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Multiple segment parallel compressor program for analyzing circumferential total pressure distortion effects on compressor surge margin and performance

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Roy J. Schulz, Major Professor

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Date March 8, 1991

MULTIPLE SEGMENT PARALLEL COMPRESSOR PROGRAM FOR ANALYZING CIRCUMFERENTIAL TOTAL PRESSURE DISTORTION EFFECTS ON COMPRESSOR SURGE MARGIN AND PERFORMANCE

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Mark H. Amundson
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PREFACE

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ABSTRACT

Aircraft turbine engine compression system response to inlet total pressure distortion may result in reduced engine stability margin and in some cases a complete loss of stable engine operation. The engine and compression system performance characteristics can also be influenced. A computer model, based on the multiple segment parallel compressor technique has been written as part of this research investigation to predict the engine compression system response to various types of circumferential total pressure distortion.

The computer model was compared to actual compressor data from three different engines with various types of circumferential distortion profiles. The Allison XC-1 Lift Engine, the General Electric J85-13, and the Pratt & Whitney F100 (3) were the three compression systems used in the comparison.

Comparison of the computer model results against experimental data yielded encouraging results with stability margin (surge margin) predicted to within a couple percent. The computer model is currently unable to predict the trend of increasing surge margin as circumferential extent decreases. The compressor performance predictions were significantly less than the experimental data. The correct distorted performance trend of decreased corrected airflow and increased pressure ratio were predicted.

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NOMENCLATURE

A2	Compressor inlet area
A25	Compressor exit area
AIR	Aerospace Information Report
ANGLE	Segment Angle
AREA	Normalized Segment Area
ARP	Aerospace Recommended Practice
DSPR	Distortion Surge Pressure Ratio
ft	Feet
GE	General Electric
IGV	Inlet Guide Vane
in	Inches
lbm	Pounds Mass
M25	Compressor Mach Number
MSPC	Multiple Segment Parallel Compressor
N2R	Compressor Corrected Speed
OGV	Outlet Guide Vane
PR	Pressure Ratio
PRO	Operating Pressure Ratio
PROL	Lowest Inlet Pressure Ratio Operating Point
PR1	Clean Surge Pressure Ratio
PS25	Compressor Exit Static Pressure
psi	Pounds force per square inches
PT2	Compressor Inlet Total Pressure
PT25	Compressor Exit Total Pressure

P&W	Pratt & Whitney
R	Gas constant for Air
RAD	Radius
rev	Revolutions
rpm	Revolutions per minute
SBSC	Stage-by-Stage Compressor
SDI	Sample Distortion Index
Sec	Seconds
SM	Surge Margin
TS25	Compressor Exit Static Temperature
TT2	Compressor Inlet Total Temperature
TT25	Compressor Exit Total Temperature
V25	Compressor Exit Velocity
W2R	Compressor Inlet Corrected Airflow
W25R	Compressor Exit Corrected Airflow
η	Compressor Adiabatic Efficiency
γ	Ratio of specific heats
Γ	$(\gamma-1)/\gamma$

Subscripts

avg	Average
i	Ring number
j	Ring segment (division) number
max	Maximum
min	Minimum

CHAPTER I

INTRODUCTION

Stable operation of an aircraft gas turbine engine compression system is essential for the aircraft to operate safely. In addition the engine should deliver the performance which it is designed to provide. The compression system response to inlet total pressure distortion may result in reduced engine stability margin (surge margin) and in some cases a complete loss of stable engine operation. The engine and compression system performance characteristics can also be affected when operating under the influence of distortion.

Turbine engine compression system response to distortion can be characterized through experiments and compressor models. Experimental techniques are based on positioning flow distortion generating devices in front of the engine face, such as distortion screens. To measure the distorted surge margin requires back pressuring the compressor (throttling) until a surge is encountered and measuring the compressor performance at surge. On the other hand, many types of analytical or mathematical compressor models have been developed to analyze total pressure distortion affects on compressor surge margin and performance. Some of these models are the parallel compressor (PC) model, the multiple segment parallel compressor (MSPC) model, and the stage-by-stage compressor (SBSC) model.

A computer model, that has been written to predict the engine compression system (which is the fan and/or the compressor) response to various types of circumferential total pressures distortion, is the subject of this research investigation. The model makes uses of an expanded parallel compressor theory. Multiple segment parallel compressors (MSPC), which are treated as isolated compressors working in parallel, are used to provide a detailed definition of the inlet circumferential distortion profile. The parallel compressor and MSPC theories are based on the assumption that the overall compressor distorted performance is the average of the performance (airflow, pressure ratio, and adiabatic efficiency) of the isolated parallel compressors, each operating with a different inlet total pressure (to match the inlet distortion) but the same exit static pressure. There is no attempt to make individual segment performance adjustment to account for two-dimensional and unsteady flow affects such as engine-induced inlet flow redistribution, circumferential crossflow, and unsteady flow due to rotor movements through a distorted flow field.

In the present research, the MSPC model was validated by comparing theoretical results obtained with the MSPC model to experimental data. Experimental data was obtained for three compression systems: the Allison XC-1 Lift Engine, the General Electric (GE) J85-13, and the Pratt & Whitney (P&W) F100(3). The P&W F100(3) validation was limited to the fan portion of the compression system. The theoretical and experimental parameters compared were the surge margin, the distorted airflow, and the distorted pressure ratio.

A parameter sensitivity study was conducted to determine which of the input parameters that characterize the compression system have a significant affect on the compression performance predicted by the MSPC program. The study yielded some general guidelines about the accuracy needed for each input parameter.

It is expected that the MSPC model will be used extensively in the future as an engineering tool for obtaining first order approximations of the affects of circumferential distortion on compressor surge margin and overall performance. Because of the simplified structure of the MSPC model, relatively little detailed information on compressor design parameters is required as input to the program. Moreover, much of the input required can be found in the open literature; thus, the program can be used to check for possible errors or inconsistencies in experimental data sets obtained from compressor research programs. The program requires little knowledge about axial flow compressor behavior and the influences of distortion. Therefore, the program can be used as a training tool for engineers new to the turbine engine operability field.

CHAPTER II

THEORY

Multiple Segment Parallel Compressor (MSPC)

A computer program was written based on the MSPC theory for analyzing the affects of inlet circumferential total pressure distortion on axial flow compressor surge margin and performance. The parallel compressor theory described in Reference [1][1] is included as background for the development of the theory. The major assumption made in the parallel compressor theory is that a compressor can be divided into two flow regions: one region with a high pressure ratio across it and one with a low pressure ratio across it. The essential points of the theory as illustrated in Figure 1[2] are: (1) the compressor performance in each region behaves similar to that obtained during uniform inlet flow operations, (2) circumferential crossflow within the compressor is negligible, and (3) exit static pressures for both regions are equal. The theory will not account for the influence of different circumferential distortion profile extents on surge margin Figure 1a shows a 1/rev circumferential distortion profile with an extent of 180°, which is modeled by dividing the compressor into two 180° segments operating in parallel. The first segment has as its input a pressure higher than the average; the second a pressure lower than the average. Figure 1b shows the operating point of one parallel compressor

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[1] Number in brackets refer to similarly numbered references in the List of References.

[2] Figures and tables are found in the Appendix.

segment operating at a lower than average pressure ratio (point 1), and the second parallel compressor operating at a higher than average pressure ratio
(point 2). In the theory, it is assumed that a compressor surge will occur when the pressure ratio of segment 2 (Point 2) reaches the surge line of the compressor. The compressor distorted performance is calculated by averaging the corrected airflow and pressure ratio for Points 1 and 2 on Figure 1b.

Parallel compressor theory has been expanded by using multiple parallel compressor segments to provide a detailed definition of the distortion profile. The same assumption and approach which apply to the parallel compressor theory are used in the MSPC theory.

MSPC Equations

The compressor exit static pressure is calculated based on the area averaged inlet total pressure and the assumption that the compressor operates under uniform flow conditions equal to the average inlet flow. The inlet total pressure distortion profile is averaged to calculate the uniform or clean inlet total pressure.

$$PT2_{avg} = 1/A2 \sum_{j=1}^{n} (PT2_j AREA_j) \qquad (1)$$

The compressor overall performance parameters of inlet corrected airflow (W2R), pressure ratio (PR), and adiabatic efficiency (η) are defined based on the experimental compressor map. After the compressor performance parameters have been defined for uniform inlet flow conditions, the compressor exit total pressure and total temperature can be calculated.

$$PT25_{avg} = PR\ PT2_{avg} \qquad (2)$$

$$TT25_{avg} = TT2_{avg} \left[\frac{PR^{\Gamma} - 1}{\eta} + 1 \right] \qquad (3)$$

The compressor exit static pressure is calculated assuming inlet airflow equals compressor exit airflow.

$$W25R = W2R \qquad (4)$$

An equation for compressor exit airflow is developed below using the static and total pressure and temperature relationships and the Mach number velocity relationship.

$$PS25_{avg} = \frac{PT25_{avg}}{(1 + \gamma\Gamma/2\ M25^2)^{\Gamma}} \qquad (5)$$

$$TS25_{avg} = \frac{TT25_{avg}}{(1 + \gamma\Gamma/2\ M25^2\ )} \qquad (6)$$

$$V25 = M25\ \sqrt{\gamma\ R\ TS25_{avg}} \qquad (7)$$

$$W2R = A25 \left[\frac{PS25_{avg}}{R\ TS25_{avg}} \right] V25 \qquad (8)$$

Equation (8) is solved by iteration by using iterated values of exit Mach number in Eq. (5), Eq. (6), and Eq. (7). The calculated value of inlet airflow is compared to the compressor map value until the difference between the two meets a defined tolerance. The method of halving [2] was selected as the iteration scheme. After a value of exit Mach number has been determined, the compressor exit static pressure calculated with Eq. (5) remains constant throughout the rest of the theory.

The next step is to calculate the performance parameters for each parallel compressor segment. The inlet conditions for the segments are defined from the prescribed distortion profile. The procedure used to calculate the performance parameters is described as follows: a value of compressor corrected airflow is guessed for the segment and values of pressure ratio and adiabatic efficiency are determined based on the compressor map corrected speed curves. The equations used in calculating exit conditions for each segment are identical to those defined above. Equation (2) and Eq. (3) are used to calculate exit total pressure and total temperature respectively. The exit Mach number is calculated by solving Eq. (5) since exit static pressure has been calculated. The exit static temperature is calculated using Eq. (6), and the exit velocity is calculated using Eq. (7). A new value of corrected airflow is calculated using Eq. (8) and compared with the guessed value. This is repeated until the value of airflow does not change to within a define tolerance for successive iterations. The Secant method [2] was used for the iteration process. The Secant method has the advantage of obtaining a solution using initial guesses which do not have to surround the actual value. Once the iteration process has been accomplished for all segments, the compressor distorted performance and surge margin can be calculated.

Distorted performance is calculated by area averaging the airflow, pressure ratio, and adiabatic efficiency for all the segments. The distorted compressor performance can then be compared to compressor clean inlet performance to determine effects. The surge margin is based on the parallel compressor operating point that falls closest to the surge line as will be explained in detail in the next section.

ARP 1420 Stability Assessment

The surge margin is calculated in accordance with SAE Aerospace Recommended Practice (ARP) 1420 [3] and SAE Aerospace Information Report (AIR) 1419 [4]. The definition of surge margin (SM) to be used in this report will be based on a constant corrected airflow definition. The surge margin is the difference between the distorted surge pressure ratio (DSPR) and the clean operating pressure ratio (PRO), normalized by the PRO.

$$SM=100\,\frac{(DSPR-PRO)}{PRO} \tag{9}$$

Equation (9) requires the experimental distorted surge pressure ratio be known, which is not always the case. The surge margin can also be calculated by using the clean surge pressure ratio (PR1) and the compressor segment with the lowest inlet pressure operating point (PROL) normalized by the clean operating pressure ratio. This method will be used for calculating the surge margin for the MSPC program results.

$$SM=100\,\frac{(PR1-PROL)}{PRO} \tag{10}$$

The distorted surge pressure ratio can be calculated for a constant airflow by equating Eq. (9) and Eq. (10) and rearranging.

$$DSPR = (PR1 - PROL) + PRO \qquad (11)$$

CHAPTER III

MSPC COMPUTER PROGRAM DESCRIPTION

The MSPC computer program was written by the author for a Personnel Computer using the American National Standard Program Language FORTRAN 77 (ANSI X3.9-1978). Therefore, the program should be completely transferable to other computers. The program consists of about 1000 lines of code and was written to be executed in an interactive mode.

A schematic of the solution procedure is shown in Figure 2. A compressor map is input by selecting six data points which define each speed line for the pressure ratio and adiabatic efficiency curves. The program uses a least-squares 4th order polynomial curve-fit routine for modeling the compressor map curves. The curve-fit routine was programmed as a subroutine, so different curve-fit techniques could be substituted. The curve-fit subroutine calculates the coefficient matrix which is solved by a Gaussian-elimination with backward substitution subroutine. These subroutines together calculate the least-squares 4th order polynomial curve-fit coefficiencies for use throughout the program.The compressor exit area is input after the compressor map data has been entered.

