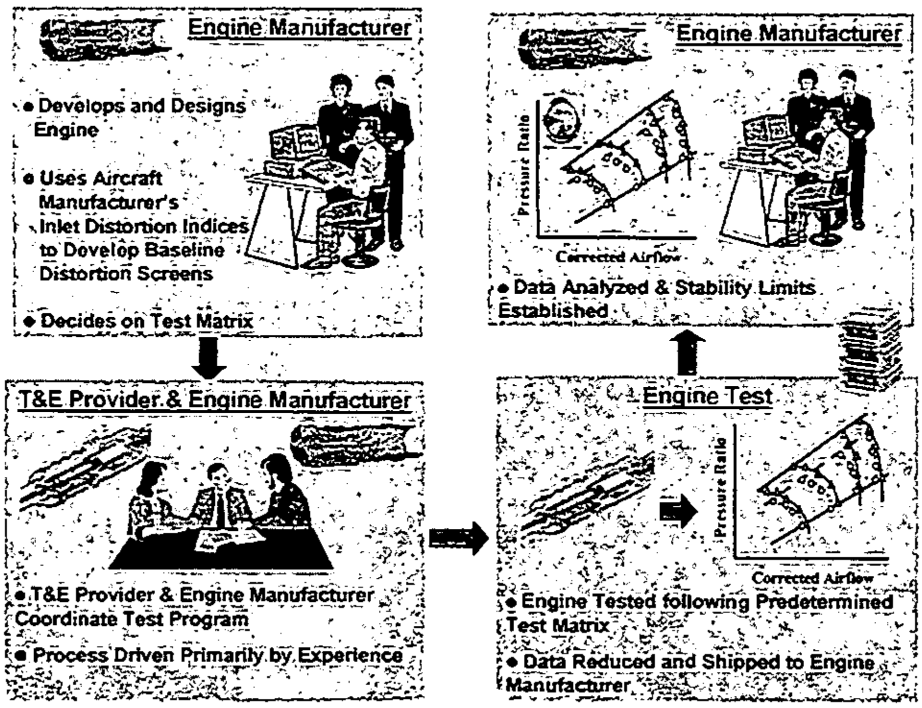

Fig. 13.—Schematic of Current Process for Engine Testing and Analysis

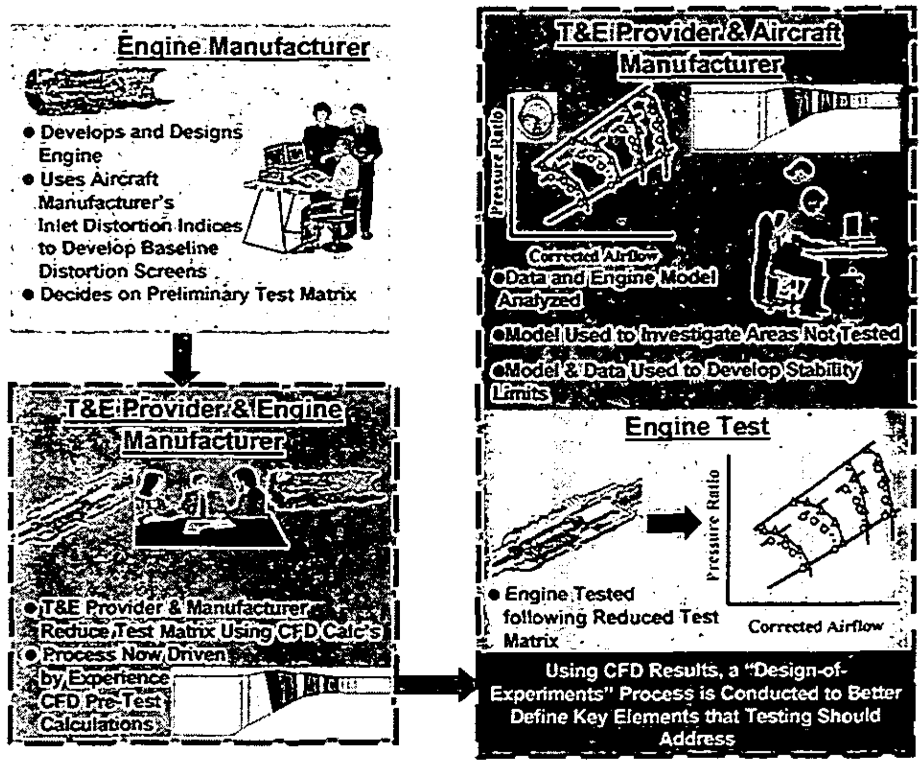

Fig. 14.—Schematic of Envision Improved Process for Engine Testing and Analysis

In the near term, computational simulations of both the inlet and engine, used in a fully integrated manner prior to testing, can help to focus the test matrix on critical operating conditions and reduce the test matrix by identifying those conditions which are more benign. Computations also provide the test customer with more comprehensive information by filling in areas of the envelope that are not scheduled for testing or cannot be tested due to test facility limitations. In the long term, the combination of computational methods with new test methodologies will provide a much more realistic ground simulation of the static and dynamic conditions that an engine-airframe combination will encounter in flight.

Finally, once the accuracy of a simulation is established on a subscale test, computations provide an approach to extend the analysis to full-scale flight conditions, thus, providing a link between the measured subscale distortion from inlet testing to the distortion patterns utilized in full-scale engine testing.

In the final analysis, flight testing is conducted to operationally verify the mated inlet/aircraft with the propulsion system. Generally, the flight test article is sparcely instrumented as compared to the ground test vehicle. In this environment, a go or no-go decision is all that can be made. With properly validated simulations of both the inlet and the engine, a virtual mating of the full propulsion system can be made and numerically flown at the desired flight condition prior to the actual flight test. The full spectrum of the integrated test and evaluation process is illustrated in Figure 15. The implementation of this vision has already begun with the development and application of one-dimensional engine-inlet simulations such as those reported by Garrard,1997, Numbers, 1997, and Clark, 1995.

