



# AEROSPACE INFORMATION REPORT

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## An Assessment of Planar Waves

### RATIONALE

This document contains information that is fundamental to the discipline of inlet-engine compatibility and is expected to remain stable for the foreseeable future.

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## FOREWORD

As applications for turbine engines have become more sophisticated and the operating conditions more severe, inlet planar time-variant full-face total-pressure variations, usually accompanied by spatial total pressure distortion, can become a significant destabilizing factor. The SAE S-16 Turbine Engine Inlet Flow Distortion Committee has recognized the need for guidelines and procedures that would address inlet planar waves and the desirability of documentation similar to SAE documents ARP1420 and AIR1419 that were written for inlet spatial total-pressure distortion.

This Aerospace Information Report (AIR) brings together information and ideas that are required to address the planar wave problem. A common industry practice has yet to be established.

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## 1. SCOPE

"An Assessment of Planar Waves" provides background on some of the history of planar waves, which are time-dependent variations of inlet recovery, as well as establishing a hierarchy for categorizing various types of planar waves. It further identifies approaches for establishing compression-component and engine sensitivities to planar waves, and methods for accounting for the destabilizing effects of planar waves. This document contains an extensive list and categorization (see Appendix A) of references to aid both the newcomer and the practitioner on this subject.

The committee acknowledges that this document addresses only the impact of planar waves on compression-component stability and does not address the impact of planar waves on augments rumble, engine structural issues, and/or pilot discomfort.

## 2. REFERENCES

The references for this document encompass SAE publications, papers and reports to support the material in the body of the report, and papers and reports that were reviewed and may be sources for added insight for the interested reader.

### 2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

#### 2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), [www.sae.org](http://www.sae.org).

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## 2.4 List of Nomenclature and Symbols

TABLE 1

| SYMBOL            | TITLE                                                                                   | UNITS                  |
|-------------------|-----------------------------------------------------------------------------------------|------------------------|
| AMP               | One Half of Peak-to-Peak Planar Wave Pressure Fluctuation                               | psi                    |
| Ao/Ac             | Inlet Mass Flow Ratio                                                                   | -                      |
| AIP               | Aerodynamic Interface Plane                                                             | -                      |
| C                 | Offset Coefficient                                                                      | -                      |
| CR                | Empirically Determined Factor Used to Relate $\Delta PRS_{PEAK}$ and $\Delta PRS_{RMS}$ | -                      |
| ECS               | Environmental Control System                                                            | -                      |
| G                 | Gain                                                                                    | -                      |
| Hz                | Frequency in Cycles per Second                                                          | sec <sup>-1</sup>      |
| IDC               | Inlet Distortion, Circumferential                                                       | -                      |
| IDCMX             | Inlet Distortion, Circumferential Maximum                                               | -                      |
| IDR               | Inlet Distortion, Radial                                                                | -                      |
| IDRH              | Inlet Distortion, Radial at Fan Hub                                                     | -                      |
| IDRT              | Inlet Distortion, Radial at Fan Tip                                                     | -                      |
| Kp(f)             | Sensitivity of Compression Component to Planar Waves ( $\Delta PRS/(\Delta P/PIGV)$ )   | -                      |
| M                 | Mach number                                                                             | -                      |
| NLR               | Low Pressure Rotor Corrected Speed $N/\sqrt{\theta}$                                    | rpm                    |
| (PAV)i            | Ring i Average Total Pressure                                                           | psi                    |
| (PAVLOW)i         | Circumferential Distortion Intensity Element for Ring i                                 | psi                    |
| PFAV              | Average Total Pressure at Fan Inlet                                                     | psi                    |
| Pi (t)            | Time-Varying Total Pressure at the i-th of N probes                                     | psi                    |
| PIGV              | Total Pressure at Engine/Inlet Guide Vanes                                              | psi                    |
| $\hat{P}(t)$      | Time-varying Spatial-Average Total Pressure at the AIP                                  | psi                    |
| P-P               | Peak-to-Peak Pressure Differential                                                      | psi                    |
| PT0               | Free-Stream Total Pressure                                                              | psi                    |
| PT1/PT0           | Total Pressure Recovery at Measurement Plane                                            | -                      |
| $\Delta P$        | Incremental Pressure                                                                    | psi                    |
| PSD               | Power Spectral Density $(PT0)^2/Hz$                                                     | (psi) <sup>2</sup> /Hz |
| $(\Delta PC/P)_i$ | Circumferential Distortion Intensity Element, Ring i                                    | -                      |
| $(\Delta PR/P)_i$ | Radial Distortion Intensity Element, Ring i                                             | -                      |
| $\Delta PRS$      | Loss of Stability Pressure Ratio                                                        | -                      |
| S                 | Sensitivity, $\Delta PRS/(\Delta P/PIGV)$                                               | -                      |
| W1R               | Corrected Airflow at the Engine Face $W_1\sqrt{\theta/\delta}$                          | lb/s                   |
| $\alpha$          | Angle of Attack                                                                         | deg                    |
| $\beta$           | Angle of Sideslip                                                                       | deg                    |
| $\delta$          | Ratio of pressure to standard reference pressure                                        | -                      |
| $\Phi$            | Phase change from input to output                                                       | deg                    |
| $\psi$            | Angle of Yaw                                                                            | deg                    |
| $\eta_r$          | Inlet total pressure recovery                                                           | -                      |
| $\eta(t)$         | Time variant total pressure recovery at AIP                                             | -                      |
| $\theta$          | Ratio of temperature to standard reference temperature                                  | -                      |
| $(\theta)_i$      | Circumferential Distortion Extent Element, Ring i                                       | deg                    |
| $\Phi(f)$         | Power Spectral Density Function                                                         | (psi) <sup>2</sup> /Hz |

### 3. SUMMARY

The subject of planar total-pressure waves has been reviewed to determine the feasibility of developing a consensus methodology that can account for the effect of planar waves on inlet/engine compatibility.