The circumferential distortion profile is defined in the following manner. The inlet pattern is divided into a series of rings and the rings are divided into sections (Figure 3). The total pressure for each section or parallel compressor segment is defined to represent the inlet distortion profile.

The program was designed to handle the face average inlet total pressure defined to equal standard pressure and temperature which are 14.7 psi and 513.0° respectfully.

The technique for solving the equation for each segment was explained previously based on the assumption that all segments exit to the same static pressure. The equations used to calculate the exit static pressure are listed in part d of Figure 2. The average inlet total pressure is calculated for the compressor. The exit static pressure is calculated based on this pressure assuming that the compressor operates at its normal operating point.

The computer program then calculates the operating point for each segment based on the constant exit static pressure. The equations used to make this calculation are listed in Figure 2 part e. After the performance for each segment has been calculated, the program is ready to output some useful information.

The distorted performance can be compared to clean inlet compressor performance for corrected airflow, pressure ratio, and adiabatic efficiency by area averaging each parameter. The distorted surge margin is calculated based on the segment with lowest inlet total pressure. The equations for calculating this parameter are listed in part f on Figure 2. The program currently outputs the results for distorted performance in a table format (Figure 4).

CHAPTER IV

MSPC COMPUTER PROGRAM VALIDATION

The MSPC computer program was validated by assessing the accuracy of the mathematical and analytical techniques and comparing computed results to experimental data. The program output was compared to actual compressor and fan data from three different engines with various types of circumferential distortion profiles. The comparison included predicting clean and distorted surge margin and distorted compressor performance where data were available. A parameter sensitivity study was conducted to determine which input parameters require careful treatment and which can be input using gross approximations.

Mathematical and Analytical Techniques

The program uses a least-squares 4th order polynomial curve-fit technique to model a compressor map pressure ratio and adiabatic efficiency curves by using discrete points obtained from the curves. The results of the MSPC model curve-fit are used internally throughout the program. Figure 5 is an example of a typical compressor map which could be used. The map shown is for the Allison XC-1 Lift Engine compressor [4]. The compressor map was used to validate the least-squares 4th order polynomial curve-fit technique. Since much of the experimental data has been scaled from graphs and the experimental uncertainties were unknown, percent difference is used instead of percent error to compare actual and curve-fit data. The percent difference is defined as the input value (compressor map) subtracted by the output value (curve-fit) normalized by the input value.

$$Percent\,Difference = 100\,\frac{(Input - Output)}{Input} \tag{12}$$

To validate the MSPC equations used in the program and to investigate the possibility of computer generated errors, such as truncation and precision, a uniform inlet total pressure profile was used instead of a distorted profile. Because the inlet profile was uniform, the calculated distorted compressor performance should equal the clean operating compressor performance. Figure 1b is used to explain this concept. Since the low pressure and high pressure segments are set to equal each other (uniform total pressure profile), Points 1 and 2 will have a value equal to the clean operating point. Equation (13) was used to calculate the percent error introduced as a result of combined internal computer program calculations and computer truncation and precision errors.

$$Percent\,Error = 100\,\frac{(Actual - Calculated)}{Actual} \tag{13}$$

Experimental Comparison

The MSPC computer program usefulness was determined using three different aircraft turbine engine compression systems: an Allison XC-1 Lift Engine Compressor, a General Electric J85-13 compressor, and a Pratt and Whitney F100(3) fan. Various types of circumferential distortion profiles and intensities were used. The Simple Distortion Index (SDI) is a representation of the distortion profile intensity.

$$SDI = \frac{(PT_{max} - PT_{min})}{PT_{avg}} \tag{14}$$

The Allison XC-1 Lift Engine uses a four-stage compressor (Figure 6). The compressor dimensions and design performance parameters are provided in Table 1. The Allison XC-1 Lift Engine compressor map (Figure 5) was used for this portion of the validation. The compressor experimental data were obtained during the Propulsion System Flow Stability Program using a compressor test rig [5]. The compressor was highly instrumented with interstage total pressure and total temperature probes. The compressor data obtained in this program has been used in validating compressor models since the late 1960s. Classical 1/rev circumferential distortion profiles with extents of 60° and 180° were used in the comparison. Figure 7 shows the experimental XC-1 compressor distortion pressure ratio results for a compressor speed of 90% with a complex inlet circumferential distortion profile [6]. The distortion profiles and SDI levels are shown in Figure 8.

The GE J85-13 turbojet engine has an eight-stage axial-flow compressor. A cross-section view of the J85-13 engine compressor and combustor region is provided in Figure 9. The compressor design information and characteristics are given in Table 2. The data used for the J85-13 comparison were obtained as part of the NASA Casing Treatment

Program [7]. The J85-13 compressor map (for which the comparison was based on) is shown in Figure 10.

An adiabatic efficiency map for a J85-13 was unavailable, so an arbitrary constant value of 0.80 was selected. The J85-13 engine was tested with a variety of inlet distortion screens. The experimental data for a 1/rev circumferential distortion profile with an extent of 180° was selected for the comparison. The screen had a 42% blockage section. The screen and SDI levels for the different compressor corrected speeds are provided in Figure 11.

The PW F100(3) is twin spool, augmented turbofan engine. The engine compression system consist of a 3-stage fan (Figure 12) and a 10-stage high compressor. The data was obtained as part of a F100(3) distortion test [8] at NASA Lewis Research Center. Compressor data from the F100(3) fan was used for this portion of the comparison. The F100(3) fan characteristics and design parameters were unavailable. F100(3) fan corrected speed curves for 101.5% are shown in Figure 13. Classical 1/rev circumferential distortion profile with an extent of 180° was used to produce SDI levels of 0.15 and 0.22 (Figure 14).

Parameter Sensitivity Study

In the discussion on the MSPC theory, it is understood that the compressor map pressure ratio curves must be known and modeled accurately to give reasonable estimates of surge margin and distorted compressor performance. As mentioned previously, the analysis was based on average inlet total pressure and total temperature defined equal the standard values of 14.7 psi and 513.0° respectfully.

The inlet area is not a critical parameter for the program since the MSPC theory does not use inlet area in any of the internal calculations. However, care needs to be taken in dividing the inlet into the multiple segments so the total inlet area equals the sum of all the segment areas.

Two parameters which are directly used in the computer internal calculates are compressor exit area and adiabatic efficiency. Often the compressor exit area is unknown and must be scaled from drawings or estimated. Typically the adiabatic efficiency is provided as part of the compressor map. However, for the J85-13 compressor no adiabatic efficiency curves could be located, so an arbitrary constant value was used. The two input parameters will be varied over a range of values and compared to determine their effects on the program output. The Allison XC-1 compressor data will be used with a 1/rev circumferential distortion profile with an extent of 180° and a SDI of 0.1.

CHAPTER V

MSPC COMPUTER VALIDATION RESULTS

Mathematical and Analytical Techniques

The results of the least-squares 4th order polynomial curve-fit of the Allison XC-1 engine data are shown in Figure 15 and Table 3. Table 3 gives the results for the curve-fit in percent error calculated using Eq. (13). The maximum percent error of -3.47% for pressure ratio and -4.29% for adiabatic efficiency occurred for a compressor speed of 80%. The curve-fit maximum percent error goal was 5% for any point on the curve which is in the bounds of interest. For a compressor pressure ratio of 5, this would equate to 0.25 psi error. The results are below the 5% goal for all curve-fit data used in the validation. However, some general trends can be observed from the curve-fit results (Figure 15). The least-squares 4th order polynomial curve-fit technique has difficulty modeling sharp changes in slope. This is seen in the results of the pressure ratio and adiabatic efficiency curve-fits for a compressor speed of 80%. Significant curve-fit errors can be introduced as a result of scaling pressure ratio and adiabatic efficiency data from experimental compressor maps. This was detected when the initial curve-fits yield large errors and required an iterative process to achieve the results shown in Figure 15 and Table 3. The least-squares curve-fit technique will help reduce the compressor map curve scaling errors through smoothing the data. However, the smoothing tends to cause problems in modeling sharp slope changes.

The results of the accuracy check for the MSPC computer calculations are shown in Table 4 for two different Allison XC-1 compressor speeds.

The data show outstanding agreement between MSPC program curve-fit values and clean inlet values. The accuracy in all cases exceeds the computer program tolerance values set at ± 0.01 lbm/sec for the airflow iteration procedures. The errors introduced through MSPC calculations and computer truncation and precision errors can be neglected for distorted surge margin and performance calculations.

Experimental Comparison

The results of the distorted surge margin comparison for the Allison XC-1 Lift Engine compressor are presented in Figure 16. The comparison was made for a compressor speed of 90% and a airflow of 35 lbm/s. The MSPC computer program accurately estimated the distorted surge margin. Table 5 list the calculated surge margin for the MSPC model and compares those values to the experimental results. The difference between the surge margins is less than 4% for all inlet profiles. The MSPC model predicts the same surge margin for a circumferential distortion profile with an extent of 180° and 60° for constant SDI values. The experimental data trend is for increasing surge margin as circumferential extent decreases. The assumption that crossflow between the low and high pressure regions can be neglected does not enable the model to account for circumferential extent affects on surge margin. Also, the difference between PT_{max} and PT_{min}, used to calculate SDI in Eq. (14), will increase as the circumferential extent decreases. Therefore, the program will calculate less surge margin as this difference increases.

The comparison of computer calculated distorted airflow versus the experimental distorted airflow for the complex circumferential distortion pattern is shown in Figure 17 and Table 6. The trend of less airflow due to circumferential distortion for the MSPC model and experimental data agree, but the magnitudes are significantly different. The percent error calculated based on distorted airflow subtracted from clean airflow for MSPC and experimental values; then using Eq. (13) yielded a error of 74%. The reason appears to partially lie in the curve-fit routine and its ability to handle curves with steep slopes which occurs for the XC-1 compressor map pressure ratio curve at a corrected compressor speed of 80% around the operating line (Figure 15).

The GE J85-13 results for the circumferential distortion profile of an extent of 180° at compressor speeds of 80, 87, and 94% are presented in Figure 18. Figure 18 shows the J85-13 pressure ratio map with experimental clean surge line, distorted surge line, and the MSPC calculated surge margin values at the three airflows. The figure shows good agreement between MSPC computer and experimental values of distorted surge margin. The MSPC computer program slightly overpredicts the distorted surge margin. The numerical value of surge margin are presented in Table 7 with a maximum difference of 3.6% at a compressor speed of 94% and a airflow of 39.6 lbm/sec.

The results of the distorted performance comparison for the J85-13 compressor speed of 94% are presented graphically in Figure 19. The trend of lower corrected airflow and higher pressure ratio exist for the J85-13 as existed for the XC-1 compressor. The MSPC program overpredicts distorted airflow and underpredicts distorted pressure ratio (Table 8).

The results of the F100(3) fan experimental and MSPC model calculated distorted surge margin are shown in Figure 20. The program overpredicts the surge margin for a corrected fan speed of 101.5% and a constant percent corrected airflow. The comparison was performed for a circumferential distortion profile of an extent of 180° at two SDI levels 0.15 and 0.22. The surge margin calculations are listed in Table 9. The computer program predicts the surge margin to be about 2.0% less than the experimental calculations.

No analysis of distorted operation point was performed because experimental data were not available.

Parameter Sensitivity Study

The parameter sensitivity study was based on varying the compressor total exit area and the overall adiabatic efficiency and using the Allison XC-1 Lift Engine compressor data at a corrected speed of 90% with a 1/rev circumferential distortion profile (Figure 8). The values compared in the sensitivity study were distorted airflow and pressure ratio. The results shown in Table 10 indicate that a small error (0.019% for corrected airflow and -0.097% for pressure ratio) occurred over the range of exit areas tested. The results were expected due to the approach taken in the MSPC model and can be explained by reviewing the theory and equations. The first step in the MSPC program is to average inlet conditions so a constant compressor exit static pressure can be calculated. By varying the compressor exit area, the exit static pressure and Mach number will change, but all other parameters will remain the same. The calculated exit conditions for the individual segments (different inlet total pressure) are based on a constant exit static pressure. Therefore, the segment exit conditions, such as corrected airflow and pressure, will be a function of inlet conditions, and different exit areas should have little affect on the final values, so long as the compressor is operating at speed ranges far from outlet choking conditions for the compressor.

