Engine/Inlet Compatibility Analysis Procedure

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New analysis and testing techniques have been developed during the past five years to identify and fix potential compatibility problems before flight. These techniques are described, and examples of compatibility data are given for a supersonic inlet and a turbofan engine. The engine/inlet interface is defined in terms of maximum time-variant distortion and time-averaged inlet pressure. Model inlet test data and engine component data are combined by dynamic simulation to audit compatibility and to identify components which need improvement. Compatibility audits also include the effects of control transients, component interactions, Reynolds number and engine-to-engine variations. Tests become more sophisticated as components become better developed. Engine testing with distortion simulated by simple inlet screens is replaced by more expensive but more realistic testing with an inlet simulator. Individual component testing evolves into dual-spool testing and engine testing. The final proof of compatibility requires combined inlet and engine testing. By this time, the data bank should contain sufficient knowledge to assist in quick identification and solution of any new problems.

Introduction

A SUBSTANTIAL portion of aircraft propulsion system development must be directed toward assuring engine/inlet compatibility, before first flight and at minimum cost. Compatibility in this instance means stable operation, both steady-state and transient, with the required levels of system performance when subjected to all destabilizing influences.

From an engine man's point of view, the most important destabilizing influence is the complex inlet flow conditions at the engine/inlet interface that are characterized by total pressure and total temperature variations in both space and time. These variations, illustrated for total pressure in Fig. 1, are classified under two general headings. First, time-variant distortion (Fig. 1a) includes both time-independent spatial variations (steady-state distortion) and time-dependent spatial variations (random turbulence). Second, variations which have no spatial dependence but do vary in time are denoted as in-phase oscillations (Fig. 1b).

Time-variant distortion lowers the surge line, while in-phase oscillations disturb the engine operating line. Both effects reduce engine stall margin. Other destabilizing influences which further reduce stall margin are engine transients, control tolerances, augmentor lightoff, low Reynold's number flight conditions, engine-to-engine variations, and engine deterioration. Sufficient positive stall margin must be designed into the engine to allow the superposition of all these effects in various magnitudes and combinations.

The choice of total pressure and temperature as the describing parameters for the inlet flowfield is partially dictated by the instrumentation available for ground and flight tests. The accuracy and reliability of total pressure and total temperature instrumentation are particularly attractive. Further, experience shows that total pressure and temperature can account for all interface effects that have been identified to date. Because temperature distortion is handled essentially in the same manner as pressure distortion, this article will consider only the effects of pressure distortion.

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Steps to Compatibility

Step I-Component Definition

Select distortion factors

At the onset of a propulsion system program, several preliminary goals are set. Over-all mission requirements are known at this early stage in terms of altitude, Mach number, and the general configuration (size, weight, etc.) of the aircraft. Optimization studies by engine and airframe contractors lead to definition of the engine cycle and component characteristics. For the purpose of this article, assume that the optimum engine cycle is a moderate bypass ratio, turbofan engine.

Characteristics of the compression system coupled with past experience lead to an initial parameter, called a distortion factor, that quantifies the effects of time variant distortion. Figure 2 describes such a parameter, known as "equivalent 180° square wave," $\Delta P/P\square$, which defines a simple pattern with the intensity adjusted to produce the same loss in stall margin as a more complex pattern.

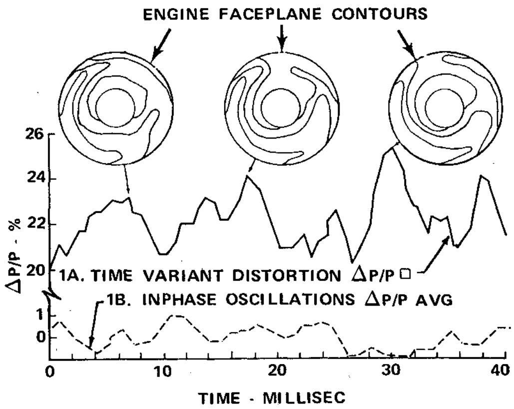


Fig. 1 Time variant distortion and in-phase oscillations define the inlet interface.