The review includes a problem assessment, a discussion of possible approaches to methodology definition, a description of testing requirements, conclusions, recommendations, and the results of a document review of planar wave material.

The problem assessment showed that planar waves have occurred at propulsion system operating conditions within normal flight envelopes during a number of aircraft development programs. Planar waves generally occur at low mass flow ratio and become more severe with increasing Mach number and decreasing airflow. Other sources, both internal and external, also can generate planar waves.

Planar waves often occur in combination with spatial total pressure distortion. The peak destabilizing event may not correspond to either a peak planar excursion or a peak spatial distortion. Because of the complex nature of the combined disturbance problem and the practice of exercising avoidance procedures, no well-developed consensus method exists for treatment of the combined planar wave/spatial distortion problem. This report defines an approach that is useful in methodology development.

A potential approach to methodology development is discussed which includes the following four key elements: (1) categorization of inlet planar waves, (2) determination of engine response to planar waves, (3) planar wave analysis methods, and (4) combined spatial total-pressure distortion and planar waves, including stability margin accounting. Elements of methodology validation are discussed in Appendix C.

Inlet and compression system component testing will be required to apply the proposed methodology to a specific system. Inlet testing is used to define the planar wave component at the AIP and compression system testing defines the response of the compression components to planar waves.

An assessment of the available data and published information from a document review identified some recent data that define the physical characteristics of planar waves. Several publications describe planar wave test techniques and compression system analytical models.

This report recommends that a well-planned analytical and experimental program be conducted to explore the sensitivities of turbine engines to planar waves in combination with various spatial distortion patterns.

### 4. INTRODUCTION

The information contained in this report represents the results from an effort to determine the feasibility of establishing and recommending a consensus methodology for identifying and assessing the effect of planar total-pressure waves on inlet/engine compatibility. It is intended to provide complementary guidance to the material provided for steady-state total-pressure distortion in References 2.1.1.1 and 2.1.1.2.

This effort was undertaken because it has been determined by engine tests and simulations that engine stability margin loss may occur due to one-dimensional, unsteady total-pressure fluctuations at the compressor face. These fluctuations are hereinafter referred to as planar waves and occur as in-phase total pressure oscillations. Reported sources of planar waves include both inlet-generated and externally-generated disturbances. The inlet-generated disturbances include separation, shock/boundary layer interaction, supersonic flight buzz/unstart, interaction with adjacent inlet/engines, instability during subsonic flight at low mass flow ratio, and supersonic inlet response to inlet control system inputs. Externally-generated total-pressure oscillations include vortex ingestion and ingestion of wakes from nose gear and/or bomb bay doors. Other external disturbances such as atmospheric gusts and explosions produce planar pressure ramps that are not oscillatory in nature. Explosions and armament firings have temperature ramps and/or spatial distortions associated with them. This document does not address either planar pressure ramps or temperature ramp/distortion effects. For an assessment of inlet/engine temperature ramp and distortion effects, the reader is referred to Reference 2.1.1.3.

Current recommended practices for handling engine inlet flow distortion do not account for the effects of planar waves on engine stability. Guidelines for handling planar waves and planar waves in combination with spatial total-pressure distortions are needed for inlet/engine systems.

This report assesses the planar wave problem through case histories and a discussion of combined spatial pressure distortion and planar pressure waves. It reviews techniques for categorizing inlet planar waves, reviews techniques for predicting engine response characteristics, presents an analysis methodology, and discusses the application of the methodology to combined planar waves and spatial pressure distortion. Validation of the methodology and testing requirements are also discussed. Finally, conclusions and recommendations are presented. Results of a review of documents related to planar waves are included in Appendix A.

The terms stability limit line, stability margin, and the loss of stability pressure ratio are used in this report to define impacts on the stability of a compression component. These terms are intended to represent, as appropriate or applicable, surge, stall, rotating stall, or other stability limits.

## 5. PROBLEM ASSESSMENT

In a number of aircraft development programs, planar waves have been detected by high-response pressure measurements at the aerodynamic interface plane (AIP). The planar waves have occurred at flight and propulsion system operational conditions within normal envelopes, i.e., their occurrence is not restricted to extreme corners of the flight or maneuver envelopes. Tests and computer simulations of compressors and engines with planar waves have indicated that engine stability can be adversely affected by these waves, depending on the frequency and amplitude of the disturbance.

Trends in aircraft design that may impact planar wave generation include:

- Increased use of internal bays for weapons carriage and the need to have full envelope weapons capability, resulting in increased risk of wake ingestion when they are open.
- Aircraft post-stall maneuvering capabilities, which could lead to conflicts between flow dynamic boundaries and aircraft maneuvering requirements not previously encountered in traditional designs.
- Active control of the engine stability margin for performance optimization. This reduces available stability margin in parts of the flight envelope, compared to prior stability margin design criteria.
- Minimizing the inlet/engine airflow for "supersonic lock-up" to improve aircraft deceleration characteristics from high Mach number conditions.
- Low observables features in the air induction system.

With these items increasing the probability of encountering inlet planar waves, there is reason to believe that future designs are at increased risk. Therefore, it was considered necessary to determine whether a methodology could be established to predict the effect of planar waves on stability margin, in order to ensure continued inlet/engine compatibility.

To assess the planar wave problem, case histories where planar waves occurred were examined and the problems of analyzing combined planar waves and spatial total pressure distortion were investigated. The results from these studies are presented in Sections 5.1 and 5.2.