The sensitivity to variations in adiabatic efficiency is summarized in Table 11. The adiabatic efficiency was varied between 0.70 and 0.95 on a constant value basis (straight line) for the entire compressor corrected speed relationship. These results were compared for the actual curve shown in Figure 5. The percent difference between the baseline value and constant adiabatic efficiency values remain less than 0.015% for distorted airflow and pressure ratio. Also, a different curve was input into the program for comparison. The results again showed little change (less than 0.01%) for both parameters. The results indicate that the MSPC model is insensitive to variations in adiabatic efficiency. The results were expected and is explained by the MSPC theory and equations. By inspecting Eq. (3), it is clear that as adiabatic efficiency increases, compressor exit total temperature and exit Mach number increase and exit static pressure will decrease sightly. Again, the exit static pressure is used only to set a constant condition for each individual segment so the exit conditions can be calculated. The inlet total pressure will continue to drive the exit condition of interest: distorted airflow, pressure ratio, and surge margin.

CHAPTER VI

CONCLUSIONS

The least-squares 4th order polynomial curve-fit used in modeling compressor maps had good overall results. The least-squares technique was selected because of its ability to smooth out possible input errors. These errors were assumed to occur as the result of scaling information from compressor maps. A 4th order polynomial was selected to give good curve definition without requiring a large number of data points to define each compressor curve. The results previously discussed indicated the curve-fit technique had difficulty fitting curve with sharp slope changes. This can lead to excess errors if care is not taken in checking curve-fit results. Further, refinement or possible selecting a new curve-fit technique such as a higher order polynomial may yield improved results.

The MSPC equations modeled within the program have been validated to within a fraction of a percent at most against the set of experimental data selected for comparison. Computer generated truncation and precision error checks were made to see if they were detectable in program output; none were present. From an analytical standpoint, the program is capable of being used to calculate compressor and/or fan surge margin and performance when subject to both clean inlet conditions and with inlet circumferential total pressure distortion.

Comparison of the program results against experimental data yielded encouraging results. The program predicted distortion surge margin to within a couple of percent for the cases tested. The MSPC model needs improvement to enable the program to accurately model the trend of decreased surge margin as circumferential distortion extent increases at a constant SDI. The distortion performance predictions were not consistent with experiment, showing predicted trends of less airflow and higher pressure ratio at given speed, but with magnitudes that were overpredicted. It is hoped that this can be improved by using different curve-fit routines.

The MSPC program has room for growth and improvement. Users of the program should take care in interpreting the MSPC computer results for circumferential distortion profiles of various extents. The MSPC program could be expanded to include the capability of calculating surge margin and performance for both temperature only and combined pressure and temperature distortion. However, this will require significant program restructuring before this capability could be included.

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7. Milner E.J. and L.M. Wenzel. "Performance of a J85-13 Compressor with Clean and Distorted Inlet Flow" NASA TM X-3304, December 1975

8. Walter W.A. and M. Shaw. "Predicted F100 Engine Response to Circumferential Pressure and Temperature Distortion," AIAA Paper No. 79-1310, June 1979.

9. Shaw M. and R.W. Murdoch. "Computer Modeling of Fan-Exit-Splitter Spacing Effects of F100 Response to Distortion," NASA CR-167879, March 1982.

APPENDIX

TABLE 1
ALLISON XC-1 COMPRESSOR DESIGN INFORMATION

STAGE (STATION)	AREA (ft^2)	LENGTH (ft)	RADIUS OUTER (ft)	 INNER (ft)
1	1.1360	0.2165	0.6991	0.3565
2	0.8173	0.1558	0.6903	0.4651
3	0.6610	0.1558	0.6903	0.5159
4	0.5045	0.1386	0.6838	0.5540
5	0.4026	-	0.6816	0.5800

Design Point Performance

N2R = 18,030 rpm

W2R = 38.7 lbm/sec

PR = 4.92 (maximum)

TABLE 2
GE J85-13 COMPRESSOR
DESIGN INFORMATION

LOCATION		AREA	LENGTH	RADIUS		ROTOR INLET AIR ANGLE
STAGE	STATION	(ft^2)	(ft)	OUTER (ft)	INNER (ft)	(deg)
1	*	1.300	0.1856	0.6708	0.1900	0
2	*	1.300	0.1856	0.6708	0.1900	0
3	*	1.300	0.1856	0.6708	0.1900	0
4	*	1.150	0.1856	0.6708	0.2812	0
5	1	1.066	0.1856	0.6458	0.3156	Scheduled
6	2	0.8395	0.1364	0.6458	0.3935	5.4
7	3	0.6821	0.1116	0.6458	0.4472	12.1
8	4	0.5630	0.0977	0.6458	0.4878	14.8
9	5	0.4960	0.0873	0.6458	0.5175	19.4
10	6	0.4055	0.0789	0.6458	0.5367	23.2
11	7	0.3698	0.0775	0.6458	0.5472	22.2
12	8	0.3580	0.0988	0.6458	0.5506	21.6

* Inlet duct

<u>Design Point Performance</u>

N2R = 16,500 rpm
W2R = 43 lbm/sec
PR = 7.7 (maximum)

TABLE 3
ALLISON XC-1 COMPRESSOR MAP MODELING RESULTS

COMPRESSOR CORRECTED AIRFLOW (lbm/sec)	% ERROR PRESSURE RATIO	% ERROR ADIABATIC EFFICIENCY
COMPRESSOR CORRECTED SPEED 80%		
29.75	-3.468	-4.286
29.65	0.526	1.333
29.45	0.957	2.581
29.05	2.869	1.239
28.25	-1.825	-1.211
26.50	0.342	0.000
COMPRESSOR CORRECTED SPEED 90%		
35.25	-1.618	-1.217
35.15	0.000	0.000
35.00	0.606	1.198
34.70	1.714	1.183
33.50	-0.779	-1.214
31.75	0.250	0.000

TABLE 4
MSPC PROGRAM
CALCULATION ERROR RESULTS

COMPRESSOR CORRECTED SPEED SPEED (rpm)	% ERROR CORRECTED AIRFLOW	% ERROR PRESSURE RATIO	% ERROR ADIABATIC EFFICIENCY
80	0.0068	-0.0968	0.0000
90	0.0000	0.0061	0.0000

TABLE 5
ALLISON XC-1 COMPRESSOR
SURGE MARGIN RESULTS

DISTORTION EXTENT (deg)	SDI	EXPERIMENTAL SURGE MARGIN	MSPC CALCULATED SURGE MARGIN (SM)
CLEAN	0.0	28.5	28.6
180	0.1	19.4	23.3
60	0.1	22.7	23.3
60	0.2	12.1	13.0
COMPLEX	0.0902	23.0	22.0

TABLE 6
ALLISON XC-1 COMPRESSOR
DISTORTED AIRFLOW PREDICTIONS

DISTORTION EXTENT (deg)	SDI	EXPERIMENTAL		MSPC CALCULATED	
		CORRECTED SPEED	PRESSURE RATIO	CORRECTED SPEED	PRESSURE RATIO
COMPLEX	0.09	34.95	3.307	34.987	3.302

TABLE 7
GE J85-13 COMPRESSOR
SURGE MARGIN RESULTS

1/rev CIRCUMFERENTIAL DISTORTION EXTENT = 180 deg.

CORRECTED SPEED (%)	SDI	EXPERIMENTAL SURGE MARGIN	MSPC CALCULATED SURGE MARGIN
80	0.0	41.2	43.7
80	0.082	38.9	39.5
87	0.0	37.0	37.3
87	0.116	29.6	31.2
94	0.0	28.0	28.9
94	0.15	17.2	20.9

TABLE 8
GE J85-13 COMPRESSOR DISTORTED AIRFLOW AND PRESSURE RATIO PREDICTIONS

		EXPERIMENTAL		MSPC CALCULATED	
DISTORTION EXTENT (deg)	SDI	CORRECTED SPEED	PRESSURE RATIO	CORRECTED SPEED	PRESSURE RATIO
180	0.15	39.40	5.54	39.489	5.485

TABLE 9
P&W F100(3) FAN
SURGE MARGIN RESULTS

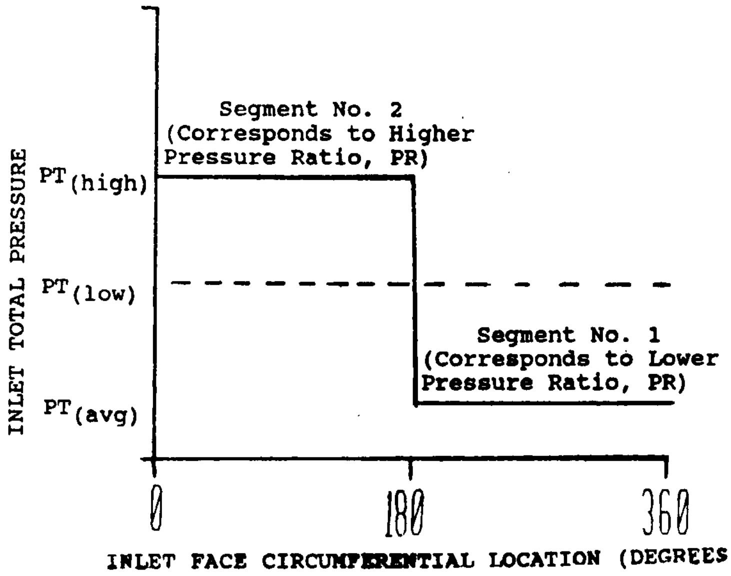
DISTORTION EXTENT (deg)	SDI	EXPERIMENTAL SURGE MARGIN	MSPC CALCULATED SURGE MARGIN
CLEAN	0.0	26.2	24.9
180	0.15	20.0	18.3
180	0.22	16.6	14.1

TABLE 10
COMPRESSOR EXIT AREA
PARAMETER SENSITIVITY RESULTS

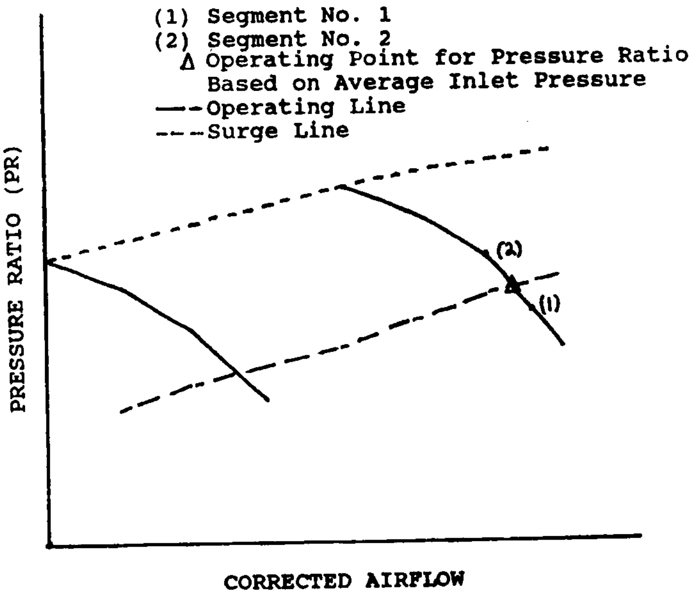
EXIT AREA	MACH NO.	% DIFFERENCE DISTORTED CORRECTED AIRFLOW	% DIFFERENCE DISTORTION PRESSURE RATIO
56	0.437	-0.015	-0.021
57	0.428	-0.019	0.001
60	0.399	-0.002	-0.097
63	0.378	-0.011	-0.009
65	0.364	-0.017	-0.009
70	0.334	-0.017	-0.006
80	0.287	-0.015	-0.009