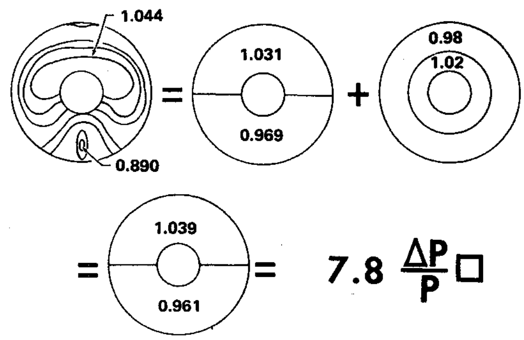


Fig. 2 Distortion factors show the relationship between inlet patterns and inlet stability. They also can relate complex patterns to equivalent simple patterns.

Early component testing

Component testing begins at the earliest possible date in a new program. The effects of distortion are evaluated in addition to the usual performance assessment. Early testing, performed with simple inlet screens, is used to: 1) assess the stability of the component, 2) track the disturbing influence throughout the component to identify weak subcomponents (e.g., stages in a compressor), 3) measure the attenuation or amplification of the disturbance as it progresses through the machine, and 4) measure any distortion generated by engine components.

As an example of such test results, Fig. 3 describes undistorted and distorted surge lines for a typical fan. Shown also is the fan operating line and the stall margins that result in each case.

The loss in stall margin (undistorted minus distorted) due to the destabilizing influence of the maldistributed inlet flow is plotted against distortion factors in Fig. 4 which shows that the distortion factor, $\Delta P/P\square$, gives a linear correlation of loss in stall margin due to distortion produced by circumferential and radial screens. A distortion factor which does not give a linear correlation should be modified to a linear factor to aid interpolation and limited extrapolation of component data.

Sensitivity to distortion

An important compressor characteristic is its sensitivity to distortion. Sensitivity is defined as the rate of loss of stall margin with distortion (i.e., the slope of Fig. 4). Both the sensitivity of a compressor and its undistorted stall margin are necessary to define stability.

Distortion attenuation

Attenuation or amplification of the inlet distortion, or generation of distortion within a compressor, affect the operating environment and stability of downstream components. Further, because there is a performance loss in each stage of the fan or compressor that experiences distortion, it is important to attenuate distortion in the first few stages so that later stages may be designed for high performance.

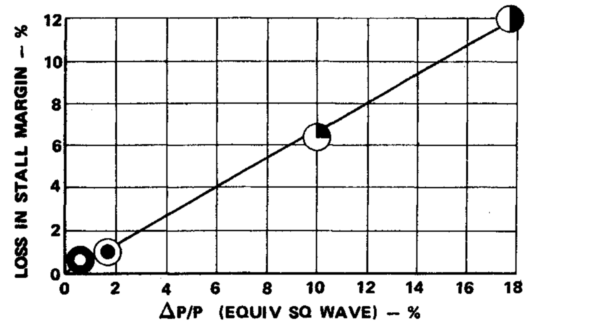


Fig. 4 Distortion factor verification—loss in stall margin caused by distortion correlates with distortion factor.

Figure 5 shows how screen-generated square wave distortion is changed as it proceeds through a fan rig with non-optimized geometry settings. Amplification of the distortion flowfield occurs at the root (12.2% $\Delta P/P$ inlet amplified to 19.8% $\Delta P/P$ outlet) while attenuation occurs at the tip. This change from amplification to attenuation is a result of the steepening work characteristics from root to tip (Ref. 1).

Several design changes may result from the component rig testing; for example, a rematching of the stage operating points (as described in Ref. 1) can improve the attenuating ability of early compressor stages. The amplification at the fan root noted on Fig. 5 was changed by adjusting variable geometry to attenuation across the full blade span, as shown in Fig. 6, (root 13.8% $\Delta P/P$ inlet attenuated to 12.0% outlet; tip 13.8% $\Delta P/P$ inlet attenuated to 1.2% outlet). This improvement was made by decreasing the incidence of the first rotor at constant flow, so that all work characteristics become steeper from root to tip.

Further testing of the improved fan shows (Fig. 7) that radial patterns produced by the fan are essentially the same irrespective of the inlet radial distortion; that is, inlet radial patterns are fully attenuated, but a discharge radial pattern is generated by the fan. A compressor downstream of this fan must be designed to accept this radial flow pattern in addition to the residual component of the inlet circumferential pattern.

