Distortion and Turbulence Interaction — A Method for Evaluating Engine Inlet Compatibility

E. A. VAN DEUSEN* AND V. R. MARDOC†
Pratt & Whitney Aircraft, East Hartford, Conn.

This paper discusses the method of evaluating supersonic-aircraft inlet steady-state pressure defects and random pressure fluctuations (turbulence) used for the purpose of establishing inlet engine compatibility for the TF30 engine. This technique has evolved from TF30/F-111 compatibility studies over the last several years and has resulted in a unique yet practical method of determining engine-inlet compatibility associated with applications of the TF30 series. A review is made of the development of a distortion factor for steady-state inlet pressure distortion, its basic inability to handle the dynamic pressure variations, the evaluation of this turbulence, and development of a technique to evaluate turbulence effect on engine stability margin.

Introduction

THE problem of maintaining compatible operation between inlet and engine is one that has been associated, to varying degrees of severity, with all jet aircraft. Incompatibility is most often characterized by the engine operation becoming unstable, resulting in the familiar stall. This is fundamental to the gas-turbine-propulsion system since the compressor can display an unstable flow characteristic associated most fundamentally with flow separation off the blade airfoil. Generally, the highest compressor efficiencies occur near the stall operating region as shown on the compressor map (Fig. 1). For performance reasons, it is desirable to operate the engine near its peak efficiency. Depending on the closeness of the engine operating line to the stall line, the compressor stability can be upset by distortion of the airflow delivered to the engine from the inlet system. This distortion can be described in varying terms like inlet distortion, flow distortion, velocity distortion, pressure distortion, all of which are trying to describe the same phenomenon; namely, a variation in the velocity of the airflow being delivered to the engine face. There are variations and refinements known as swirl, vorticity, separated flow, inlet buzz, etc., and one which has taken on much significance in recent years known as turbulence or turbulent flow. Turbulence can be best described as random pressure fluctuations, observed at a plane taken at the engine inlet. Turbulence takes on new significance as aircraft velocities increase since the turbulence associated with boundary-layer/normal shock interaction can become large enough to upset engine stability.

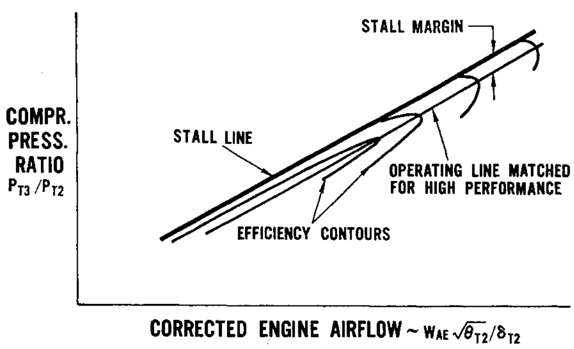

Fig. 1 Typical compressor map.

One might say that turbulence was discovered in the B-70 program and rediscovered in the F-111 program. Undoubtedly it has been present, but essentially undefined in other aircraft: the two mentioned above have pushed well beyond Mach 2.0 flight for normal operation. In the case of the F-111 aircraft, maneuvers and engine afterburning transients caused the inlet to operate off optimum and/or design point, resulting in supercritical operation (Fig. 2) which is characterized by increasing turbulent flow.

It is possible to encounter high turbulence in the normal operating region shown on Fig. 2 when, for example, an unbled boundary layer upsets a properly positioned normal shock at its attachment point. Also, in this mass-flow region, for both subsonic and supersonic-aircraft operation, separated flow in the inlet duct induced by a number of different variables can produce turbulence which may result in engine stalls.

Purpose and Background

The purpose of this paper will be to outline the development of a method to evaluate engine-inlet compatibility where turbulent flow is present. In this method, the steady-state pressure defects and random pressure fluctuations (turbulence) are treated individually, and was developed for the purpose of evaluating the stability of P&WA TF30 series of afterburning

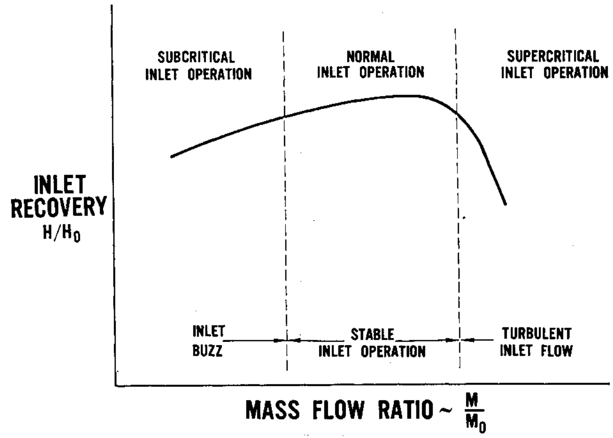

Fig. 2 Characteristics of supersonic-inlet operation.