TABLE 11
ADIABATIC EFFICIENCY
PARAMETER SENSITIVITY RESULTS

ADIABATIC EFFICIENCY	% DIFFERENCE DISTORTED CORRECTED AIRFLOW	% DIFFERENCE DISTORTED PRESSURE RATIO
0.787-0.796	0.002	-0.006
0.700	0.001	0.012
0.750	-0.001	-0.006
0.800	0.000	0.006
0.850	-0.001	0.006
0.900	-0.001	0.006
0.950	-0.001	0.009



a. Parallel Compressor for 1/rev Circumferential Distortion Profile



b. Operating Points on Compressor Map

Figure 1. Parallel Compressor Theory

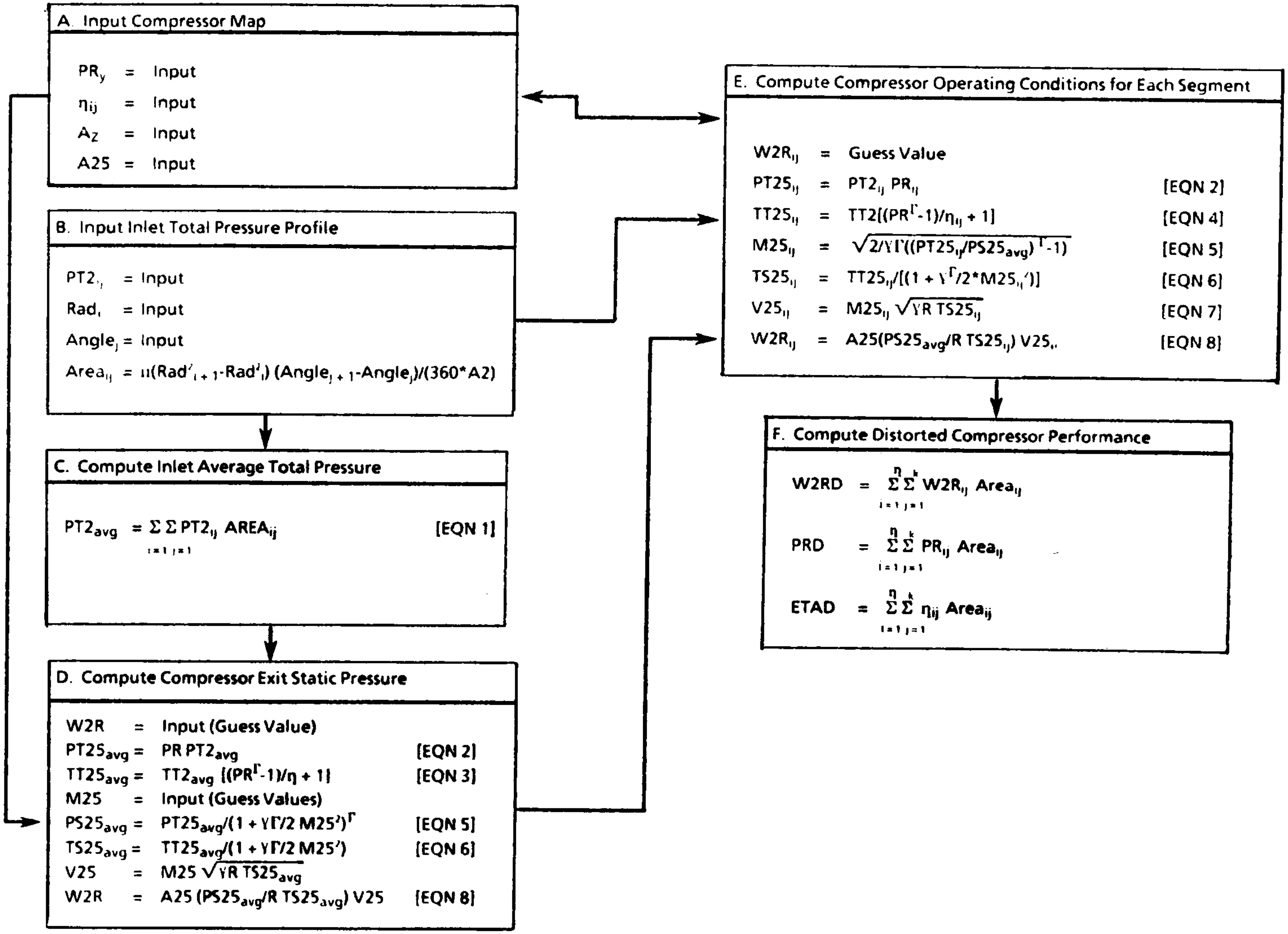


Figure 2. Schematic of MSPC Solution Procedure

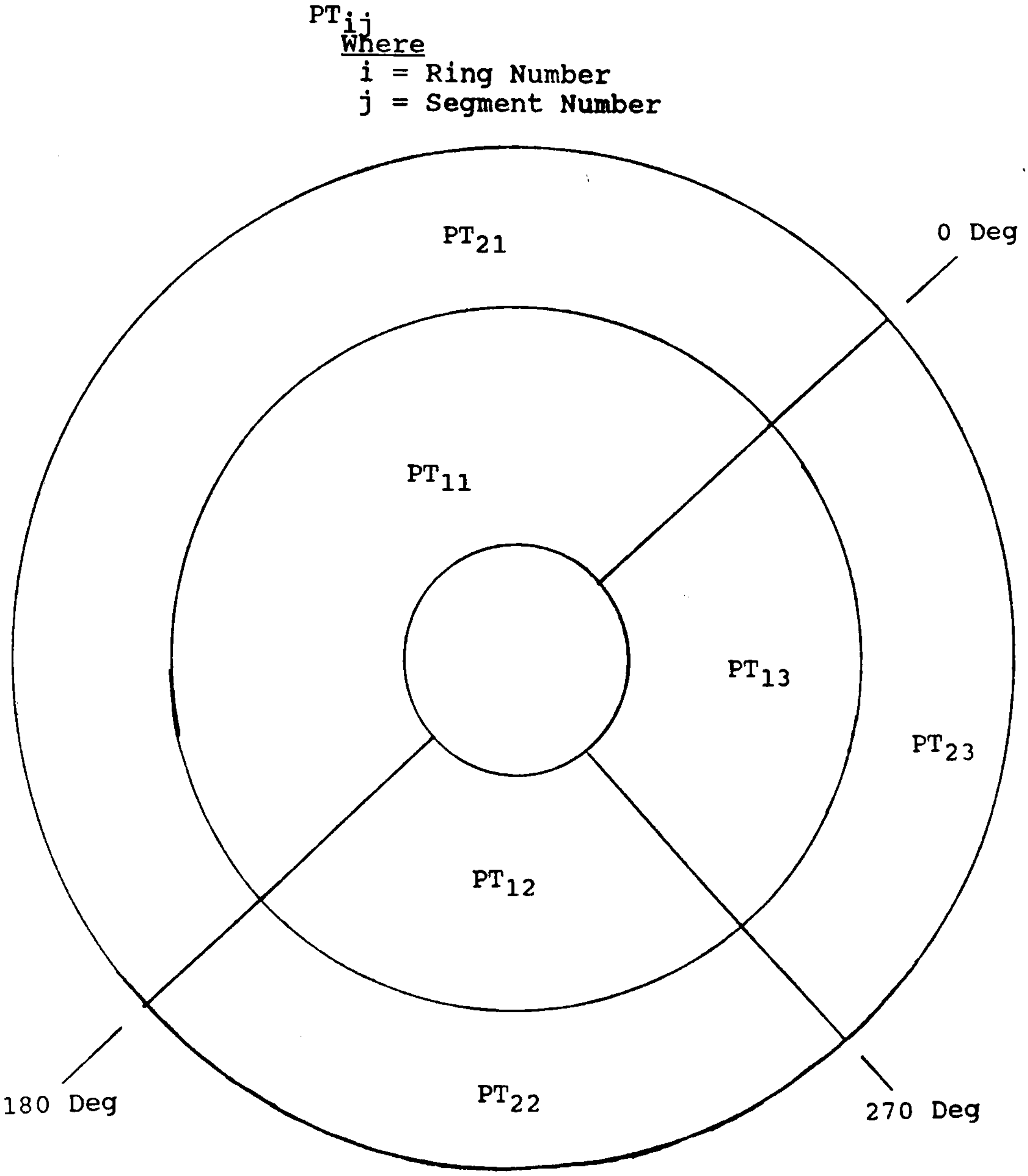


Figure 3. Computer Simulation of Compressor Inlet Total Pressure Profile

```
To read in compressor map from existing file (type 1): 1

Input data file name for compressor map: XC1.DAT

To save new inputed data type 1 for compressor map: 0

To read existing compressor face profile (TYPE 1): 1

Input inlet face file name: F180.DAT

To save new inputed data for inlet face type 1: 0

Enter compressor corrected speed: 90.

Compressor exit area57.99

from static p25a,prc,etac     48.28393936       3.28462148       0.83
Enter two guess for compressor exiting MACH No.: 0.2,0.8

Exit MACH number =       0.41870117
Exit static pressure =      42.79767990
Clean Inlet OPT point for a Corrected speed of      90.00000000
Corrected Airflow =      35.00000000
Pressure Ratio =      3.28462148
Adiabatic Efficiency =      0.83332682

Distorted Individual Segment Data
Data for ring radius from   0.00000000E-01to       7.21646690
Angle location from   0.00000000E-01to     180.00000000
Corrected Airflow =      34.54948425
Pressure Ratio =      3.51638150
Adiabatic Efficiency =      0.84083056

Angle location from     180.00000000to     360.00000000
Corrected Airflow =      35.17060852
Pressure Ratio =      3.18518519
Adiabatic Efficiency =      0.82837254

Distorted Inlet Operating point for
Distorted Corrected Airflow =      34.86004639
Pressure Ratio =      3.35078335
Adiabatic Efficiency =      0.83460152
Execution terminated :  0
```

