Statistical Analysis Method for Prediction of Maximum Inlet Distortion

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An analytical method is described that uses inlet total pressure statistical properties and a random number process to predict the most probable maximum pressure distortion and pressure distortion map at the entrance to the gas-turbine engine compression system. The method is demonstrated by comparing predicted maximum distortion levels and pressure distortion maps with measured peak distortion levels and pressure contour maps obtained from analog screening of inlet pressure data.

Nomenclature

f_c	= cutoff filter frequency
h_0, h_k	= filter weighting coefficients
M	= $(N-1)/2$
N	= number of samples averaged
P_T	= total pressure
$\Delta P_{T\mathrm{rms}}/P_T, T$	= turbulence
RN	= random number
X_i, Y_0	= filter input and output, respectively

Subscripts

dyn	= dynamic
f	= fluctuating
i	= ith pressure
0	= freestream
ss	= steady state

Introduction

THE success of advanced high-performance aircraft depends heavily on highly efficient, stable thrust generation, which, in turn, depends on a high degree of compatibility between the inlet and gas-turbine engine. Since gas-turbine engines react to transient flow distortion, an essential element in assessing that compatibility is the determination of the time-variant total pressure distortion generated by the inlet. A deterministic analysis procedure has been used extensively for processing time-variant pressure distortion data. Filtered high-response engine face pressure data are combined with their respective steady-state total pressure component and input to a set of engine distortion parameter equations. The time-variant distortion is computed as a function of time from which peak distortion levels and pressure distortion maps are determined. If the peak distortion level is less than some limit value related to an engine surge margin allocation, a compatible inlet-engine combination exists. The procedure has been a successful but conservative approach to the problem.

While the analysis process is well in hand, the complete process of large-scale model fabrication, instrumentation, test, data acquisition, and analysis is an extremely expensive and time-consuming part of aircraft preliminary design. In recent years, various methods[1-6] have been proposed that use statistics in the development of inlet flow distortion analyses. These methods use either the distortion parameter or the pressure statistical properties to predict the maximum distortion level. Some of these methods include a synthesis of the pressure distortion pattern. Distortion pattern synthesis has been accomplished by steady-state pattern intensification and the use of a random number process.

It is the use of the random number process, coupled with the inlet pressure statistical properties, that is the subject of this paper. This approach has been examined previously by three investigators.[4-6] Due to the potential of these methods, a model similar to that described in Ref. 5 was used in comparisons with several inlet distortion data sets. The initial results appeared to validate the model, particularly in terms of the predicted peak distortion level. As cases with increasing average inlet turbulence were investigated and as fewer root-mean-square (rms) turbulence measurements were used in the analysis, the quality of the predicted maps deteriorated. (Turbulence is defined as the ratio of the standard deviation or rms of the time-variant pressure to the steady-state total pressure.) In spite of these results, the approach of using random numbers to generate a synthesized pressure distortion map remained promising if improvements could be made to the method.

Two improvements have been incorporated into the basic method. First, digital filters have been added to shape the power spectral density (psd) of the random numbers to approximate the psd of typical inlet pressure data. Second, map averaging is used to provide the most probable maximum pressure distortion pattern and offers a substantial improvement in the quality of the pressure contour map.

Background

Many statistical methods have been developed to predict the maximum distortion level, and, in some instances, provide a predicted pressure contour map. Three methods that use a random number process are described in this section. The fundamental premise of these methods is that a random number process can be used to synthesize the fluctuating component of the dynamic total pressure from the statistical properties of the inlet pressure data.

It is assumed that the time-variant pressure data are random and stationary, with a normal distribution. A random number generator with a normal distribution and a zero mean, and the measured standard deviation (rms) of pressure, is used to form a synthesized fluctuating pressure component. The fluctuating component is added to the steady-state total pressure to form the dynamic total pressure. The dynamic pressures are then input to a set of engine distortion parameters and a maximum value is determined.

Motycka's method[4] consists of determining the mean rms pressure as a function of frequency, and the psd for each pressure probe. An amplitude probability density curve is generated for each pressure from the rms level assuming a normal distribution. Random numbers are converted to pressures from a cumulative amplitude probability density function

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determined from the integration of the amplitude probability density curve. The synthesized pressures are scaled to the experimental psds with a digital filter and stored. Filter coefficients are determined from an amplitude gain curve formed by dividing the psd of the test data by the psd of the random numbers. Therefore, the power spectrum for the synthesized pressure is modified to have the same power spectrum of the experimental data. The resulting equivalent pressure-time traces are then reduced in the same manner as digitized pressure data used in the deterministic approach for finding the maximum distortion level and pressure contour map.