Compression system diagnosis and improvement

The method for assessing the compressor components and evaluating design changes can be outlined as follows. The

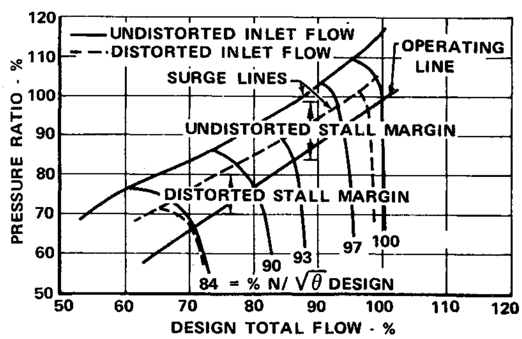


Fig. 3 Component testing establishes stall margin without inlet distortion and stall margin loss with distortion.

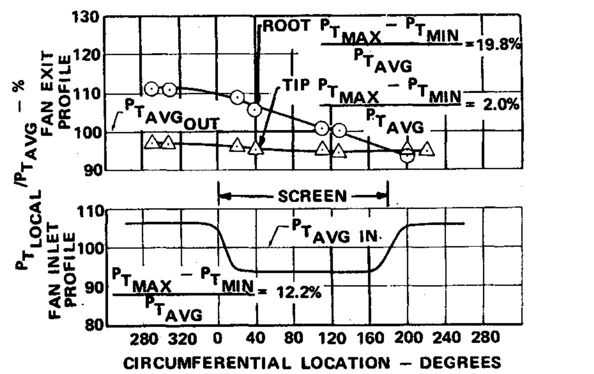


Fig. 5 Amplification before improvement—an example of distortion amplification at the root of a low hub/tip ratio fan before the geometry is improved.

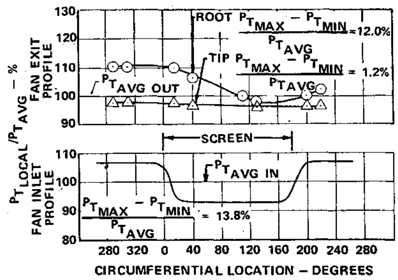


Fig. 6 Attenuation after improvement—adjustment of variable geometry attenuates across the full span.

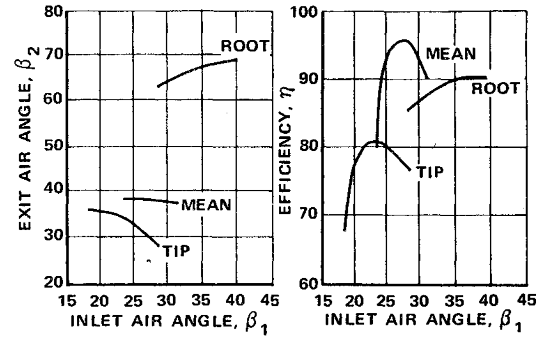


Fig. 8 Stage element characteristics.

test rigs are heavily instrumented; that is, stator leading edge instrumentation is employed at each stage. Circumferential and radial distribution of distorted flow requires that several stators (for example, eight equally spaced) be instrumented with up to six total pressure or temperature probes on each stator (located at centers of equal flow areas). High response wall static pressure probes are also employed at the interstage locations.

The data are edited and reduced, using a stage element technique, that yields radially distributed characteristic parameters that describe stage operation as shown in Fig. 8. Such test parameters are then compared with design values to locate where improvement is needed. Analysis techniques, correlated with test data, are then employed to suggest improvements for the next build of the component. Figure 9 shows good correlation of experimental data with analytically predicted performance, which builds confidence in the improvement predicted for a change in variable geometry.

Applicability of distortion factor

Early component tests are the first to show the ability of the chosen distortion factor to quantify the effects of the distorted flowfield on stability. Several tests also may be performed with representative complex screens to check out the distortion factor system. Changes in the form and formulation of this distortion factor may result. These changes, of course, are consistent with the definition of a distortion factor, for the form of the factor is not important. Its ability to account accurately for all destabilizing influences is its only measure of success.

Inlet testing

Model inlet tests, carried out by the airframe contractor, provide data for assessment of engine/inlet compatibility and propulsion system performance. Coordination between the engine and airframe contractors ensures that the instrumentation employed, data acquisition systems, and data handling techniques will give the required information. For example, it has become apparent that a sizable number of total pressure probes (a minimum of 40) with frequency response characteristics of 1000 Hz/model-scale (e.g., 6000 Hz for a $\frac{1}{6}$ scale model) are necessary to describe the flow conditions at the engine/inlet interface. Figure 10 demonstrates that rakes must be spaced sufficiently close to ensure an adequate flow field description. References 2 and 3 describe how transient phenomena are scaled in model tests resulting in instrumentation frequency response requirements described previously. Both analog and digital methods are useful for analyzing the mass of data resulting from tests with such instrumentation. Analog devices, such as those designed by the McDonnell Aircraft Company for use in inlet tests, are used for "on line" distortion factor displays and to screen data to find the points of highest distortion. Digital data reduction is used to analyze these high distortion points.