Figure 4. MSPC Computer Program Sample Output

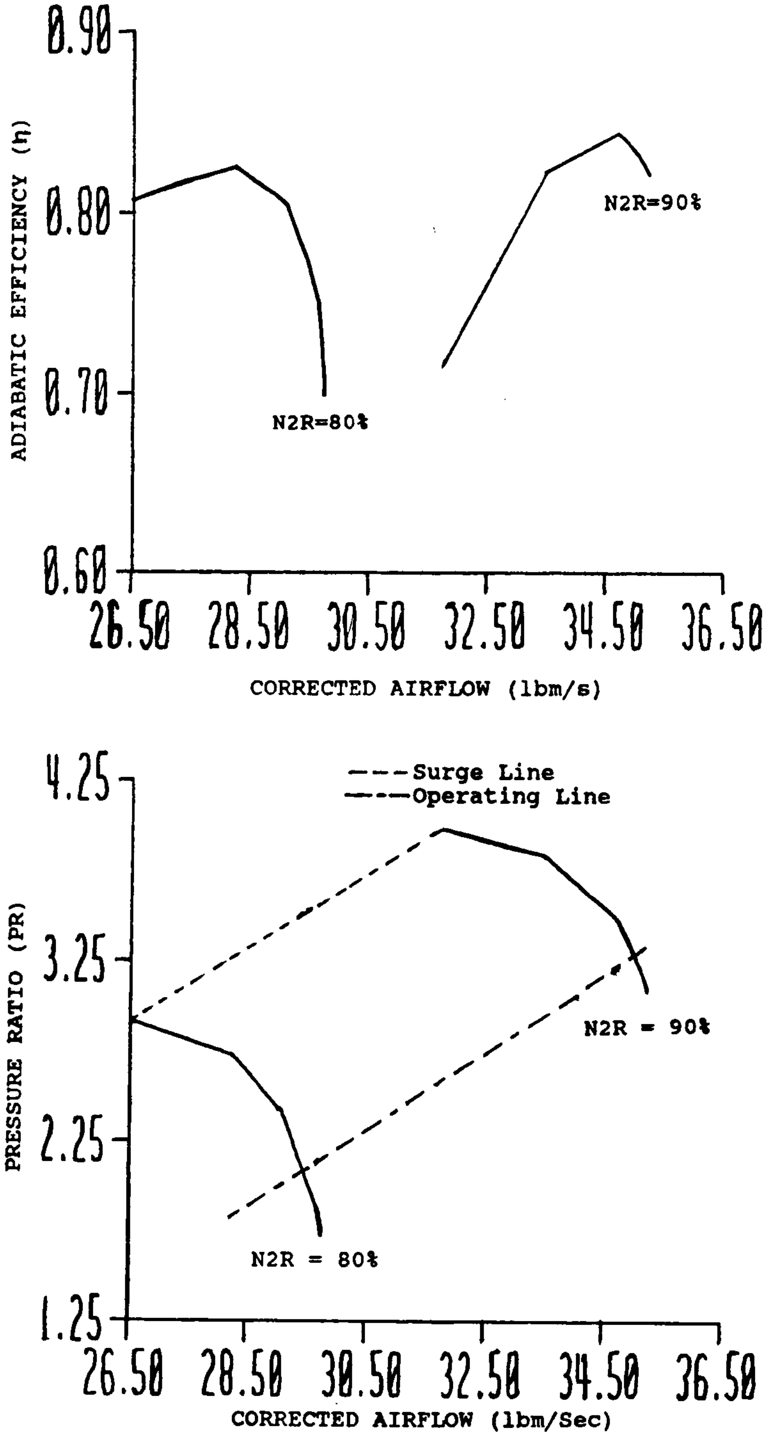


Figure 5. Allison XC-1 Lift Engine Compressor Map

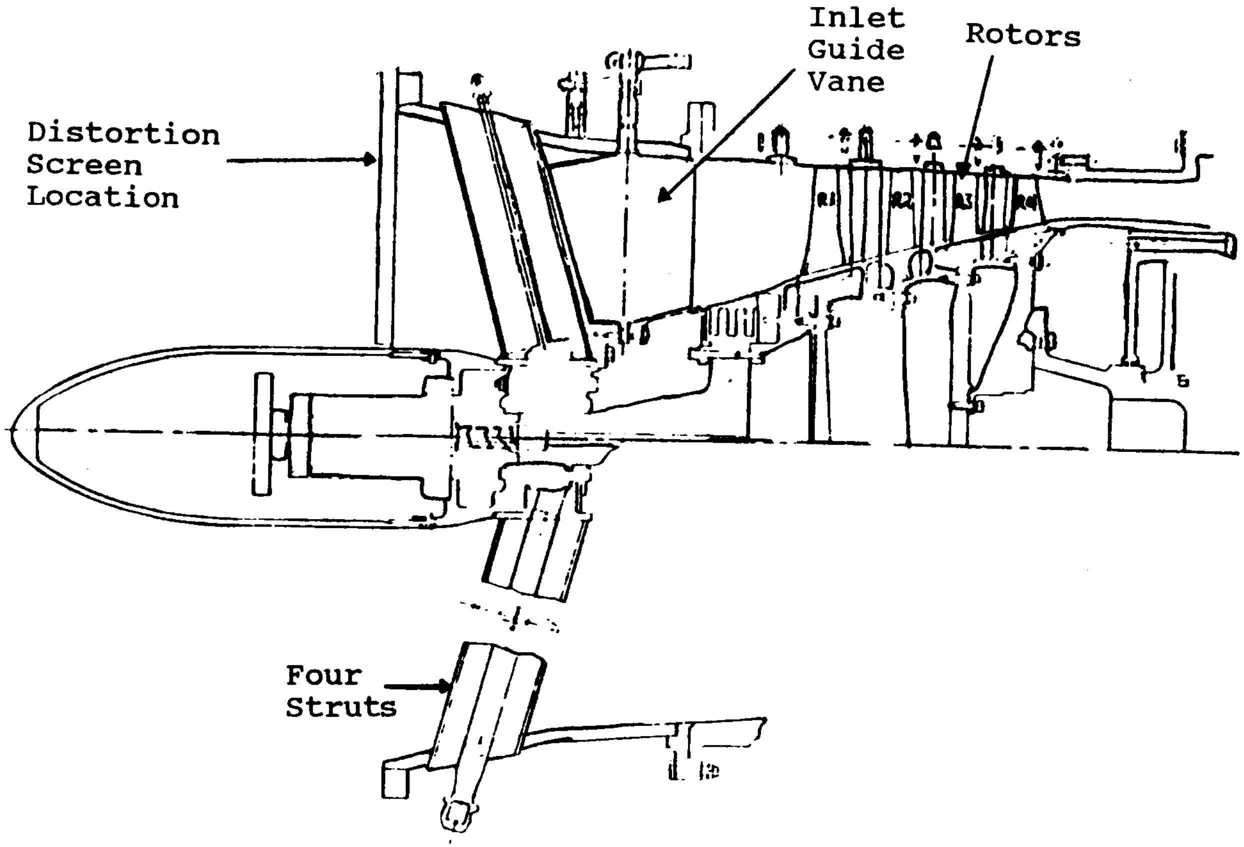


Figure 6. Allison XC-1 Lift Engine Drawing

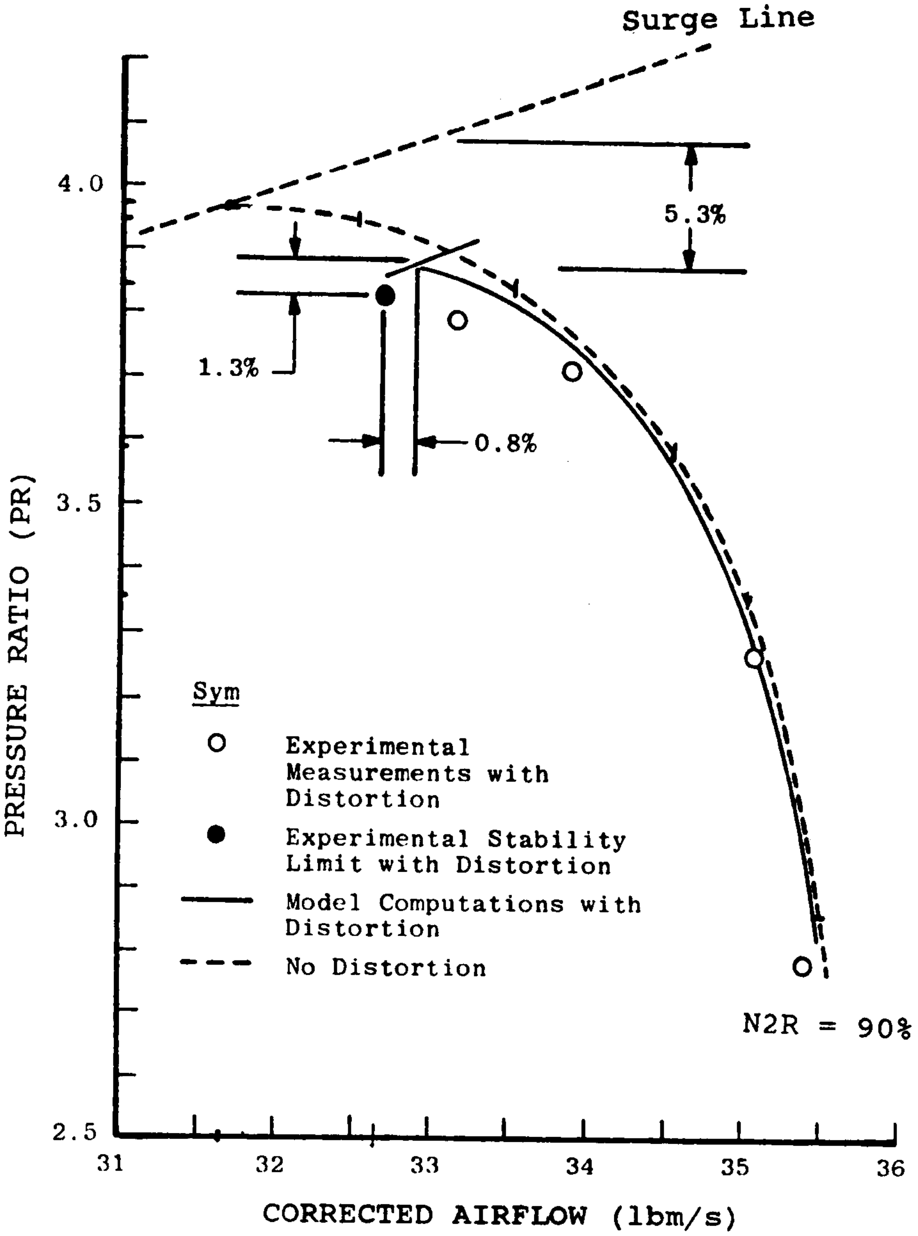


Figure 7. Allison XC-1 Experimental Complex Distortion Results for 90% Compressor Speed