Presented as Paper 76–632 at the AIAA 6th Propulsion Joint Specialist Conference, San Diego, Calif., June 15–19, 1970; submitted February 1, 1971; revision received June 24, 1971.

* Project Engineer, Current Engine Performance. Member AIAA.

† Assistant Project Engineer, Current Engine Performance. Member AIAA.

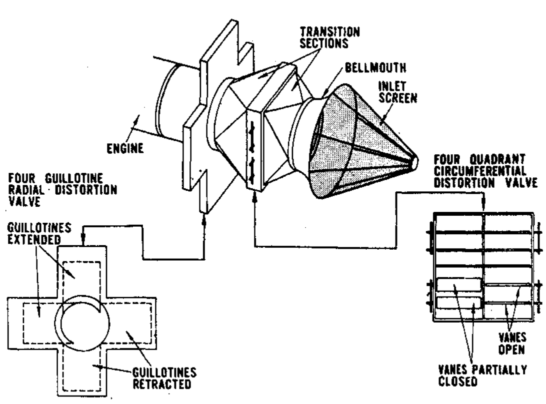

Fig. 3 Distortion tolerance development tools.

turbofan engines. Turbulence appeared as a recognizable prime variable at a time in the development of the TF30/F-111 propulsion system when significant steps were being taken toward solution of steady state compatibility problems. Theoretical and technical tools were not available to evaluate this phenomenon and, therefore, a pioneering empirical evaluation was undertaken to develop the tools of analysis. The result was a unique yet practical process of evaluating engine-inlet compatibility in the presence of turbulence applicable to installation of the TF30 engine series.

Steady-State Distortion Tests

Until a few years ago, it was considered sufficient to establish the stability limits of an engine by evaluating its tolerance to steady-state distortion. This was done in the classical manner on the TF30 engine. The test equipment for establishing steady-state distortion tolerance is shown in Fig. 3. The distortion valve develops classical distortions of flow by creating a pressure drop across two venetian blind type horizontal vanes in each of four quadrants of the distortion valve. This is done well upstream of the engine face and the defect carried to the engine face by means of longitudinal splitters. The vanes are motor controlled and can be set during engine operation to create desired distorted flow patterns (classical 90°, 180°, and 90° opposed quadrant circumferential distortions) (Fig. 4) and the low-pressure regions can be deepened in an attempt to stall the engine. The distortion valve also has OD trips which can be moved into the flowfield several inches to create OD pressure drop to simulate radial distortion profiles.

Blockage screens are useful to create or copy more specific inlet distortions, such as those derived from inlet wind-tunnel tests or full scale inlets (Fig. 5). In the development of the TF30, screens were used in the laboratory and also placed in front of the engines in the nacelle of a flying test-bed configuration.

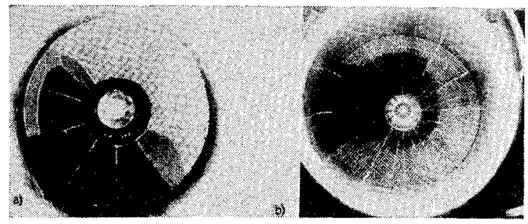

Fig. 5 Distortion tolerance development tools. Blockage screens: (a) Laboratory inlet distortion screen; (b) Flight test inlet distortion screen.

The distortion patterns created by the valve and screens were measured with 40–60 pressure probes at the compressor face. The pressures were read on U-tubes of low-response transducers with no attempt made to evaluate nonsteady pressures even though it was realized that some degree of unsteady flow was being created by these test devices.

Steady-State Distortion Analysis

The measured pressures were then evaluated in terms of distortion factors to define the maximum amount of distortion the engine could tolerate. These distortion factors become useful as guides to improving the engine distortion tolerance in the course of development, as a tool to evaluate whether or not the engine and inlet would be compatible (prior to flight), to evaluate inlet improvements derived from inlet model and full-scale tests and, to extend the compatibility analysis to other parts of the flight envelope not yet flight tested.

Prior to and into the early phases of the F-111 flight-test program the TF30 distortion tolerance was measured using the classical $\Delta P/Pt2$ i.e., $(Pt2 \text{ avg} - Pt2 \text{ min})/Pt2 \text{ avg} \times 100$, % and also some variations of the $Kd1$ distortion factor established for the $J57$ and $J75$ turbo-jet engines. The $Kd1$ factor incorporated the $\Delta P/Pt2$ mentioned above combined with a measure of the circumferential extent of the pressure defect. This factor did not correlate well for the TF30 engine nor had it for other fan-type engines. Therefore, in the course of the first several months of flight, testing an improved distortion factor shown on Fig. 6 was developed based on engine stalls in the F-111 aircraft behind the real inlet using low-response instrumentation (40 probes, 5 probes on eight radial rakes at 45° intervals at engine face) to measure the pressures at the compressor face.