## 5.1 Case History Studies

Two recent case histories were selected as examples of situations in which planar waves have occurred. These cases illustrate some of the causes of planar waves, provide examples of instrumentation used to detect and measure planar waves, and indicate the extent of configuration and operational changes accomplished to eliminate or reduce the magnitude of the planar wave problem.

### 5.1.1 System "A"

During the wind tunnel and flight test development program of System "A," several sources of planar waves were encountered. These sources included: (1) inlet duct resonance at low engine power settings and therefore low mass flow ratios, (2) Environmental Control System (ECS) precooler duct resonance and (3) nose gear wake ingestion. Details of these data are presented in Reference 2.2.1.

#### 5.1.1.1 Inlet Duct Resonance

It was found that one source of low mass flow ratio planar waves is local flow separation and re-attachment along the vertical ramp surface forward of the cowl during leeward sideslip as shown in Figure 1. This separation is due to a highly adverse pressure gradient forward of the cowl lip station interacting with the boundary layer along the forward ramp surface. As leeward sideslip increases, the flow expands around the ramp leading edge, and then decelerates rapidly to the inlet station. Local ramp pressures decrease near the leading edge which allow boundary layer thickness to increase prior to entering the high-pressure-gradient region. The process is similar, although at much lower amplitudes, to buzz at supersonic speeds caused by shock wave and boundary layer interactions. Horizontal ramp inlets experience this phenomenon at low or negative angles of attack; vertical ramp inlets experience this phenomenon at leeward sideslip.

Representative wind tunnel and flight test distortion characteristics measured at Mach 0.85 are presented in Figure 2. Power spectral densities identify the presence of discrete frequency components with a fundamental frequency of 60 Hz (0.2-scale; 12 Hz full scale). This frequency corresponds well with open-closed end organ pipe theory, calculated as

$$f = c/[4(L+X)]$$

where:

c = speed of sound

f = first fundamental frequency of the duct

L = duct length from cowl lip to the reflection plane represented by the engine

X = organ pipe end correction (sometimes set to 1.4 x effective diameter of duct)