Use of early testing

Information obtained from early model inlet and engine components tests is used to redefine the intensity and distribution of the engine/inlet interface patterns for future component development testing. The effects of these distortion patterns on the stability of the individual components can be determined through compatibility audits, during which the stability of the propulsion system is obtained by superposition of the results of individual component tests. Also, a better formulation of the chosen distortion factor system may be obtained. The results of these tests are then sent back through the design and analysis system previously described. This iterative process of design-test-analysis-design results in components that are sufficiently mature for systems integration.

Step II Analytical System Integration

Dynamic simulations and their uses

Several types of dynamic simulations are used for compatibility analysis. The engine and control simulation

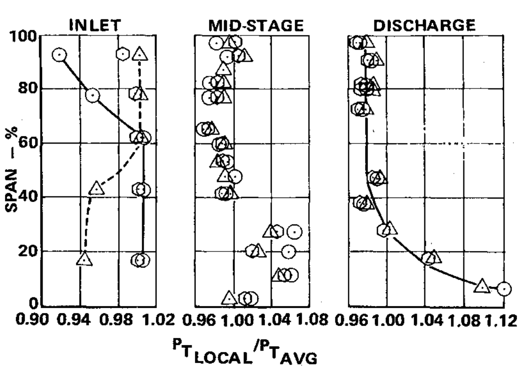


Fig. 7 Fan removes all radial inlet distortion—exit radial profiles are identical irrespective of inlet radial profiles.

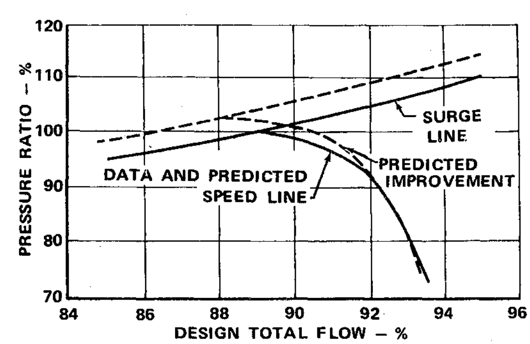


Fig. 9 Analytical tools are used to predict optimum geometry positions for surge line improvements.

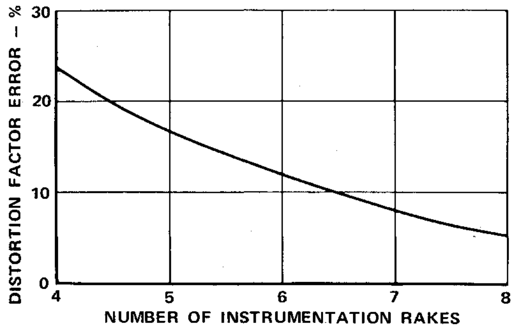


Fig. 10 Evaluation of distorted flowfields requires adequate instrumentation.

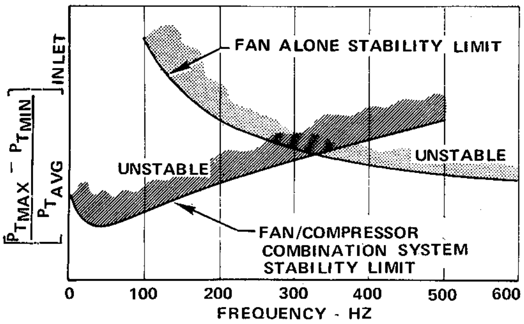


Fig. 12 Amplitude-frequency stability plot—effects of interaction change tolerance to in-phase oscillations.

represents the entire engine from the compressor through the nozzle with the interactions of all engine control systems (Ref. 4). This type of simulation is particularly suited for generating control schedules, studying engine transients, and evaluating methods of controlling around problems, such as control reset to accommodate gas ingestion disturbances caused by rocket firing.