Fundamental to this new factor was an observation that pressure defects toward the ID were more prone to cause stall than the same magnitude of defect at the OD. This distortion factor, $Kd2$, therefore, recognized spanwise distribution and provided those involved in the F-111/TF30 flight-test program with a much improved tool, capable within certain accuracies

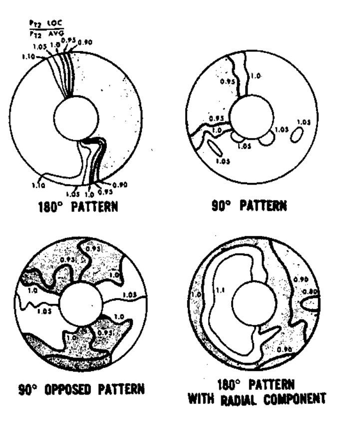

Fig. 4 Classical distortion valve pressure patterns

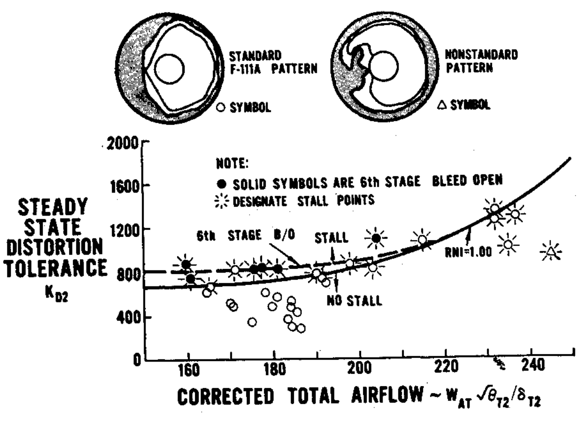

Fig. 6 TF30 distortion factor development.

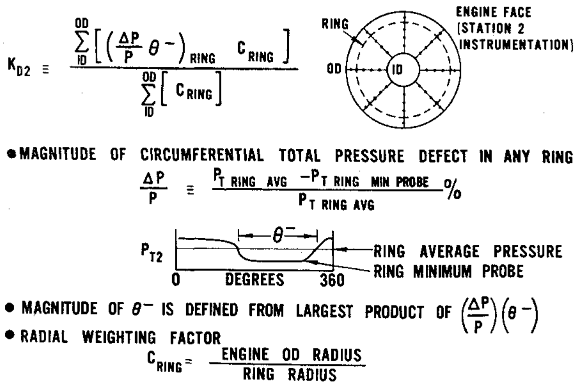

Fig. 7 Elements of empirical steady-state distortion correlation factor for TF30 engine with F-111 inlet.

of evaluating the effect that inlet and engine improvements would have on compatibility on the entire propulsion system (namely, inlet and engine as an operating unit). The flight-test stall points used to develop this factor were mainly steady engine and steady aircraft nonmaneuver conditions, which were typical F-111 type distorted patterns as shown in the figure. Nontypical patterns did not correlate well as may be seen by the triangular symbol at high airflow, and depicted on the figure as circumferential distortion with smaller circumferential extent i.e., 90° approximately.

*Kd*2 Steady-State Distortion Factor

The elements of *Kd*2 are shown in Fig. 7. For each of the five rings of data the pressure defect in terms of a $\Delta P/Pt2$ is multiplied by a Θ^- representing the arc in degrees which subtends the pressures below average and then further multiplied by the radial-weighting factor which emphasized the defects at the ID.

Inlet Turbulence "Discovered"

The F-111 flight-test program entered a new phase with inlet revisions and a more distortion tolerant low-compressor available for the TF30 engine. The improved compressor was incorporated into flight-test engines and a tolerance to distortion was predicted based on laboratory tests as shown in the band on Fig. 8. As the flight program progressed, it was noted that stalls occurred at *Kd*2 levels generally less than predicted, as may be observed from the recorded steady-state distortion at stall. However, telemetered inlet pressures and ground reduced "quick look" oscillograph traces were showing a build up of inlet pressure fluctuations coincident with an audible noise build up at high *Mn*.

It was not obvious that the *Kd*2 factor should not correlate for this portion of the flight-test program. Instead, it was suspected that the inlet "noise" was contributing to engine stalls and should be evaluated as a prime variable. Toward this end, the flight-test magnetic tapes of compressor face pressures were analyzed to evaluate the effect of noise on engine stability limit.