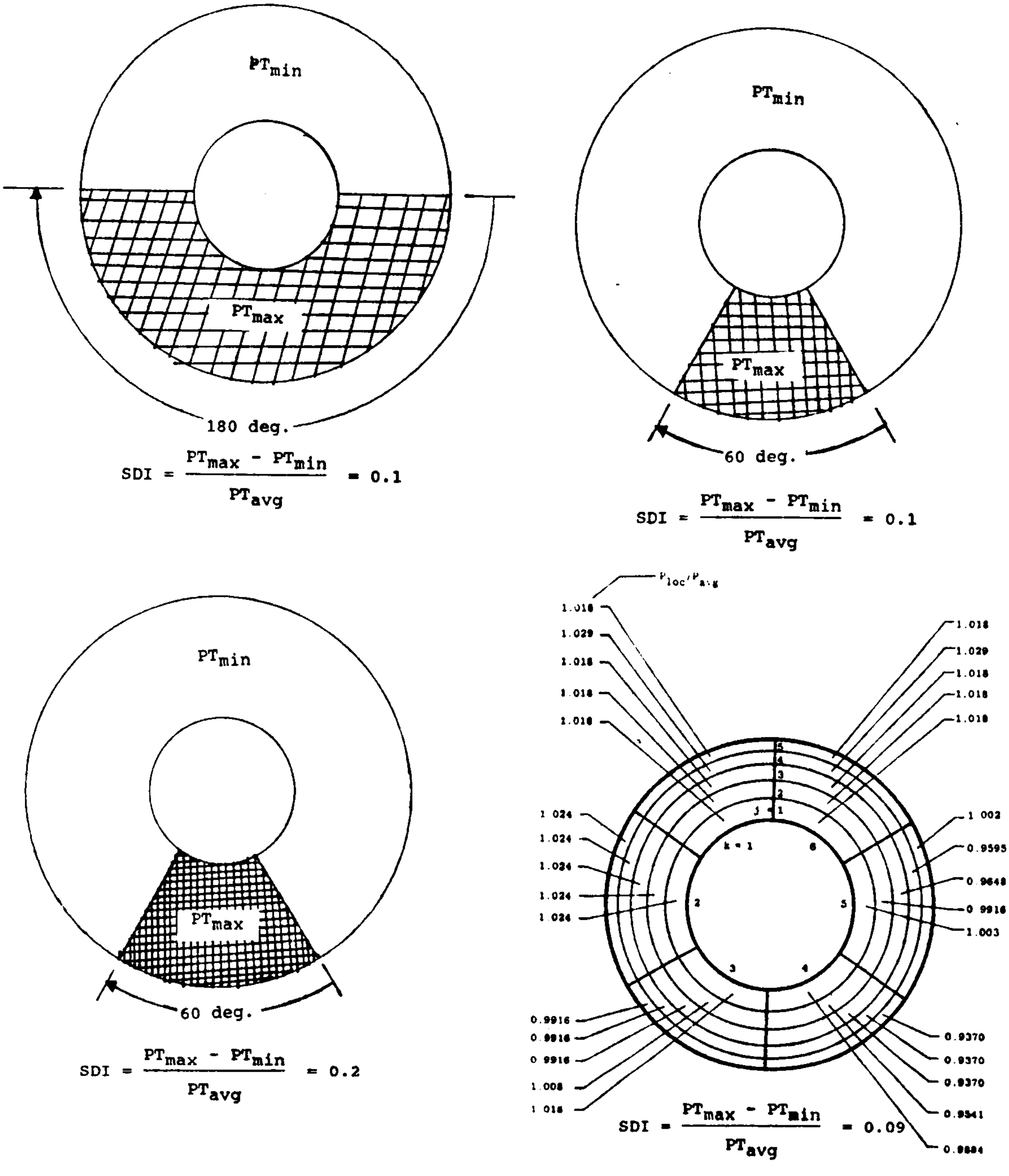


Figure 8. Allison XC-1 Circumferential Distortion Profiles

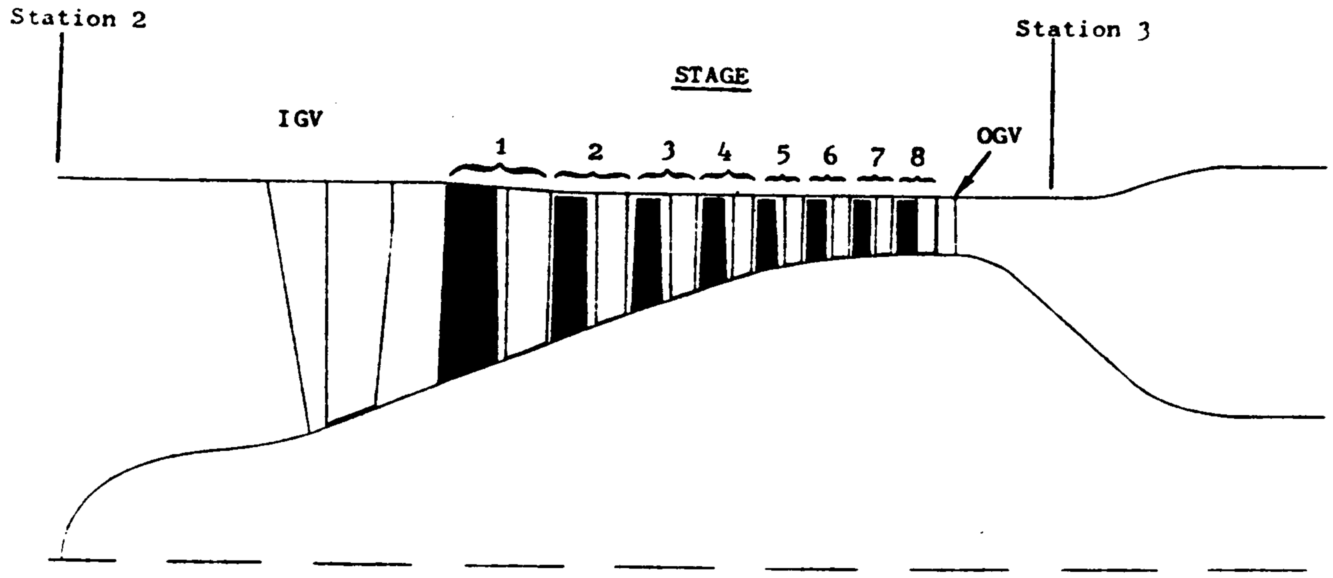


Figure 9. GE J85-13 Compressor Cross-Section

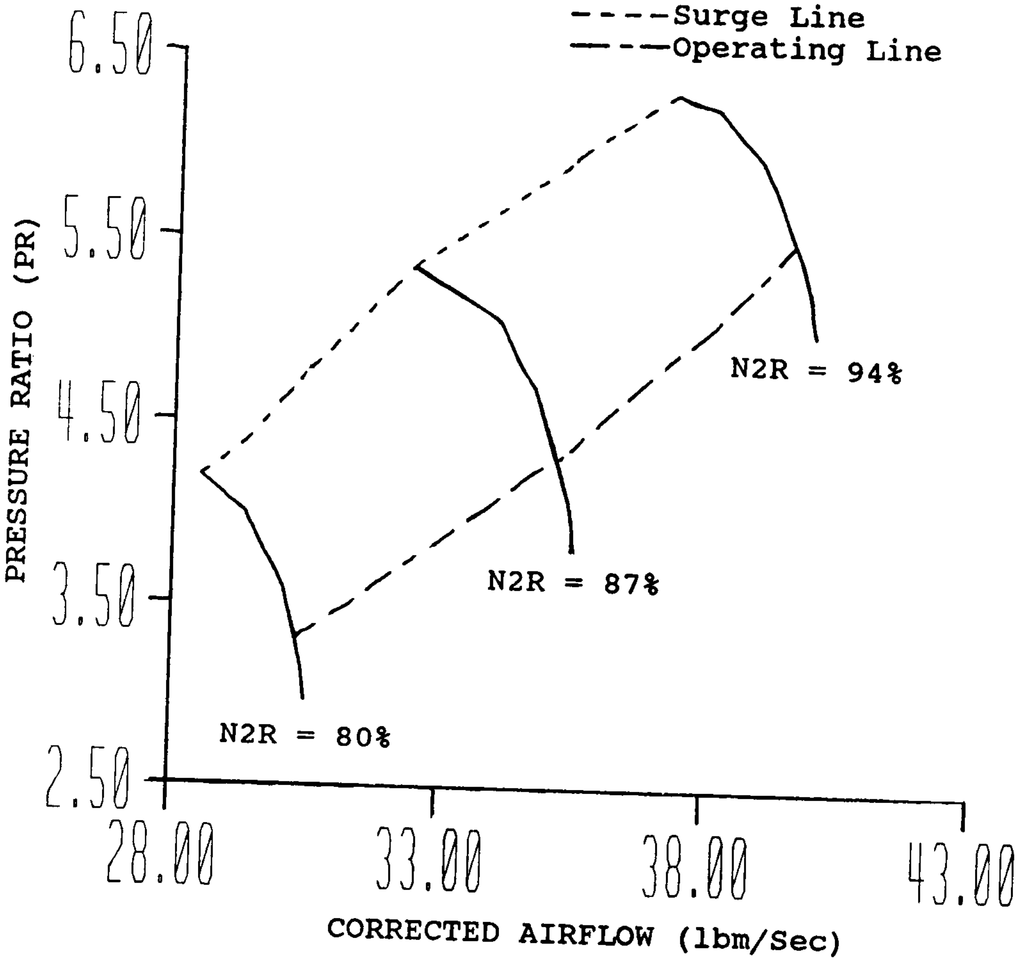
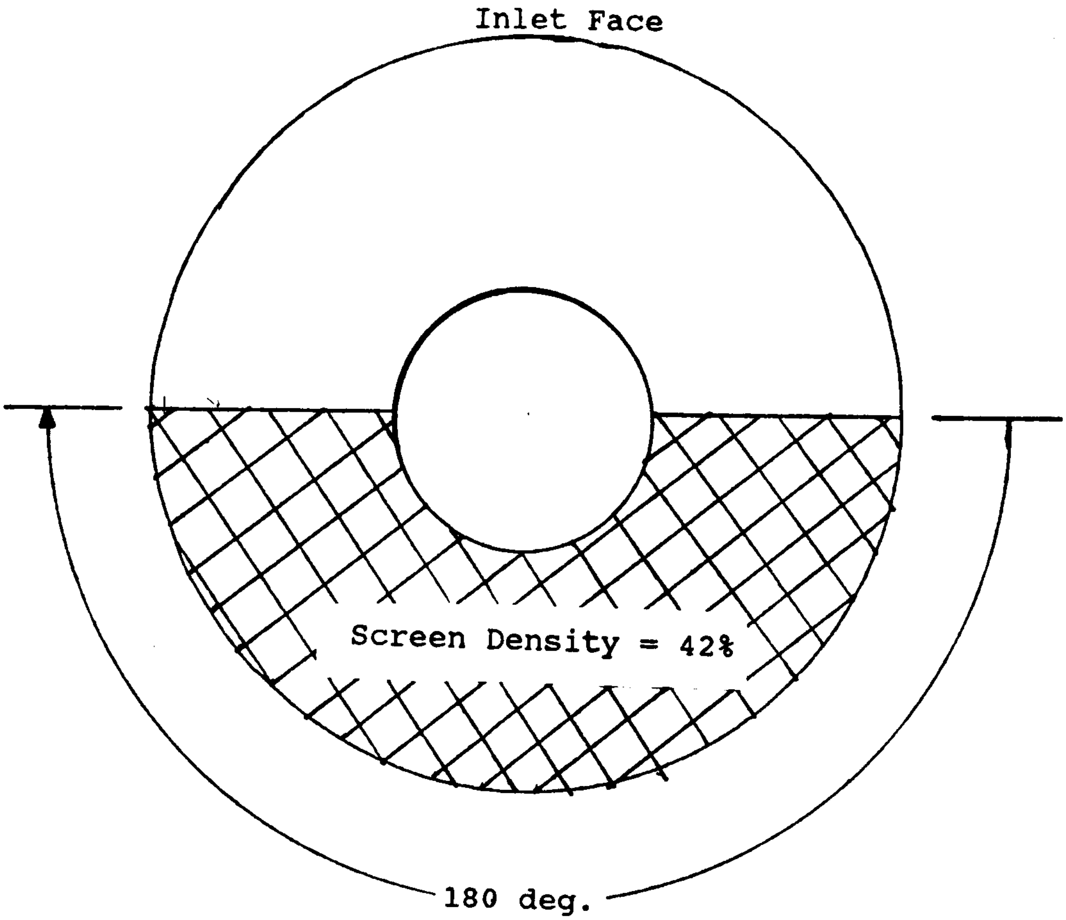