The engine and control simulation is generally limited in frequency response to less than 10 Hz, which is adequate to describe engine/control transients. Subcomponents such as those in the compression system are known to respond to much higher frequencies. To study these effects, and to describe compression system operation in greater detail, a fan and compressor dynamic simulation has been found necessary (Ref. 5), which has an order of magnitude better frequency response than the engine and control simulation. This simulation is also known as a stage-by-stage dynamic model, since the characteristic subcomponents are normally the individual stages. Other simulations of interest include a fuel-control/fuel-system model and a combined engine/inlet/control model. The latter model is used to investigate interactions of all propulsion system components.

Engine and control simulations, constructed using the best component performance data available, are the only way of estimating component interactions in the early phase of the development program. They are invaluable in determining the effects of operating line shifts caused by engine transients and control tolerances and in describing the effects of in-phase oscillations in the lower frequency range (Fig. 11).

The fan and compressor simulation, on the other hand, can estimate the interactions between the several compressor components in the presence of perturbations. As an example, Fig. 12 illustrates a frequency-stability plot for a fan alone and a fan/compressor combination. As can be seen, the compressor generates the system instability at low disturbance frequencies and stabilizes the fan at higher frequencies.

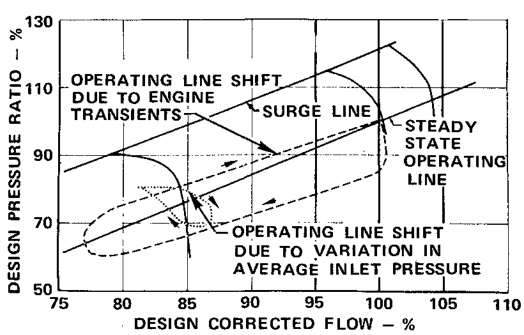


Fig. 11 Destabilizing transients—fan/compressor and engine/control digital dynamic simulations can describe transient operating point excursions early in a development program.

The importance of having several simulations available that can cover a large frequency spectrum is illustrated by the comparison of two different simulations in Fig. 13. The loss in stall margin given by the fan and compressor simulation is greater than the engine and control simulation for an inlet buzz type of excitation. This is because the fan and compressor simulation responds to higher frequencies which can cause stage interactions. The resulting shift in operating point for the compression system could become extremely important if combined with other effects that also degrade stall margin, such as an engine transient.

Analytical predictions of the effects of time-variant distortions can be made using a dynamic simulation in conjunction with a transient parallel compressor technique and the distortion factor system. An example showing good correlation between predictions and test data is shown in Fig. 14.

It should be clearly understood that the models can only relate back to the user the information put into them. It is essential, therefore, to review and update simulations as new data becomes available. Extrapolations should be made with caution and engineering judgment.

The rest of Step II efforts are associated with continued engine component and model inlet testing. Data from these tests, along with updated simulations, yield a better understanding of the propulsion system performance and compatibility. Compatibility improvements result from systematically revealing problem areas, investigating possible solutions, and performing necessary corrections to components and controls. Continual compatibility audits (Fig. 15 and Table 1) identify components which need improvement.

Step III Combined Component Testing

The combined component testing portion of engine development is extremely important in that it culminates all previous efforts. The best engine components have been developed within the limitations of performance, weight, and

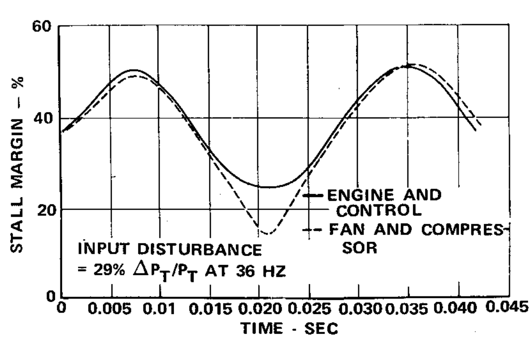


Fig. 13 Fan and compressor dynamic simulation has greater response to inlet oscillations.

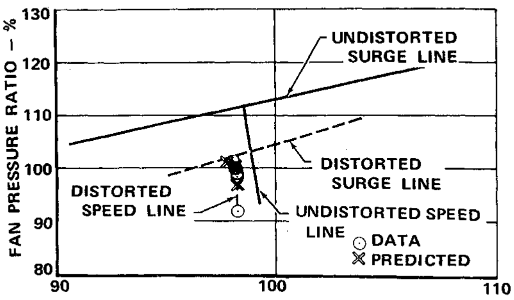


Fig. 14 Dynamic parallel compressor techniques predict distorted fan performance.