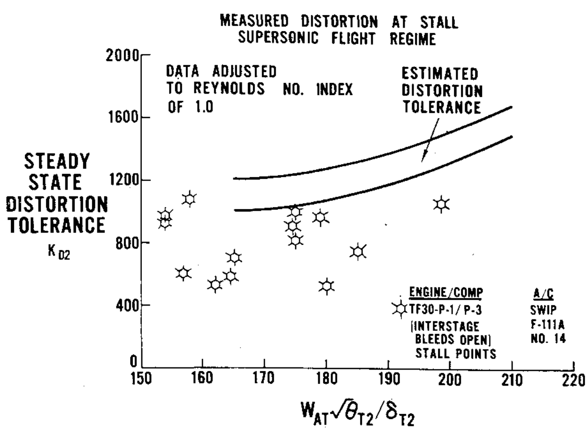

Fig. 8 F-111 flight-test results.

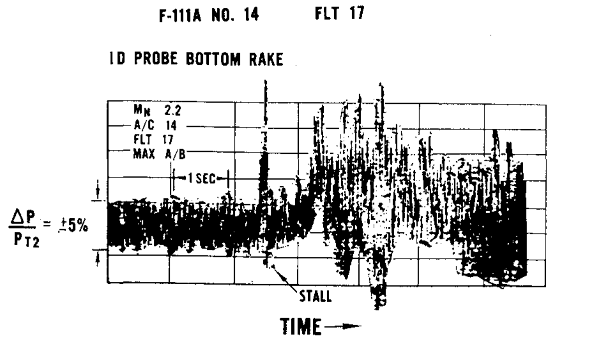

Fig. 9 Visicorder trace of fluctuating inlet pressure, *Pt*2.

Evaluation of Flight Turbulence

The inlet pressure information on the flight tapes was processed in two specific ways. First, as shown on Fig. 9, expanded visicorder traces were made of selected inlet pressures preceding and during engine stalls to establish within system response limits a better understanding of the turbulent pressure phenomenon. The figure shows a typical result indicating a fluctuating pressure of approximately +5% leading up to a single stall followed by engine recovery for about 1 sec and then by series of engine stalls. The steep pressure rise off the scales indicate the surge event as the compression process breaks down and the hammer shock appears from a downstream direction at the engine face. All stall events analyzed showed the typical characteristic build up of fluctuating pressure prior to the engine stall.

Second, the pressure signals from the tapes were submitted to a classical spectral analysis as shown on Fig. 11. This shows a curve of normalized power spectral density with normalized power, $(\Delta Prms/Pt2)^2/B$ plotted vs frequency. Turbulence is defined on Fig. 10 as a percent variation of the root-mean-square (RMS) of the time variant pressure normalized to the total pressure, *Pt*2. As indicated, it is equivalent to the square root of the area under the PSD curve. The

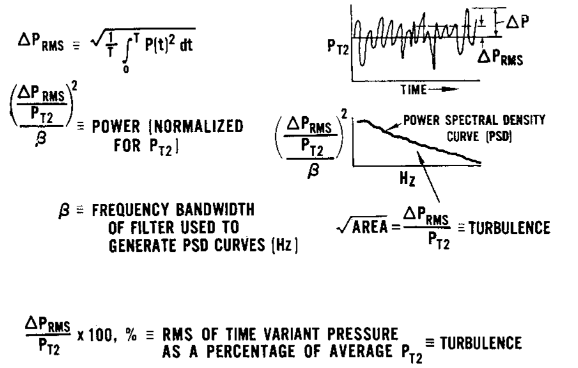

Fig. 10 Turbulence nomenclature.

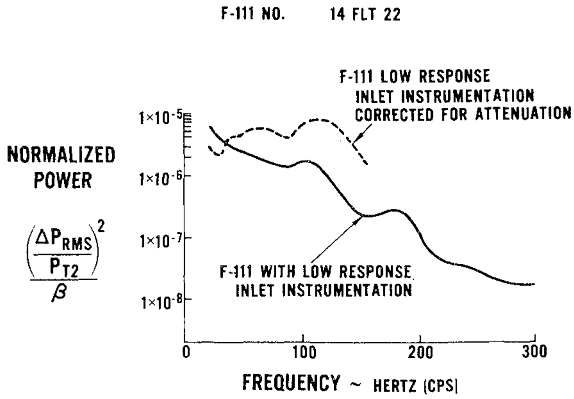

Fig. 11 Spectral analysis corrected for attenuation.

turbulence could then be evaluated to any desired frequency to establish the amount of turbulent energy.

Development of a Flight-Test Correlation

It was strongly suspected that this turbulent energy was reducing the steady state *Kd*2 distortion tolerance of the engine and the next step was to determine if a correlation did in fact exist. It was decided to use two ID probes. One was chosen at top-dead center (TDC) and another at bottom-dead center (BDC). The ID probe was chosen since the frequency response of the transducer recording system was greatest on the inner probes (0-145 Hz approximately).

The turbulent energy was evaluated to 150 Hz on the premise that turbulent pressure fluctuations were creating a "quasi-steady-state" distortion of increased severity which, if it existed for 1/150th of a second (about one engine revolution) would be recognized by the compressor. The power spectral densities (PSD) were adjusted for attenuation of the signal due to 86″ of tube length to the transducer (Fig. 11).