Motycka presented a single case, and, while there was good agreement between measured and predicted results, he could offer no general conclusions regarding the accuracy of the method. An extreme value analysis[3] was accomplished from which it was concluded that the influence of the filter was to reshape an extreme value distortion vs time relationship. As a consequence, Motycka suggested that the digital filter could be eliminated if the maximum expected value is for a relatively long operating time.

Sanders[7] evaluated Motycka's method using three distortion factors and four sets of inlet data. There was a tendency to overpredict the maximum distortion level using General Electric (GE) distortion parameters, and a tendency to underpredict the measured values using Pratt & Whitney Aircraft (PWA) and William Research Corporation (WRC) distortion parameters. This tendency to underpredict was attributed to an invalid assumption of normality for the pressure data. The prediction of distortion patterns was considered good but the agreement between measured and predicted maps decreased significantly for turbulence levels greater than 0.02.

The method developed by Stevens et al.[5] is very similar to that of Motycka, with two differences. First, the pressure data are processed at a cutoff filter frequency consistent with expected engine sensitivity in determining the probe rms turbulence levels. Second, no power spectrum shaping is used in the analysis. Large sample sizes are considered necessary to represent dynamic pressure data accurately. For example, if the highest frequency of interest is approximately 1000 Hz, and five or more samples are required per cycle, then some 150,000 samples or time slices are required to analyze an equivalent 30 seconds of data.

Predicted peak distortion levels and pressure contour maps were compared to F-15 and F-18 inlet data bases. Peak distortion levels, based on PWA and GE distortion parameters, were approximately 10% under and over the measured values, respectively. This result is consistent with Sanders' analysis of Motycka's method. Stevens also investigated the use of fewer measured turbulence values to predict the peak distortion levels and found that the results were about the same as when all the measured rms turbulence values were used. A comparison of predicted vs measured pressure contour maps using both 16 and 48 rms turbulence values was also accomplished. It was concluded that the pressure contours obtained using the statistical model with 48 rms turbulence values generally agree well with the measured contours, but for the reduced number of turbulence values, the predicted contours were only representative of the measured contours.

Forner and Manter[8] used Stevens' method to predict peak distortion levels, based on the WRC distortion parameters, for cruise missile inlet configurations. Comparisons between predicted vs measured peak distortion levels showed that almost all of the data fell within a +10 to −20% band. There were a number of cases where there was poor agreement between the predicted and measured pressure distortion maps. Other patterns were judged to be good on a qualitative basis, but exhibited fairly large differences between individual predicted and measured probe values. The duct flow was known to be highly dynamic with regions of separated flow. Forner and Manter also investigated the use of fewer turbulence measurements and found that four, eight, or twelve values provided as good a prediction of distortion as with 40 turbulence measurements. However, as fewer measured turbulence values were used, fewer predicted patterns agreed with measured patterns.

A third investigator to report on the development of a statistical synthesis method using a random number generator and local rms pressure data was Borg.[6] In his method, the normally distributed random numbers were generated by adding 12 independent random numbers from a uniform distribution applying the central limit theorem. Briefly, the central limit theorem states that "the sums of independent random variables under fairly general conditions will be approximately normally distributed, regardless of the underlying conditions."[9] The rms pressures were determined using a suitable cutoff filter frequency. Borg used the Pratt & Whitney and Rolls-Royce distortion parameters to evaluate his method. Results with the PWA parameters were consistent with that of Stevens and Sanders. One interesting aspect of the study was the use of the average rms pressure value at all probe locations. Since there was no drastic change in the distortion level correlations, Borg concluded that a reduced number of turbulence values could be used if they reflected the average turbulence intensity. No comparisons were made between predicted and measured peak distortion maps.

Statistical Model Development

The basis for the method is that a synthesized fluctuating pressure component can be constructed and added to the steady-state pressure to form the dynamic total pressure. The fluctuating pressure is assumed to be stationary and random with a normal distribution.