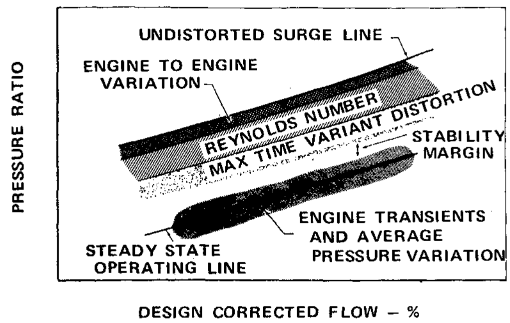


Fig. 15 Stall margin allocation.

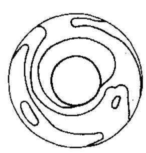
compatibility trades. A distortion factor system has been validated within the limits of the test program. Compatibility has been shown on the basis of individual component data which has been integrated into a propulsion system by dynamic simulation. However, the effects of component interactions on compatibility need to be tested.

Dual-spool testing

Combined fan and compressor (dual-spool) rigs are run to obtain overall compressor response to distortion for several reasons. First, interaction effects must be isolated and described, so that dynamic simulations may be checked and improved, if required. Second, amplification or attenuation of signals must be observed, and results used to improve the attenuation characteristics by geometry or control changes. Analytical simulation tools are beneficial in suggesting directions for these changes. Figure 16, for example, shows the maximum extent of one type of twin-spool interaction effect on stability limits as estimated by the parallel compressor theory. This theory shows that the compressor can stabilize the fan by inducing a static pressure gradient that reduces the loss in the fan stall margin due to inlet distortion. This gradient, however, also reduces the attenuation of inlet distortion by the fan, which in turn will reduce compressor stability. There is, therefore, a small potential trade between fan and compressor stability which can change the engine distortion tolerance within the shaded boundaries of Fig. 16. Other types of twin-spool effects are the effect of bypass ratio on fan stability with a close-coupled splitter; changes in fan discharge profile with fan operating point which affects compressor stability; unsteady flow from the fan or transition duct affecting compressor stability; twin spool dynamics during transients.

Table 1 Compatibility audits identify components which need improvement

MAXIMUM TIME VARIANT INLET PATTERN
$\Delta P/P\square$ = 25.4%



LOW SPOOL	
STALL MARGIN LOST DUE TO:	
CIRCUMFERENTIAL DISTORTION	39.0%
RADIAL DISTORTION	42.0%
ENGINE REMATCH	−8.5%
REYNOLDS NUMBER	0%
ENGINE TRANSIENTS	14.2%
IN-PHASE OSCILLATIONS	0%
TOTAL STALL MARGIN LOST	86.7%
REMAINING STALL MARGIN	13.3%
AT HIGH SPOOL INLET	
REMAINING RADIAL DISTORTION	0
REMAINING CIRCUMFERENTIAL DISTORTION	3.2% $\Delta P/P\square$
EQUIVALENT TEMPERATURE DISTORTION	0.3% $\Delta P/P\square$
HIGH SPOOL	
STALL MARGIN LOST DUE TO:	
PRESSURE AND TEMPERATURE DISTORTION	16.0%
ENGINE REMATCH	5.5%
REYNOLDS NUMBER	0%
ENGINE TRANSIENTS	25.0%
IN-PHASE OSCILLATIONS	10.0%
TOTAL STALL MARGIN LOST	56.5%
REMAINING STALL MARGIN	43.5%

Inlet simulation

To this point, time variant distortion has been measured on scale model inlets and simulated during rig testing by inlet screens, which are used to produce a steady-state distortion equal to the maximum time-variant distortion. In other words, the effect of turbulence has been taken into account by intensifying a steady-state pattern to produce the equivalent effect on engine stability. At this point, however, components are sufficiently developed to justify testing with time-variant distortions using a turbulence generator (turbulator) or inlet simulator. Both devices produce time-variant distortion by setting up a shock system. The difference is that a turbulence generator is designed to produce a given range of turbulence levels, whereas an inlet simulator is designed to set up the same type of shock system and flow passages as the inlet and thereby reproduce the environmental flowfield at the entrance to the engine in as realistic a manner as possible.