The above assumptions having been made, a correlation was attempted and is shown on Fig. 12. It may be observed that the correlation indicated that the steady-state distortion tolerance, *Kd*2, of the flight-test engines generally appeared to reduce as a function of the increase in turbulent energy. The data point shown at the upper left was based on laboratory tests of the same type of compressor system as flight tested. It was plotted at zero turbulence since, at this time, the turbulence of the distortion valve had not been evaluated and was considered to be low. The "F-111 estimated" data point was the prediction for the new compressor system shown on an earlier curve (Fig. 8). The arrow indicates a lack of knowledge of the turbulence for this predicted *Kd*2 value but would in fact have the turbulence of initial F-111 flight tests. Both of these data points can now be adjusted, as shown, on the curve. The fact that the analysis did result in a correlation, confirmed that there was a valid concern for the deterioration effect of turbulent energy on the steady-state distortion tolerance of the TF30 compressor system.

In this time period, the report of Kimzey and Lewis based on tests of a J93 at Arnold Engineering Development Center became available to the authors and the similarity of results was observed.[1] Their analysis resulted in a correlation which showed a loss in stall margin with the increase of turbulence. There is a general interrelation between stall margin and distortion tolerance.

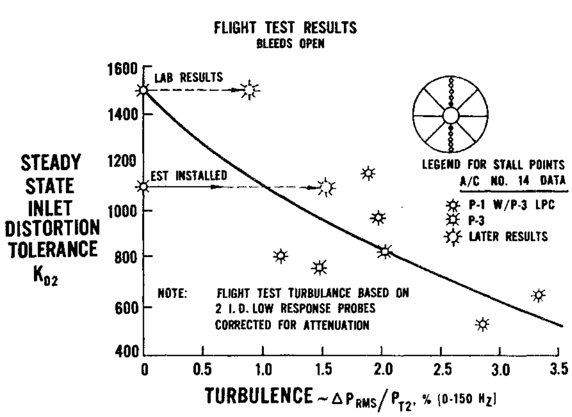

Fig. 12 Effect of turbulence on steady-state *Kd*2.

Turbulence Tests in the Laboratory

On the bases of these findings, it was decided that testing should continue in the laboratory using high-response instrumentation and a turbulence generating device similar to that employed at AEDC.

Laboratory Tests

Figure 13 is a sectional view of the turbulence generator constructed for laboratory tests at P&WA. The purpose of this device is to produce random pressure fluctuations or turbulence as caused by shock boundary-layer interaction. Engine airflow is accelerated over the variable geometry plug to obtain a normal shock downstream of the throat section. The shock strength is controlled by the airflow, throat area and pressure ratio across the shock. The plug has the flexibility of being able to translate both fore and aft as well as laterally so as to provide some control over the turbulence strength and distribution.

The instrumentation used to record the total pressure distortion and turbulence generated at the inlet face consists of eight total pressure rakes with five high-response piezoelectric type (Kistler) transducers per rake located at the center of equal area. The high-response Kistler probe was used to measure the AC portion of the pressure signal while the DC signal was recorded with a standard transducer which obtained its pressure signal from a pressure tap adjacent to the Kistler probe.

Kd/Turbulence Interaction

Testing in the P&WA laboratory with the turbulence generator confirmed the preliminary conclusions of the flight-test experience in the fact that the turbulence phenomenon caused a marked reduction in the TF30 engine stall margin. An empirically derived relationship was developed with the same data reduction techniques used to analyze the flight-test data.

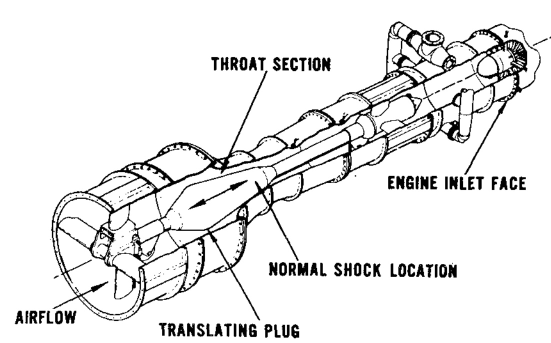

Fig. 13 Turbulence generator.

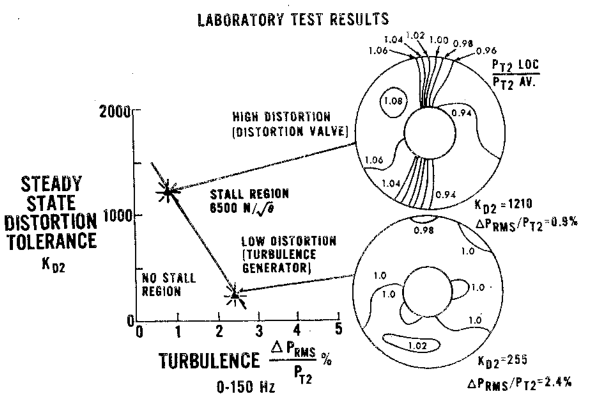

Fig. 14 Distortion and Turbulence interaction.