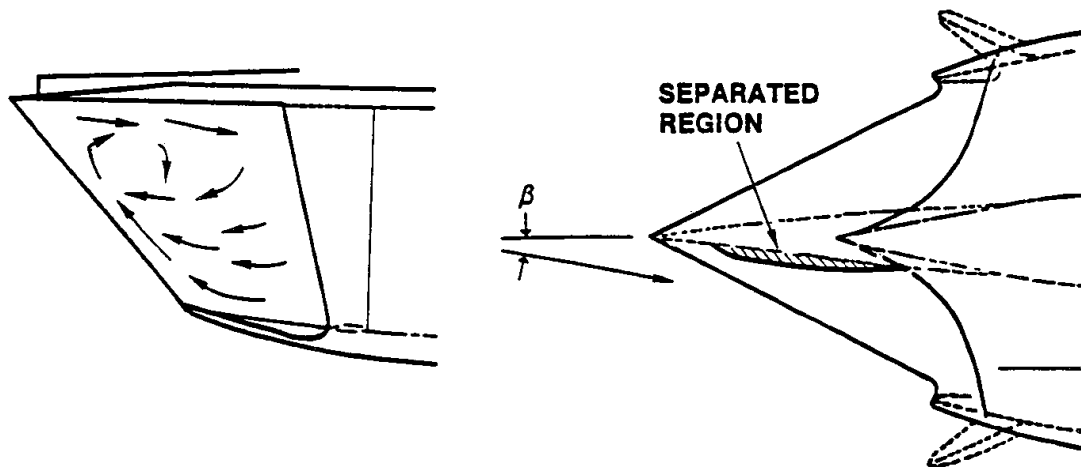


FIGURE 1 - LOCAL FLOW SEPARATION ON INLET RAMP DURING OFF DESIGN OPERATION AT LOW AIRFLOW

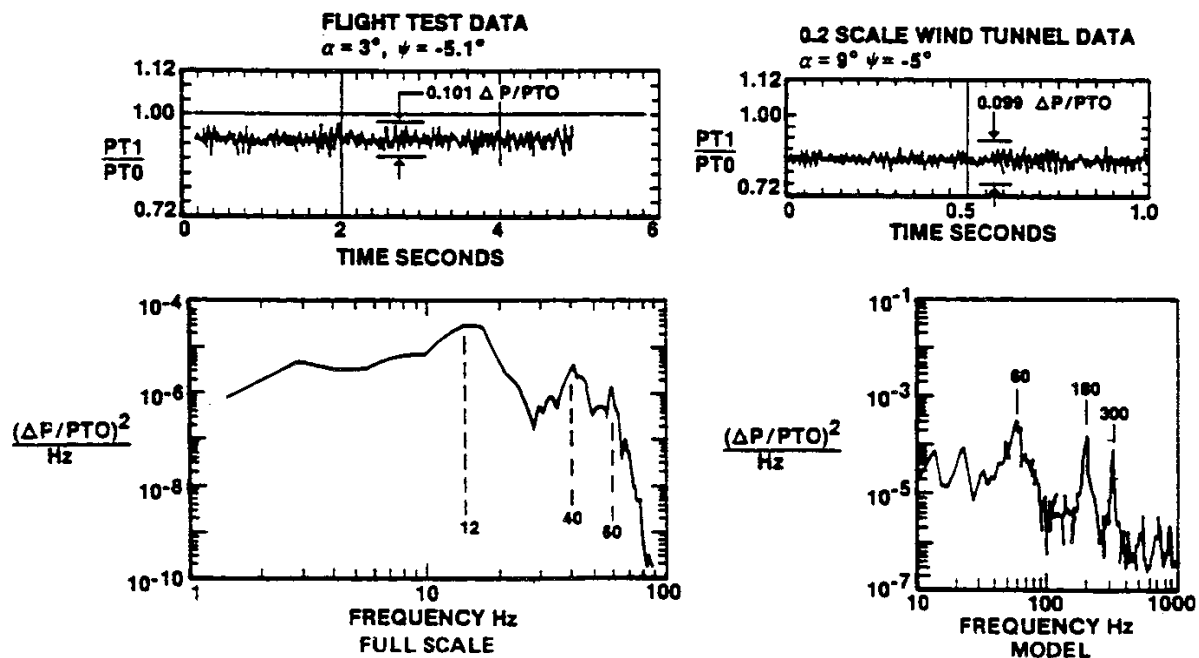


FIGURE 2 - WIND TUNNEL/FLIGHT TEST COMPARISON OF PLANAR WAVES, MACH 0.85

Magnitudes of the planar waves are strong functions of geometry, corrected airflow, attitude and Mach number. Examples of some of these factors are shown in Figure 3. The planar wave effect increases with increased Mach number and decreased flow. The peak-to-peak amplitudes of the planar waves can become quite large (e.g., 16 to 20% of mean total pressure). Representative total-pressure spatial-distortion characteristics are presented in Figure 4 as specific distortion indices. Circumferential distortion is the predominant spatial component, although both components increase almost proportionately with corrected airflow. Flight test results generally confirm wind tunnel results.

There were no discernible effects on stability due to the planar waves. A manually operated idle speed lock-up feature was incorporated to increase the minimum airflow and thereby reduce the amplitude of the planar wave.