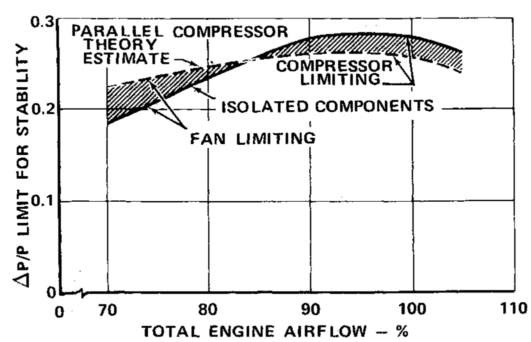


Fig. 16 Twin-spool interactions—parallel compressor theory estimate of twin-spool interaction effects on engine distortion tolerance limits.

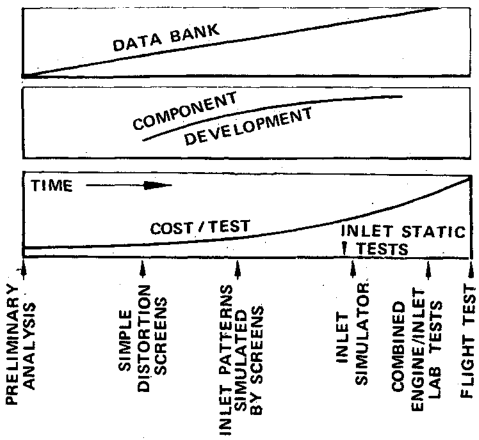


Fig. 17 Compatibility program summary—early testing is kept simple: sophisticated testing is cost effective only after components have been developed.

Inlet simulator testing is carried out on fan, dual-spool, and engine test rigs. The fan testing is used to verify the correspondence between time-variant distortion and its simulation by inlet screens. Dual-spool and engine testing describe the nonlinear superposition of surge line loss, flow loss, attenuation, and sensitivity for the individual components. Clearly, since nature is seldom linear, these effects must be investigated. It should also be noted that the simulations previously described do attempt to remove linearity restrictions by using nonlinear forms of the equations of motion.

Engine testing

Prior to or concurrent with the dual-spool tests, engines have been constructed using the best components available. The engines are run both with test-type control systems, which can be easily reprogramed to new control schedules, and with actual engine control systems. Distortion tests are carried out with simple screens, complex screens, and an inlet simulator. Throttle transients during inlet simulator testing combine the destabilizing effects of time variant distortion, ramps in average inlet pressure, and twin spool dynamics. Realistic engine/inlet interactions are obtained during these tests because the distance and volume relationships between the engine and inlet shock system are maintained.

Tests are run in a laboratory, such as those at Arnold Engineering and Development Center (AEDC) and the Naval Air Propulsion Test Center (NAPTC), so that information can be obtained at several points throughout the flight envelope. Particular regions of interest include test conditions representative of flight regimes and aircraft attitudes which produce the highest destabilizing influences.

These tests assess performance and compatibility, using instrumentation similar to that used in component tests. High response instrumentation is used at the engine inlet, selected interstage locations, and component interfaces. Sea level tests with "boiler plate" inlet hardware are also run, since this may be a high turbulence operating condition for inlets which are required to operate supersonically.

The information obtained is used to judge the adequacy of the stability prediction systems when applied to a fully integrated system and to locate any additional problem areas. Such problems should be correctable with small adjustments in control schedules, e.g., variable geometry schedules, bleed schedules, nozzle area adjustments and the like. A typical problem that has surfaced in several recent programs has been a coupling between the compressor and the augmentor in a turbofan engine. For example, pressure perturbations destabilizing both the fan and compressor were observed during sequential ignition of portions of an augmentor burner system. Additional instrumentation was incorporated which clearly showed the problem area. A dynamic simulation of the fuel system and augmentor was then used to isolate the problem component in the augmentor fuel system and to suggest corrections.

It is important to minimize internally generated destabilizing influences, such as augmentor zone transfer, to allow additional margin for unforeseen, externally-generated influences that may appear during flight.

Human Aspects of Compatibility

One point should be made that has been discussed only lightly up to now—the required coordination and cooperation between the airframe and engine contractors. A free exchange of requirements, ideas, and data are necessary for a successful program. Exchange of both steady state and dynamic computer simulations is useful. A responsive attitude by each to the other's suggestions and requests is beneficial. The compatibility teams at the two companies should become almost a single unit. Tradeoffs between what is asked and what can be given must be made, of course, but a full discussion between the parties always results in better and more useful information.

Summary

The procedure of analysis and testing discussed in previous paragraphs should lead to a compatible inlet/engine configuration before first flight. This procedure is summarized below.