Figure 14 shows the basic empirical relationship that was developed, which relates the steady-state distortion tolerance ($Kd2$) to the measured turbulence ($\Delta Prms/Pt2$). It was shown that with engine distortion-tolerance tests behind the turbulence generator, the TF30 engine could be made to stall with relatively high levels of steady-state inlet distortion and minimal levels of turbulence and conversely, stall could be induced with relatively low levels of steady-state inlet distortion but rather high levels of measured turbulence. Any combination of steady-state distortion and turbulence above the correlation line could be in the engine stall region. The absolute level of engine distortion tolerance was found to vary as a function of engine corrected speed or corrected airflow; however, the interaction of distortion tolerance and turbulence appeared to be the same for all engine speeds.

Figure 15 shows the unique comparison of engine distortion tolerance and turbulence interaction as determined in laboratory tests on TF30 engines. A comparison is also made with flight-test data on P-1 and P-3 engines. The flight-test data was obtained from relatively low-response inlet total pressure probes corrected for attenuation due to 86″ of pneumatic line length. Since the absolute levels of distortion are different for each of the engine versions and engine speeds, the relationship presented as a delta $Kd2$ loss in distortion tolerance as a function of turbulence level $\Delta Prms/Pt2$.

Although this relationship was derived from strictly empirical means, it does provide a valuable analytical tool. Its significance is that it is no longer reasonable to measure only steady-state levels of inlet generated pressure distortion to determine inlet-engine compatibility, but the requirement now is to use high-response inlet instrumentation to determine the contribution of turbulence to the loss in engine stall margin.

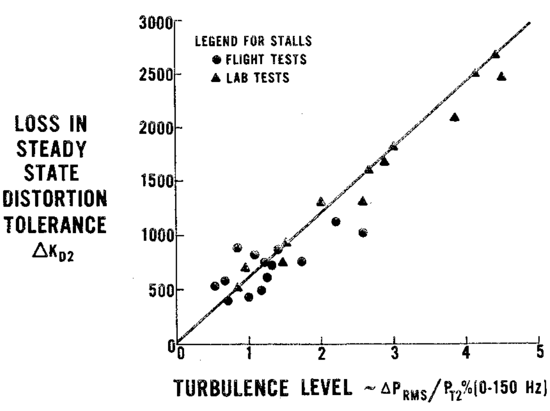

Fig. 15 TF30 engine distortion-turbulence interaction.

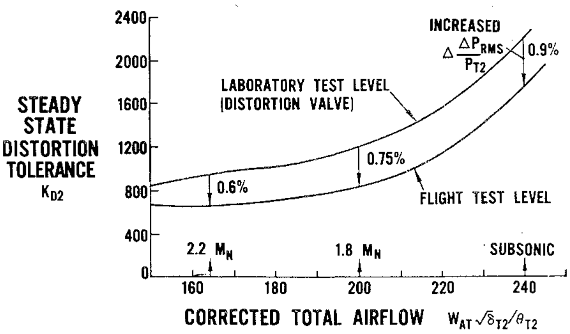

Fig. 16 Estimated effect of flight-test turbulence.

Effect of Inlet Turbulence on Distortion Tolerance

The relationship of the steady state distortion tolerance of a TF30 engine plotted against corrected total engine airflow for a RNI of 1.0 is shown in Fig. 16. This is the level and shape that would be measured in a laboratory test behind a distortion valve. When this or an equivalent engine is flight tested, a similar relationship is developed; however, the flight-test level was usually found to be from 200–300 $Kd2$ lower in absolute level than the laboratory level. The production engine specification estimate was based upon this lower level of distortion tolerance derived from flight-test experience. This apparent difference was explained from the fact that the distortion valve will generate one level of turbulence while a specific inlet can generate another level of turbulence.

Knowing the interaction between $Kd2$ and turbulence allows the determination of this difference in turbulence level. The difference was found to vary in the F-111 from 0.9% $\Delta Prms/Pt2$ for subsonic-aircraft operation to 0.6% for supersonic operation. A measurement of the absolute level of turbulence generated by the distortion valve will then provide an estimate of the turbulence generated by the inlet.

Figure 17 is a plot of the percent turbulence measured behind a distortion valve as a function of engine total airflow. The levels of turbulence measured were obtained from an average of six high-response probes located at the engine inlet face. A frequency range of from 0 to 150 Hz was used to determine the turbulence level. A distortion tolerance calibration of an engine behind a distortion valve will be subjected to this level of turbulence in addition to the steady state distortion created by the distortion valve. The implied level of turbulence built into the engine specification could be determined from this fundamental relationship.