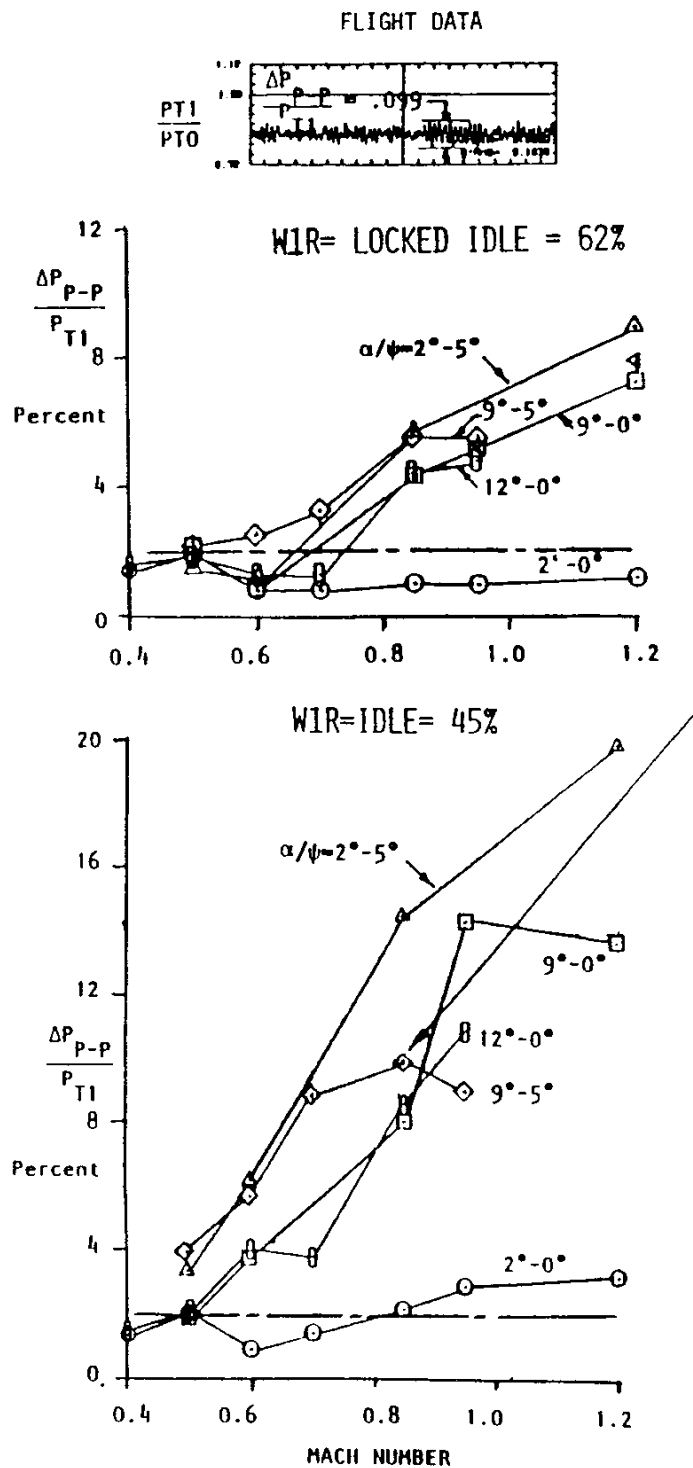


FIGURE 3 - PLANAR WAVE AMPLITUDE

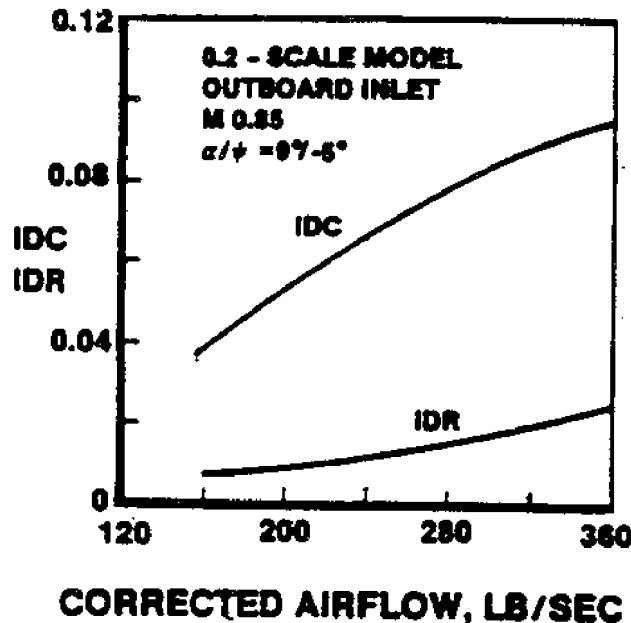


FIGURE 4 - SPATIAL DISTORTION CHARACTERISTICS

#### 5.1.1.2 Inlet Precooler Resonance

Auxiliary air inlets were also found to be a source of internally generated disturbances. A scoop installed on the ramp side of each inlet to precool ECS bleed air (Figure 5) acted as a resonator (open-closed organ pipe). The resulting pressure disturbance propagated to the AIP. High-response pressure transducers located just upstream of the flapper door in the aircraft identified duct resonance at frequencies corresponding to an open-closed organ pipe. During static operation at maximum engine airflow, power spectral densities (Figure 6) identified a fundamental frequency at 77 Hz (full-scale) as well as the presence of several harmonics. RMS amplitudes were approximately 2.4 psi. Because of the design of the original ECS air scoop, resonance could lead to structural damage. The flapper door was redesigned to eliminate the problem.

#### 5.1.1.3 Nose Gear Wake Ingestion

Nose gear wake ingestion was found to be a source of externally generated disturbances. System "A" flight test investigations showed that the nose gear produced planar waves (Figure 7). Peak-to-peak amplitudes of the engine-face average total pressure were approximately seven percent of the mean total pressure. The fundamental frequency was 18 Hz (full-scale) at Mach 0.40 increasing to 28 Hz at Mach 0.60. A three-position cowl lip was incorporated into the System "A" design which makes it possible to place the lip in a position that minimizes the effect of the landing gear wake ingestion. In this position, the disturbances caused no discernable impact on engine stability.

#### 5.1.2 System "B"

During the flight test program of System "B" aircraft, planar waves were recorded at a number of flight conditions (Figure 8) when the engine was operating at idle and below idle airflows during engine airstarts. These planar waves had a peak-to-peak pressure fluctuation amplitude of as much as 20% and occurred at a frequency of 11 Hz at sub-idle airflow. A data trace showing typical planar waveforms from the high-response data as well as a data trace showing the pressure fluctuations measured without the presence of planar waves are presented in Figure 9.

An analysis of the engine and inlet operating conditions at the times the planar waves occurred (Figure 10) shows that the planar waves occurred at idle and below idle airflows. Also presented in Figure 10 are the conditions where planar waves occurred as a function of inlet mass flow ratio, illustrating again the low airflow conditions under which the planar waves have occurred. The data show that these planar waves occur at low mass flow ratio and become more severe with increasing Mach number and decreasing airflow.