Figure 10. GE J85-13 Compressor Map



COMPRESSOR CORRECTED SPEED (lbm/sec)	SIMPLE DISTORTION INDEX (SDI)
80	0.082
87	0.116
94	0.150

Figure 11. GE J85-13 Inlet Distortion Screen and SDI Values

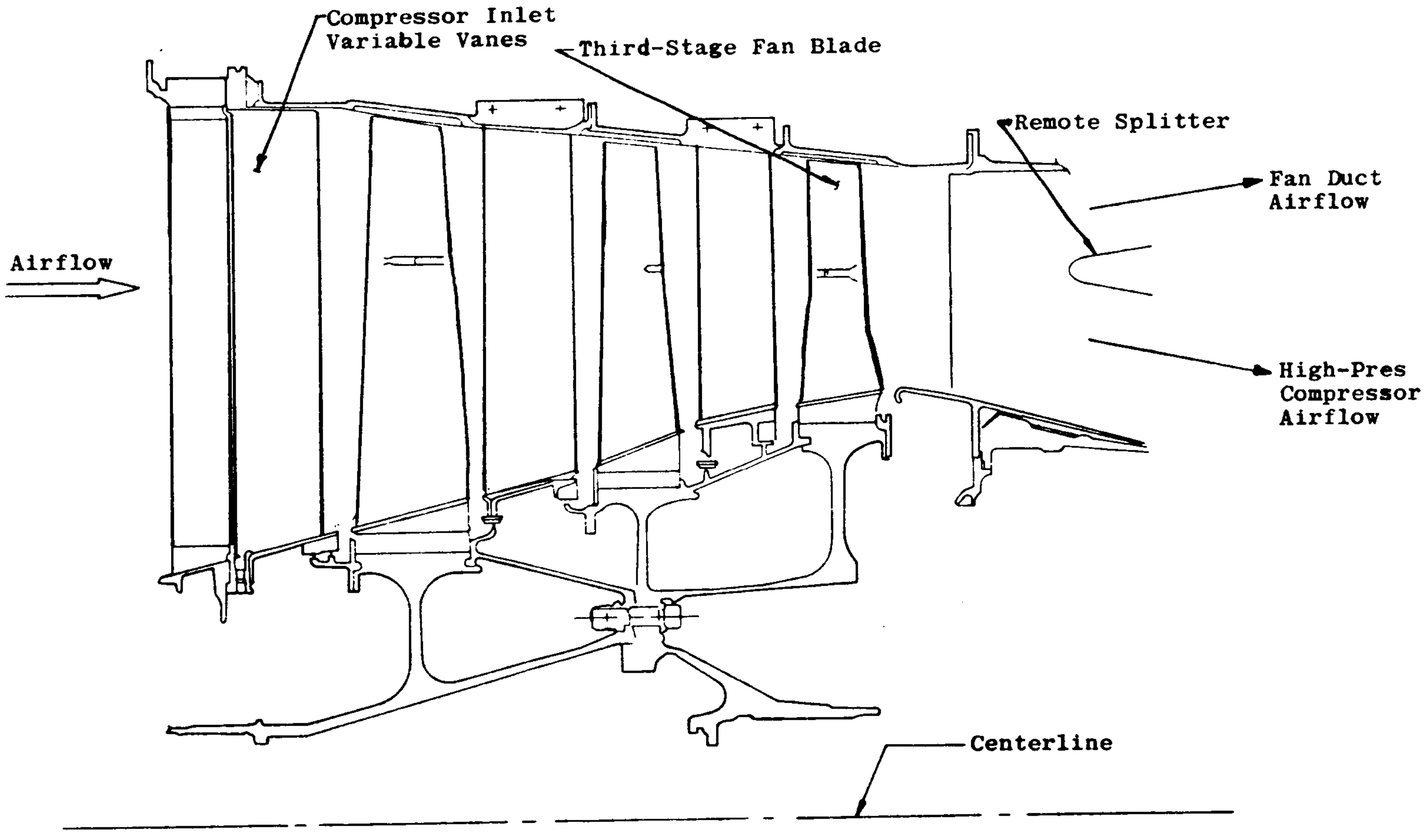


Figure 12. P&W F100(3) Fan Compressor System

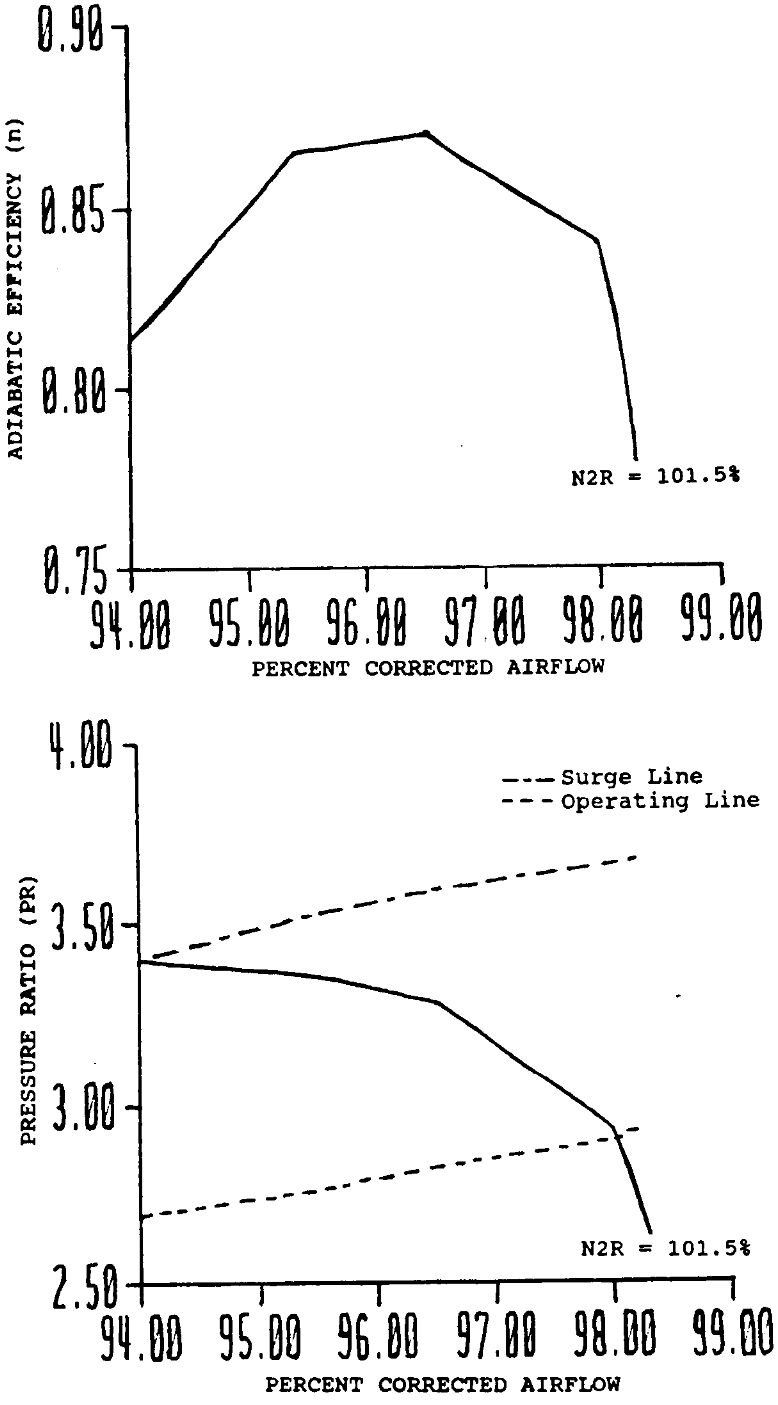
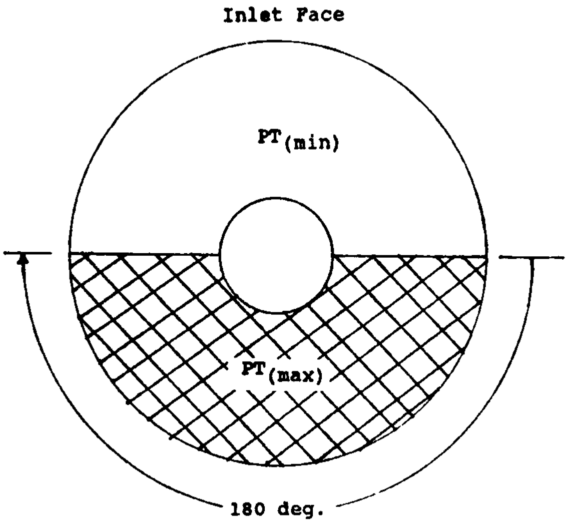
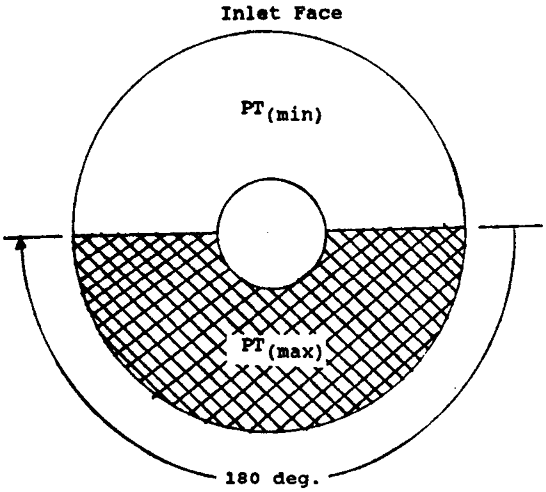