From the engine manufacturer's viewpoint, this relationship was very significant, since the aircraft-inlet designers could now be provided with the steady-state limit of inlet

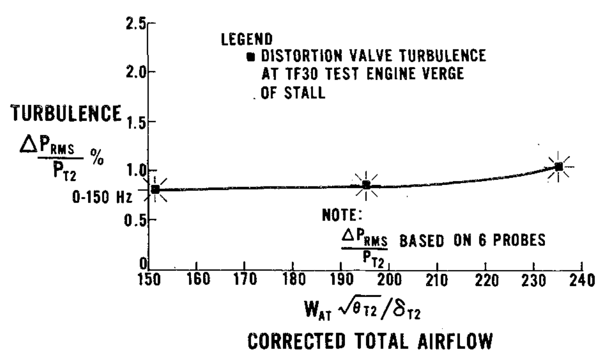

Fig. 17 Estimated distortion valve turbulence.

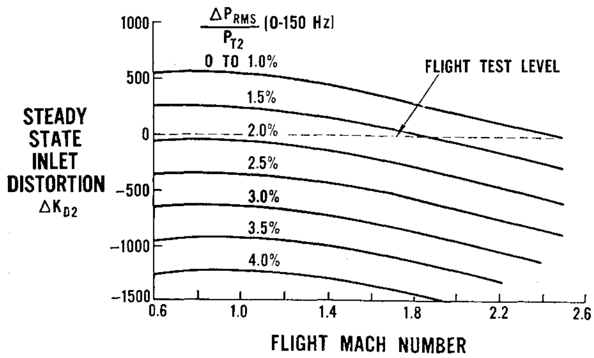

Fig. 18 Estimated effect of inlet turbulence on distortion.

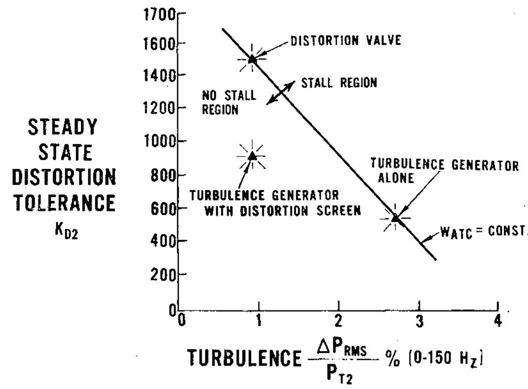

Fig. 19 Distortion and turbulence interaction.

distortion at which the engine would stall as well as the impact turbulence had on this relationship. Figure 18 shows the type of trade-off curve between turbulence and steady-state distortion which was developed to provide a limit for engine-inlet compatibility. The amount of inlet distortion tolerance ($\Delta Kd2$) that can be added to or subtracted from the nominal level of $Kd2$ can be obtained as a function of flight Mn for various levels of inlet turbulence.

Evaluation of Turbulence

Turbulence effects have been intensely studied since these early developments by the Air Force Aero Propulsion Lab, AEDC, NASA, Navy and industry and several alternative approaches have been investigated in the process. Some advanced propulsion systems are evaluating turbulence with the time variant distortion method which is perhaps the fundamental concept. This concept is based on the premise that the stall is actually caused by an instantaneous distortion of a certain minimum time duration and has been validated in several papers.[2,3]

The TF30 $Kd2$/turbulence technique approaches this method in a statistical manner and because of the back log of engine-inlet data has evolved as a valuable analytical tool.

Areas of Additional Investigation

The system of using measured turbulence to reduce the steady-state distortion tolerance of the TF30 type engine is a practical and useful tool for establishing inlet-engine compatibility. However, as with any new approach to attacking an engineering problem, a number of areas of additional investigation are apparent. A few of these areas are discussed here to indicate the work that is presently being accomplished to solve these problems.

Combining the Turbulence Generator with a Distortion Screen

In developing the engine stability limits for a newly developed TF30 series engine, in terms of a specific level of turbulence and steady-state distortion that would best simulate an inlet, it was found desirable to combine the turbulence generator with a distortion screen. One outcome of this test is shown in Fig. 19. It can be seen that the steady-state distortion and turbulence levels measured from the combined effect of the turbulence generator with a distortion screen were below the limits predicted from using a distortion valve alone or using a turbulence generator alone as the tools for this evaluation.

One conclusion drawn from these results was that the combination of a distortion screen and turbulence generator as a laboratory simulation of a real inlet was creating engine inlet disturbances which were reducing engine stability and which the $Kd2$ and turbulence technique did not adequately evaluate. It was found that there existed at least two basic reasons for this lack of correlation: 1) the radial distribution of turbulence was different when the turbulence generator was used in combination with the distortion screen and 2) the power-spectral-density characteristic exhibited a much flatter shape when measured behind a distortion screen.