Trades between stability, performance, and weight lead to a definition of the engine and component characteristics. Early component testing is carried out using simple distortion screens to simulate inlet distortion, because this type of testing is cheaper, provides the required data for component improvement, and allows distortion attenuation to be tracked through the engine.

Analytical tools are used to define component interactions, to identify potential integration problems before integrated component testing begins, and to define candidate solutions to problems.

As components become better developed, tests become more sophisticated. Testing with simple inlet screens is replaced by more expensive but more realistic testing with an inlet simulator. Individual component testing evolves into dual-spool testing and engine testing. This standard, cost-effective technique of using the simplest testing possible and developing components before carrying out complex tests is illustrated in Fig. 17.

Component and engine testing, together with dynamic modeling, should result in the first combined engine/inlet test in an altitude facility being a verification test rather than a test in which new problems are discovered. However, if problems do develop, the information obtained during component testing and the subsequent updated analytical tools form a data bank of experience which may be used to recognize and attack new problem areas.

These techniques of analysis and testing require the generation of large quantities of data and detailed analysis. While this is expensive, the success of an airplane is so closely tied to a compatible propulsion system that we cannot afford to do less than our best.

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Development of High-Response Data Analysis AIDS for Inlet-Engine Testing

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The paper describes two data analysis aids recently developed to provide easy interpretation of high-response inlet flowfield information. A light bulb display is utilized as an analog simulation of the engine compressor face. Bulbs, on a one-to-one basis with high-response pressure transducers, provide flow visualization of high-frequency (to 1000 Hz) pressure fluctuations. A second analog device instantaneously sums the inputs of a select number of compressor face probes. Its output signal is used as an index to establish the degree to which the compressor face pulsations are one dimensional. Data from a recently conducted inlet-engine test program are used to illustrate the operation of both devices.

Nomenclature

A_{BY} = bypass door flow area (in.^{2})
A_L = area of circle with diameter equal to that of the cowl lip (in.^{2})
f = frequency (Hz)
f_p = pulsator frequency (Hz)
M_O = tunnel Mach number
$N/\theta^{1/2}$ = engine corrected speed (% of maximum)
P_{T2} = compressor face total pressure (psia)
P_{TO} = tunnel total pressure (psia)
S_{IND} = summation index = R_{SN}/S_{RN} (see Appendix)
T_{TO} = tunnel total temperature (°F)
α = angle of attack (degrees)

1 Introduction

RECENT experience with supersonic aircraft has exposed several serious propulsion system problems. Specifically considered here are those concerning inlet/engine compatibility.

Compressor stall difficulties encountered during ground and flight testing of two recent aircraft systems have been reported upon by Rall.[1] Numerous other references exist. The source of these stall difficulties has been the quality of air presented to the engine. Because of these difficulties, many test data have been accumulated recently bearing on the condition of the air delivered by the inlet. The flow properties of the air are generally expressed in terms of distortion and turbulence characteristics. These two words are not always used uniformly, but the definitions used here are consistent with current instrumentation practices: "Distortion" is spatial nonuniformity in total pressure as measured by very slow response (e.g., manometer tube) instrumentation; and "turbulence" is transient activity of the compressor-face flow as measured by high-response (d.c. to 10,000 Hz) instrumentation. This may include the condition of distortion when the pattern is rapidly changing in time or pulsation when the spatial field moves in phase.

The degree to which the engine will withstand poor-quality air has also been the subject of investigation. Conclusions based on these diverse data have not always been unanimously accepted. This is readily attributed to the general lack of understanding concerning precisely how the engine is affected by the quality of air entering it. To date, theoretical foundations upon which to build this understanding are limited. Current understanding therefore rests largely on experimental data.

Thus, today, several distinctly different theories are advanced by separate investigators concerning compressor stall problems. At least three are readily identifiable; the major assertions of each are described below.

1) According to the first theory, the compressor is primarily sensitive to distortion patterns. This sensitivity extends to the case when these distortion patterns are changing rapidly in time. Thus, this theory asserts that turbulence, as defined here, is simply time-varying distortion.

2) A second theory for explaining the effect of nonsteady airflow on the operation of an engine has been suggested by a test that was run at AEDC, in which a J93 engine was operated behind a simulated inlet or "turbulator." From the results of this test, it was concluded that the reduction in surge margin of an engine can be correlated with the root-mean-square (rms) level of the time-varying component of the total pressure at the compressor face.

In this approach, based on a statistical theory, it is assumed that the most significant parameter of the nonsteady flow is

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