Figure 13. P&W F100(3) Fan Compressor Map

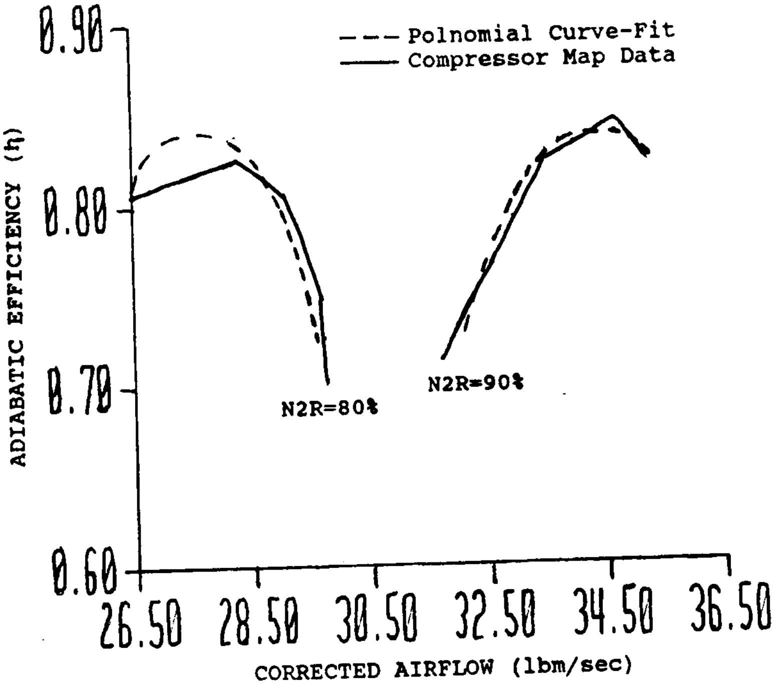


$$SDI = \frac{PT_{(max)} - PT_{(min)}}{PT_{(avg)}} = 0.15$$



$$SDI = \frac{PT_{(max)} - PT_{(min)}}{PT_{(avg)}} = 0.22$$

Figure 14. P&W F100(3) Inlet Distortion Profiles



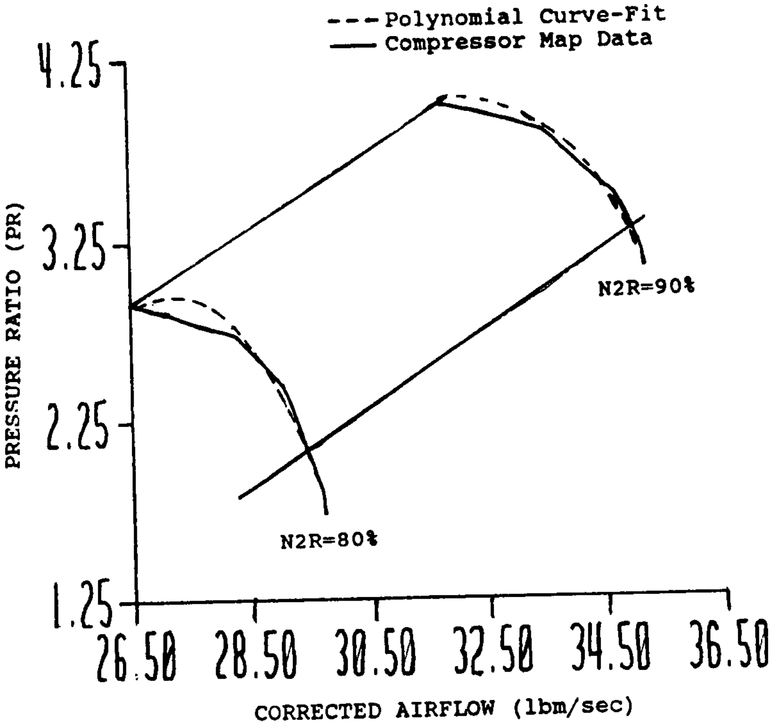


Figure 15. Allison XC-1 Compressor Curve-Fit Results

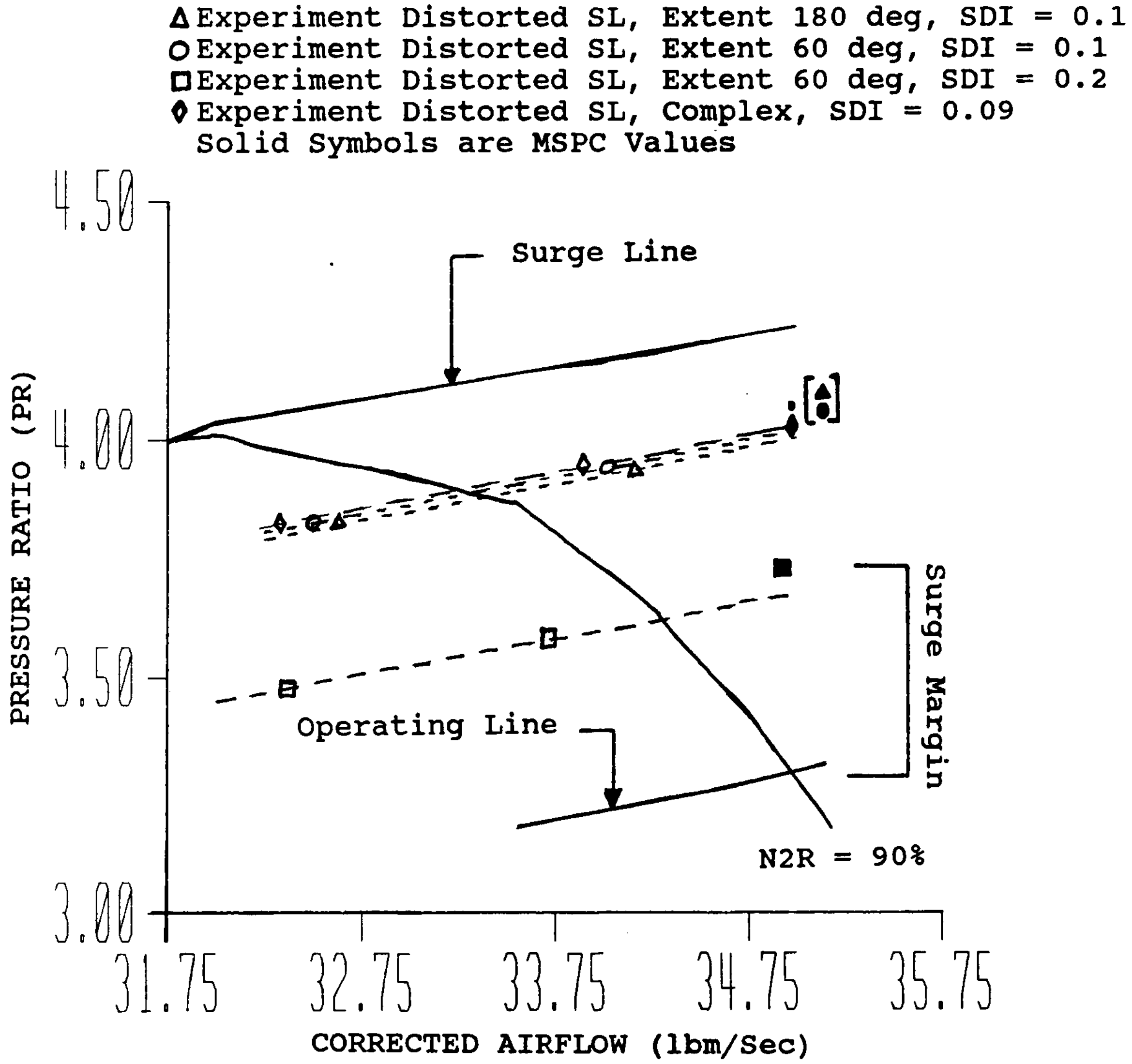


Figure 16. Allison XC-1 Compressor Surge Margin Results

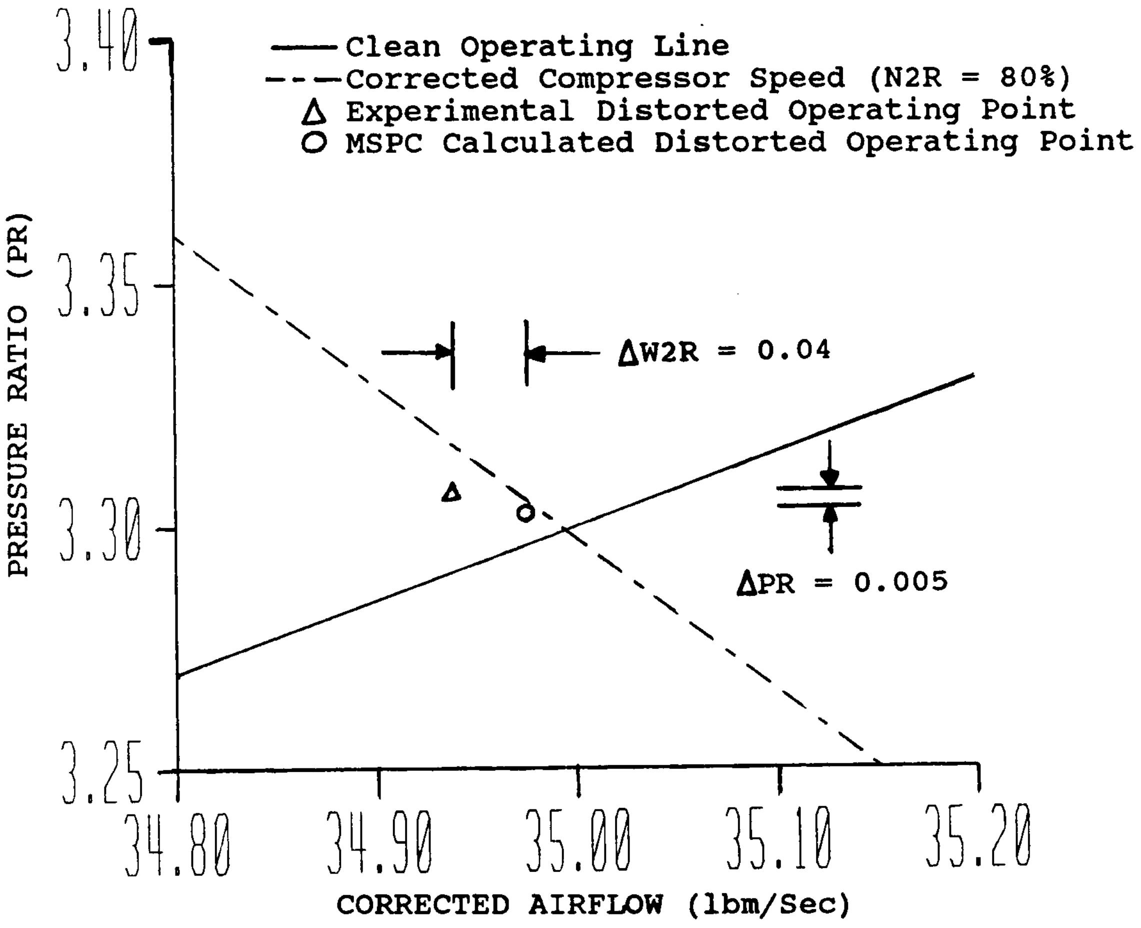


Figure 17. Allison XC-1 Compressor Distortion Performance Results

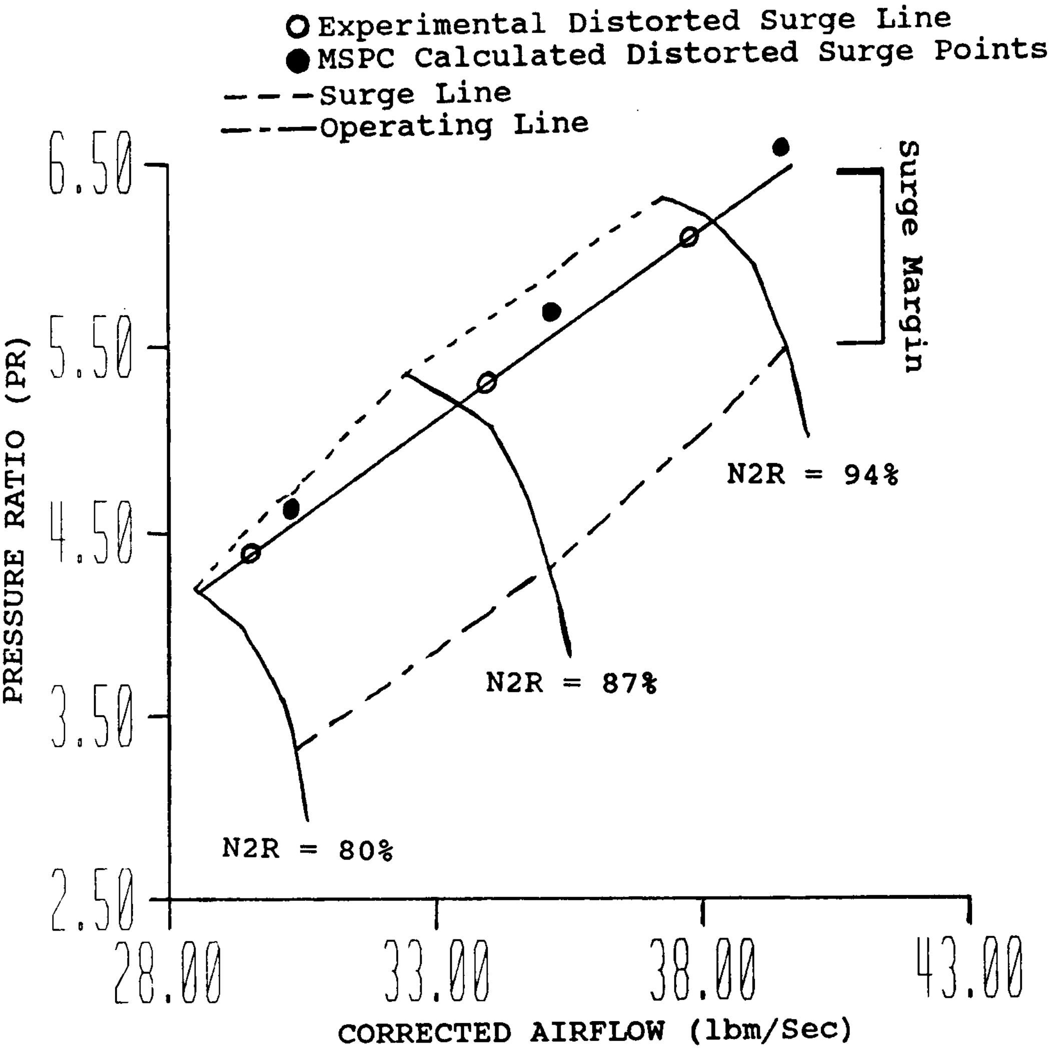


Figure 18. GE J85-13 Compressor Surge Margin Results

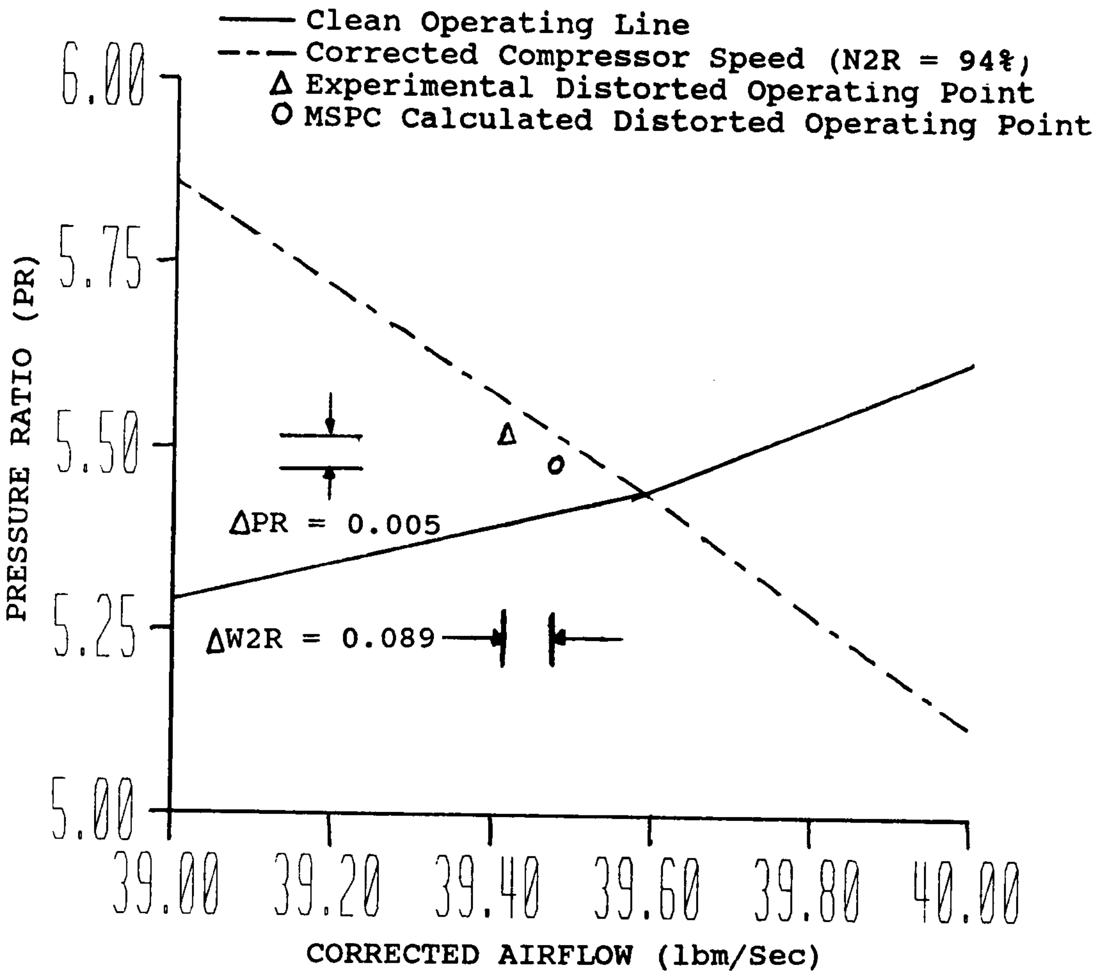


Figure 19. GE J85-13 Compressor Distorted Performance Results

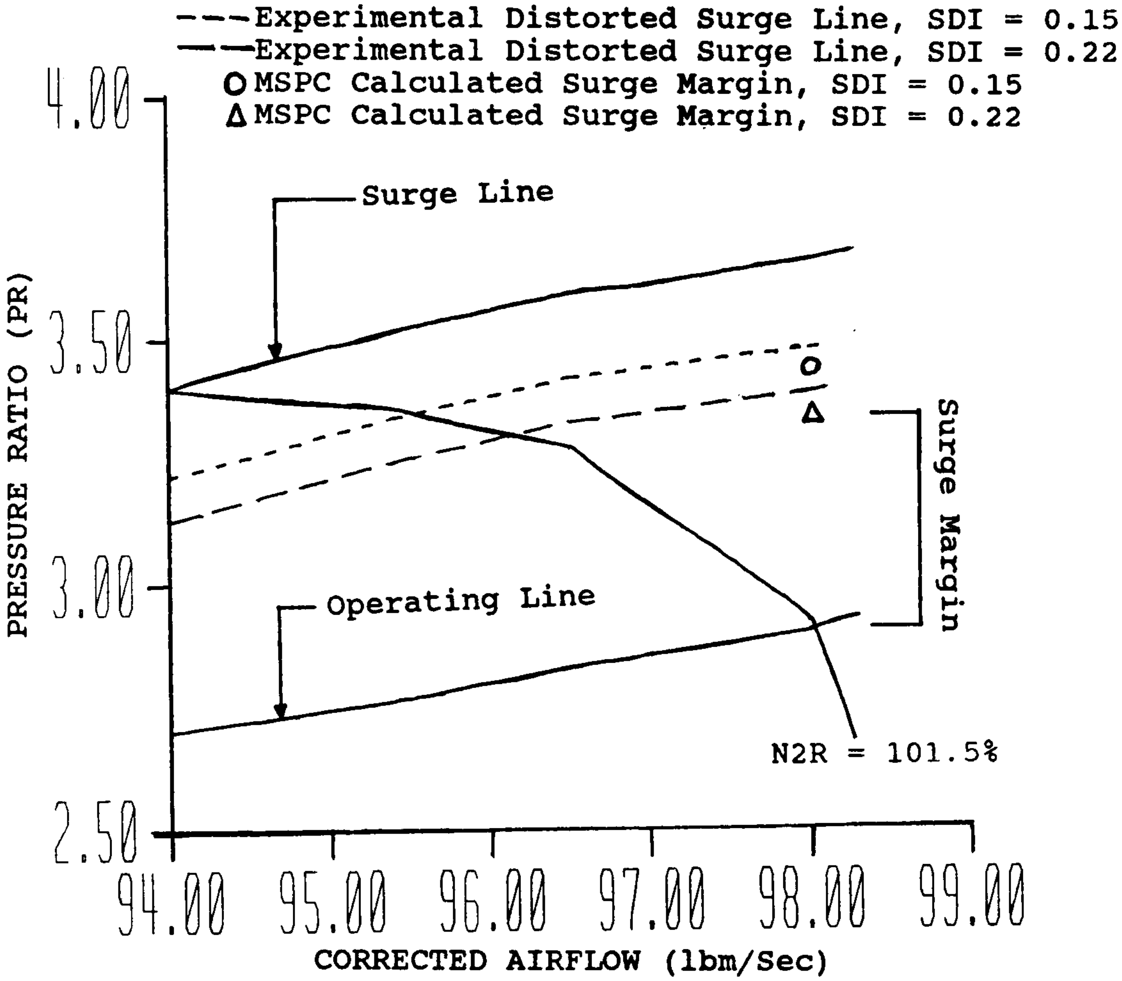


Figure 20. P&W F100(3) Fan Surge Margin Results

VITA

Mark Henry Amundson was born in Paterson, New Jersey on December 18, 1959. With his father working for large construction companies, he moved often until finally residing in Idaho Falls, Idaho. Following graduation from Skyline High School, he entered Idaho State University. Upon the death of his father, James Robert Amundson, his family relocated in Kingston, Tennessee. After going to Roane State Community College for a year, he transferred to Tennessee Technological University and in August 1984 received a Bachelor of Science degree in Mechanical Engineering.

After graduation he was employed by the United States Air Force at Arnold Engineering Development Center, Arnold Air Force Base, Tennessee in September 1984. He enrolled at the University of Tennessee Space Institute in the Spring of 1985. He received the Master of Science with a major in Mechanical Engineering in May 1991.

He is married to the former Mickie Marrie Davis of Livingston, Tennessee. They have three children-Kady, Annie, and Will.