Effect of Turbulence Distribution

The $Kd2$ turbulence correlation described is based upon the area weighted average turbulence over the inlet face. Figure 20 shows a comparison of the ring average turbulence distribution across the inlet face from ID to OD created by the turbulence generator alone compared to the turbulence generator in combination with a distortion screen. It can be seen that significantly more turbulence is generated near the engine hub when the distortion screen is used. Upon further investigation, it was found that the distortion screen had the characteristic of attenuating low-frequency pressure pulses. This suggests that various turbulence weighting factors be tried to correlate the distribution of turbulence over the inlet face. Turbulence factors that have weighed the engine hub more heavily, as does $Kd2$, have been the most successful; however, a completely satisfying weighting factor for turbulence distribution has not been determined to date.

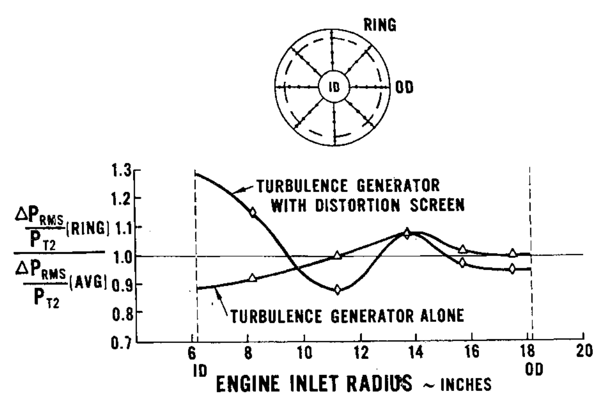

Fig. 20 Radial distribution of turbulence.

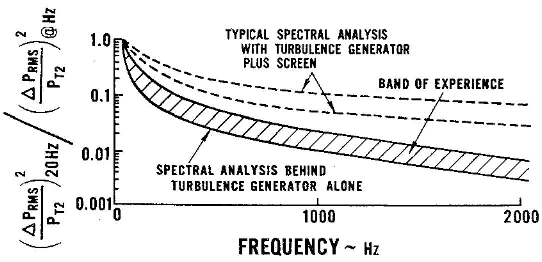

Fig. 21 Comparison of spectral analysis.

Effect of Power-Spectral-Density Characteristic

In examining the characteristic of power spectral density curves it is apparent that the shape of the *PSD* curve and the frequency range over which it is evaluated needs to be accounted for. Figure 21 shows a normalized *PSD* curve which represents the range of power-spectral-density curve characteristic obtained in using the turbulence generator alone. Also shown is the typical characteristic of a *PSD* curve obtained from the combination of turbulence generator plus screen.

This latter shape is much flatter than that observed from the turbulence generator alone. The flatter shape indicates that significant levels of the pressure energy exist at the higher frequencies; therefore, in the *Kd*2/turbulence method the turbulence may need to be evaluated to higher frequencies in order to obtain a correlation that will satisfy the possible variations in *PSD* characteristics. It is apparent that the *Kd*/turbulence method will require refinements to correlate turbulence spatial distribution and variations in the *PSD* characteristic shape.

Summary

The steady-state distortion factor was used satisfactorily for many years in establishing the distortion tolerance of jet engines, while the effect of turbulence was unsuspected. When turbulence was defined as a prime variable in the F-111 program, the *Kd*2/turbulence method of determining the stability margin of the TF30 turbofan engine evolved naturally from the index of steady-state inlet distortion tolerance.

In this paper, we have discussed the development of a technique to evaluate the effect that the turbulent energy, produced by an inlet system, will have on engine stability. The high *Mns* (>2.0 *Mn*) of the more modern aircraft in being and those envisioned is elevating turbulence to the forefront as a prime variable associated with engine-inlet compatibility. In the example of the TF30, the steady-state distortion tolerance was found to vary inversely as a function of turbulent energy, delta *P*rms/*Pt*2 from 0–150 Hz. Application of this technique in a simulated inlet environment has resulted in the necessity for refinements to handle variations in the PSD characteristic shape and/or turbulence spacial distribution.

Conclusions

1) Analysis of laboratory and flight-test data has shown that turbulence as well as steady-state-inlet distortion is a prime variable in the evaluation of engine-inlet compatibility. 2) There are several techniques for evaluating the effects of turbulence. The *Kd*2/turbulence interaction method has been applied to the TF30 engine and found to be a good engineering tool. 3) The variables of *Kd*2 and turbulence are used as guides to improve engine stability margin in the course of development, in evaluating inlet improvements from model and full-scale tests, and as a measure of engine-inlet compatibility. 4) In the laboratory environment, it is possible to introduce turbulence characteristics which result in the requirement for some refinement to the *Kd*2/turbulence correlation.

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