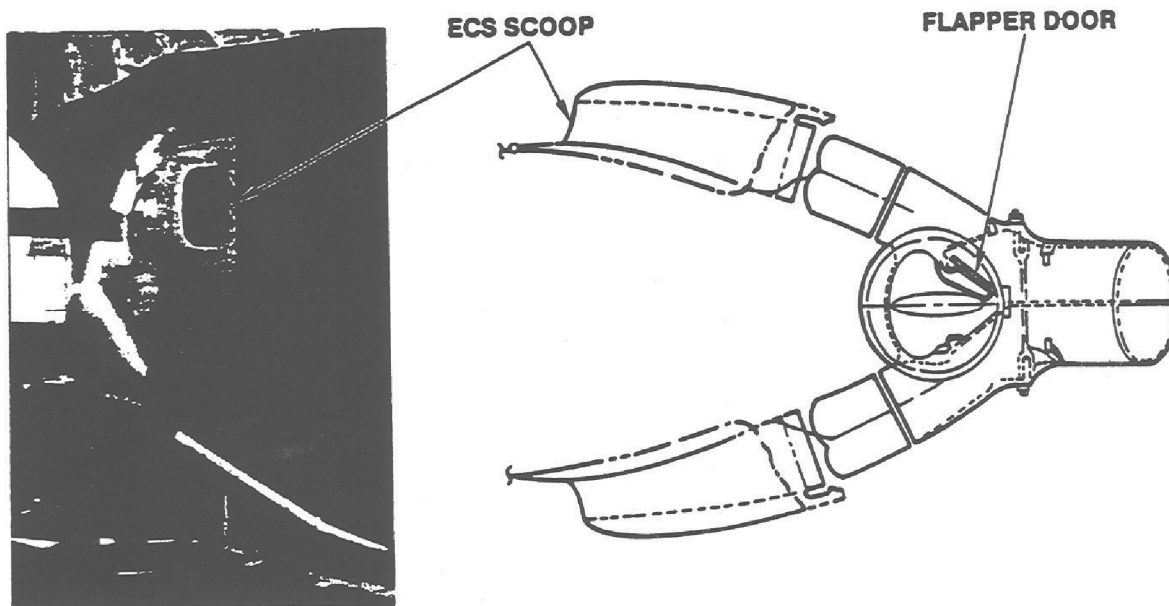


FIGURE 5 - ECS PRECOOLER ASSEMBLY

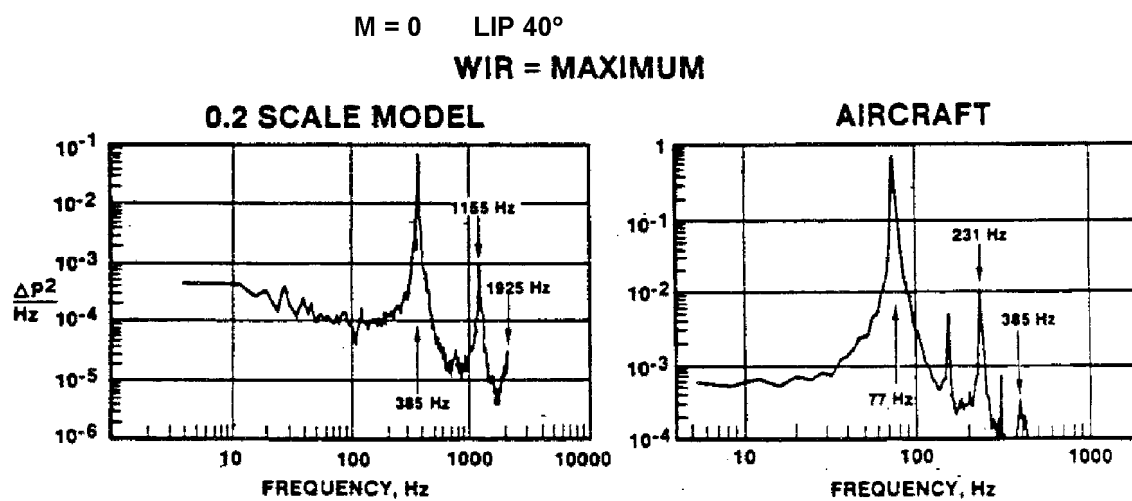


FIGURE 6 - RESONANCE CHARACTERISTICS IN ECS SCOOP INLET

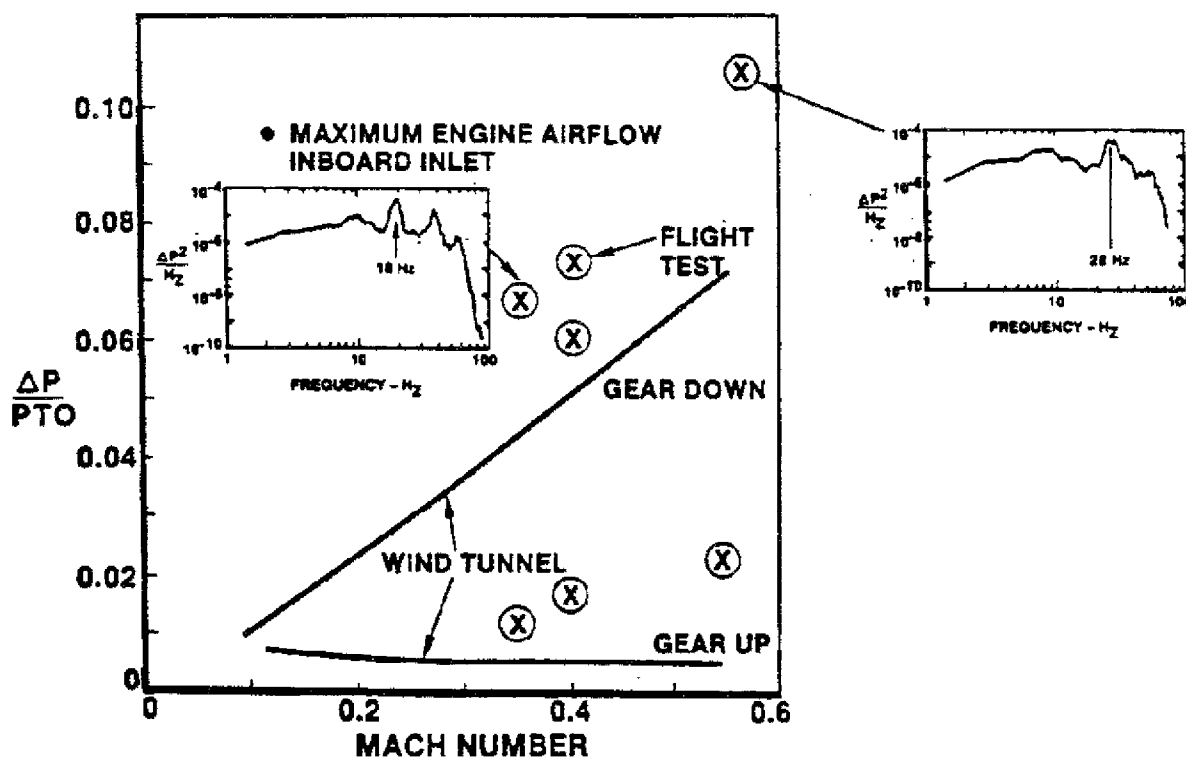


FIGURE 7 - EFFECT OF GEAR WAKE INGESTION ON PLANAR WAVES

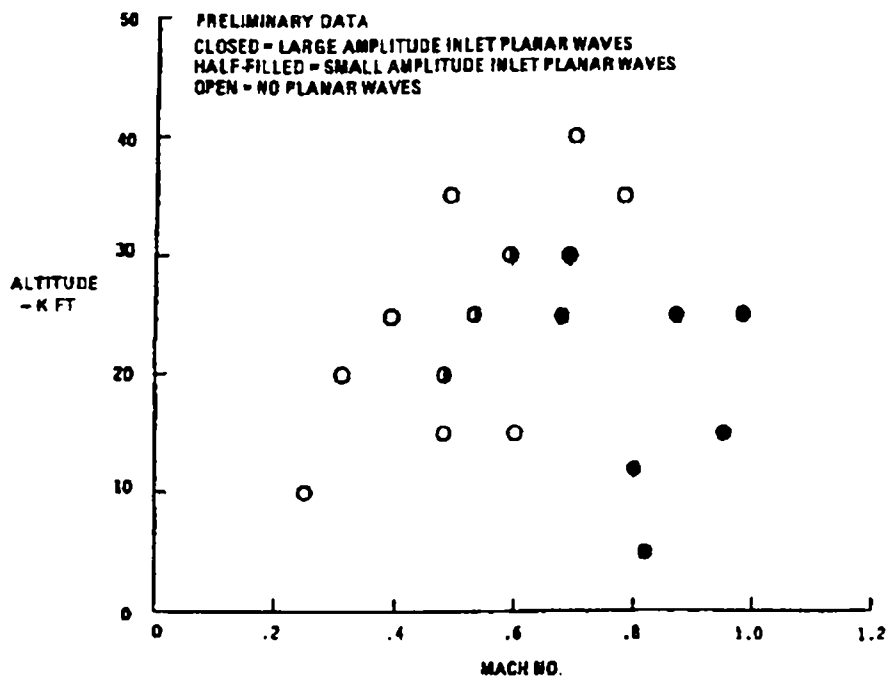


FIGURE 8 - COMPRESSOR INLET PLANAR WAVE EXPERIENCE AS A FUNCTION OF FLIGHT PROFILE FOR IDLE AND BELOW IDLE AIRFLOWS

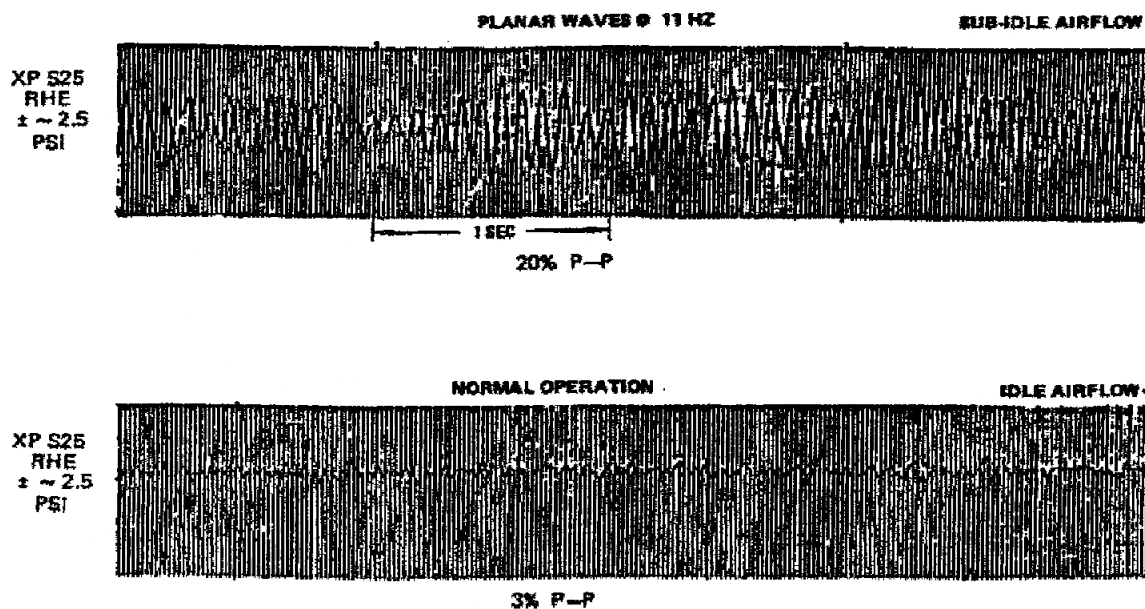


FIGURE 9 - COMPRESSOR INLET PRESSURE SIGNATURES

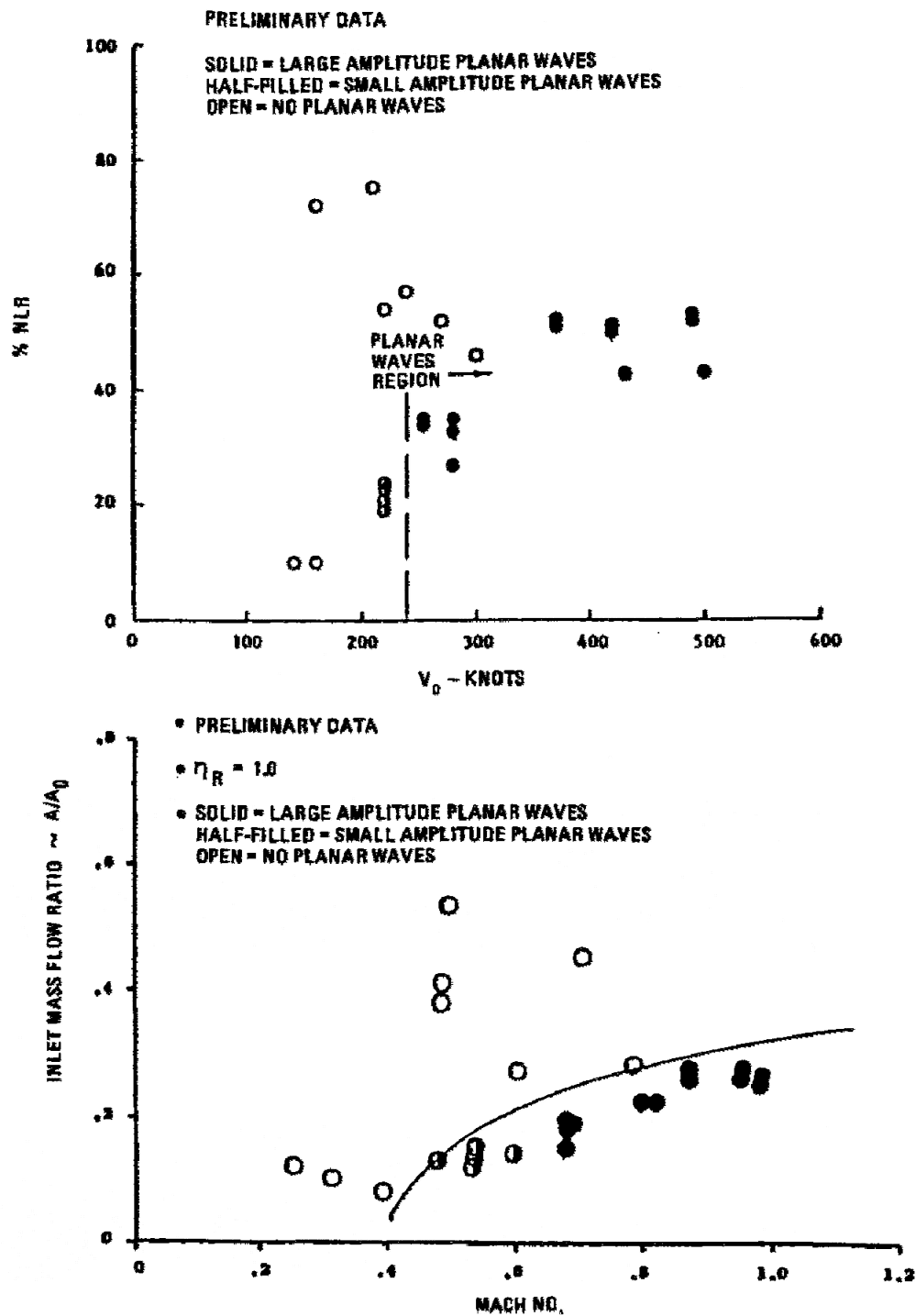


FIGURE 10 - COMPRESSOR INLET PLANAR WAVE EXPERIENCE AS A FUNCTION OF ENGINE SPEED AND INLET MASS FLOW RATIO

During development of System “B” aircraft, 1/7-scale wind tunnel model high-response data were measured. These data were analyzed to provide the compressor face waveform and total-pressure contour plots for idle airflow conditions at Mach 0.90 and 0.75. Some of these data for Mach 0.90 are presented in Figure 11 to illustrate typical planar waveforms and spatial distortion parameters. These distortion parameters were generated with procedures similar to those defined in ARP1420 (Reference 2.1.1.1). Power spectral density (PSD) plots of the waveforms and spatial distortion factors are presented in Figure 12. These PSDs identify a fundamental frequency of 50 Hz (model scale) as well as several harmonic frequencies.

From the results of the flight test experience of System “B,” it can be inferred that the potential exists for heavy pressure fluctuations at airspeeds above 240 knots during air starts. The impact of these pressure fluctuations on engine starting, however, is undefined. During the flight test program, no engine instabilities were observed during operation with planar waves at idle power setting and above.