In the fully integrated test and evaluation process, system operability can be well known before the aircraft enters a flight test program. The inlet and engine models have been validated with ground test data, usually steady state in nature. However, during flight testing, dynamic distortion will be present. This dynamic nature will become more pronounced as inlets are constructed to become more "stealthy". Validation of both inlet simulations and engine simulations is an issue as stated by Benek and Kraft in their 1998 journal article. Among the issues raised by Benek and Kraft were:

- The use of steady-state approximations to simulate time-averaged measurements of an intrinsically unsteady flowfield.
- No systematic studies of the details of the computational procedures for time-dependent inlet flow have been made. The unsteady features prevent the use of usual steady-state convergence criteria that are based upon the reduction of the residual norms toward machine zero.
- Time-accurate computations will be necessary for the simulation of unsteady (dynamic) distortion indices. Experiments must be carefully crafted from which to establish a validation database.
- CFD simulations are expensive in terms of computer resources and schedule and they must be used carefully to obtain the maximum benefit. A systematic study needs to be conducted to identify those parameters to which the simulations are most sensitive.

These issues must be addressed before a fully integrated test and evaluation process can be established.

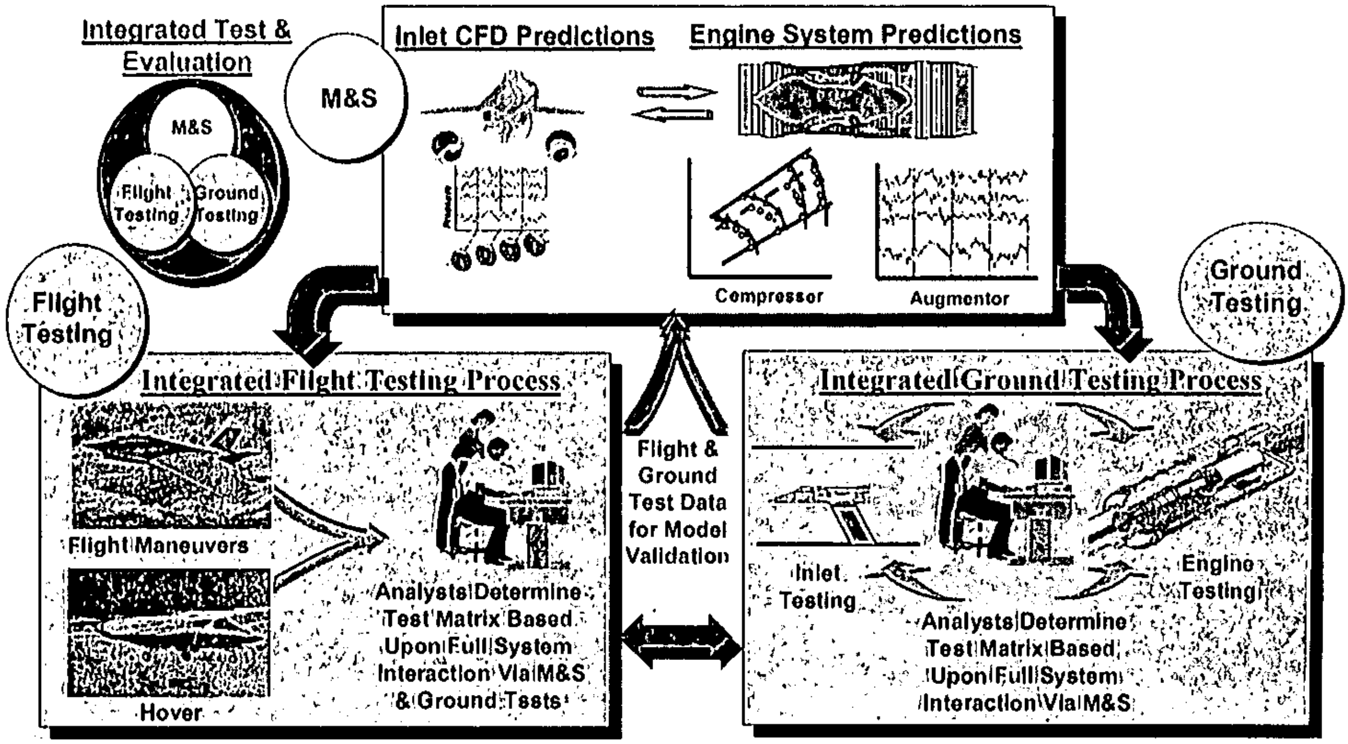

Fig. 15.—Schematic of Envisioned Integrated Test and Evaluation for Engine–Inlet Analysis

Summary

This paper has reviewed the state-of-the-art in inlet and engine testing procedures and has proposed an integrated test and evaluation process that provides additional information to the test customer at a reduced cost and schedule. That integrated test and evaluation process relies heavily on using computational simulations of both the inlet and the engine separately and in combination to provide guidance in the test process. Simulations can be used to reduce the test matrix to the absolute minimum required by providing calculations of areas not tested to a high degree of confidence. Finally, improved processes implementing advanced numerical simulations and advance test techniques are envisioned that will provide a test capability for inlets that allow modifications to the inlet during early wind tunnel tests. These inlet modifications will help ensure compatibility with the engine such that the performance of the combined inlet-engine system can be tuned to maximum system performance. Also, improved processes implementing advanced numerical simulations and advance test techniques are envisioned that will provide a test capability for engines that more accurately represent the static and dynamic conditions encountered in flight.

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