## 5.2 Combined Spatial Pressure Distortion and Planar Waves

Spatial time-variant total pressure distortion induced at the AIP by inlet turbulence is random in nature and is accompanied by random variations in face-average total pressure. An example illustrating the variation of inlet recovery factor accompanying the variation in a typical spatial-distortion-descriptor is presented in Figure 13. For most applications, the planar wave contribution is small and may be neglected. Thus, the spatial distortion elements and descriptors formulated in ARP1420 (Reference 2.1.1.1) and AIR1419 (Reference 2.1.1.2) do not distinguish between time-variant and steady-state face-average total pressure.

As indicated in Section 7 of Reference 2.1.1.2 and discussed earlier in this report, shock/boundary layer interactions in supersonic inlets can give rise to distortion with a high planar wave or “in-phase” pressure component.

Data taken from System “B” (3.1.2) present a further example. The planar waves can take various forms and be either cyclic or random in time. Where the planar-wave amplitude begins to become significant (on the order of 1% of steady-state face-average pressure), the need for a methodology to account for the combined effects of spatial and planar distortion on engine stability margin should be considered as part of inlet/engine compatibility assessment.

One approach is provided by Burstadt and Wenzel (Reference 2.2.2). The possible accounting methods are discussed in Section 6, but it is worth mentioning here that all methods require quantification of the intensities of the planar-wave and spatial distortion elements in a combinatorial algebra that takes into account their time phasing. The peak destabilizing event may correspond to neither a peak planar nor a peak spatial distortion.

As a result of the inlet/engine design practice to avoid planar waves, a well-developed method for the treatment of the combined disturbance has not been developed. Thus, while the problem is theoretically tractable and appears straightforward computationally, little or no direct validation data for multispool engines exist, at least in a systematic codification. This report presents a methodology for assessing the effects of combined spatial total-pressure distortion and planar waves on compression system stability.

## 6. APPROACH TO PLANAR WAVE METHODOLOGY

In developing the proposed planar wave stability methodology, one of the primary ground rules has been to retain the stability accounting approach used in ARP1420. That is, the definitions and measurements needed to evaluate time-variant spatial distortion should not be required to change. Stability margin accounting should continue to be implemented at constant corrected engine airflow.

In addition, a methodology to account for the effects of planar waves on engine stability should include the following three elements: (1) categorization of the planar waves produced by the inlet and upstream systems and the flight conditions at which they can be expected to occur, (2) determination of the engine response to the types of planar waves that can be expected, and (3) a prediction methodology that relates the measured inlet pressure oscillations and the engine response characteristics to a loss of stability margin. The above three elements are presented in this section of the document. Methodologies for combining planar wave effects and spatial total-pressure distortion are also presented.