The synthesized fluctuating pressure can be determined for each probe using a random number generator with a zero mean and the standard deviation derived from the measured turbulence levels. If the dynamic total pressure is defined in terms of pressure recovery, then, for each probe,

$$\left(\frac{P_{Ti}}{P_{T0}}\right)_{\rm dyn} = \left(\frac{P_{Ti}}{P_{T0}}\right)_{\rm ss} + \left(\frac{\Delta P_{T\rm rms}}{P_T}\right)_i \times \left(\frac{P_{Ti}}{P_{T0}}\right)_{\rm ss} \times RN_i \quad (1)$$

The basic method is similar to that described by Stevens et al.[5] and consists of two fundamental elements: the generation of the compressor face dynamic total pressures and the determination of the maximum distortion level and pressure contour map. Rms turbulence and random numbers are combined to form the fluctuating pressure components which are added to the steady-state pressures to form the dynamic total pressures. The dynamic total pressures are input to the distortion parameter equations and the level is determined. The pressure distortion map is also generated. Forty new random numbers are generated providing a new set of dynamic total pressures that represents data from another equivalent time slice. The distortion level is computed and compared to the current maximum value. The sequence is repeated until a desired sample size is reached.

Inlet Data Base

Forty-nine cases from two sets of inlet data with three sets of engine distortion parameters were used to assess the basic and improved methods.[10] Average compressor face turbulence ranged from approximately 0.01 to 0.08. The representative cases presented in this paper are for one inlet and one set of distortion parameters.

Compressor face instrumentation consisted of 40 steady-state and high-response probes in an eight-rake by five-ring array located on centroids of equal projected area. The fluctuating pressure data were filtered at 500 and 1000 Hz (−3 dB) consistent with engine sensitivity, inlet model scale, and available cutoff filter frequencies.

The engine distortion parameters used in the analysis of Ref. 10 were the PWA K parameters and GE ΔPRS_F and IDL methodologies. For the PWA distortion methodology, the

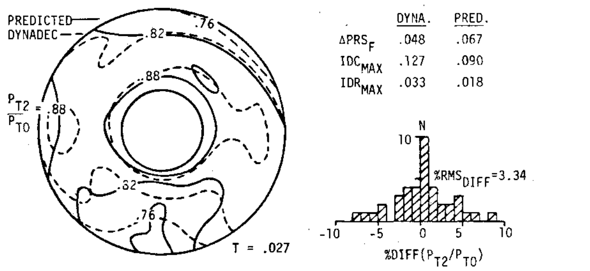

Fig. 1 Basis method – pressure contour map and histogram, moderate turbulence.

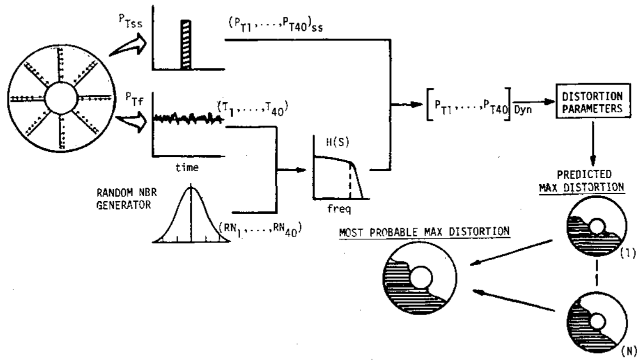

Fig. 2 Improved statistical prediction model.

total distortion is the sum of the circumferential and weighed radial distortion components

$$K_{A2} = K_\theta + bK_{RA2} \tag{2}$$

The GE parameters describe either the stall pressure ratio loss ΔPRS_F, the sum of the loss in fan stall pressure ratio due to circumferential and radial distortion, or the ratio of surge margin required to that available for distortion defined as *IDL*. Functionally, ΔPRS_F and *IDL* can be expressed in terms of the maximum circumferential and radial distortion,

$$\Delta PRS_F, IDL = f(IDC_{\max}, IDR_{\max}) \tag{3}$$

The capabilities of the basic and improved methods are illustrated using the GE distortion parameters, ΔPRS_F, $IDC_{\max}$, and $IDR_{\max}$.

Basic Method Comparisons

The limitations of the basic method are illustrated in Fig. 1. Figure 1 presents a comparison between a map predicted by the basic method and a measured peak distortion pressure contour map determined with DYNADEC.[11] The measured map was determined from filtered pressure data ($f_c = 500$ Hz) and input to the GE distortion parameters and screened for the peak distortion level. For this moderate turbulence case there is a substantial difference between the predicted and measured maps as well as the predicted and measured peak distortion levels. ΔPRS_F is overpredicted by 43%. The dissimilarity of the maps is further emphasized with a histogram showing the distribution of the difference in probe pressure recovery for the 40 compressor face probes. Twenty-two probes agree to within ±2% of their measured value with the range in predicted pressures varying from −8 to +9% of a measured value. The $\%\text{rms}_{\text{diff}}$ is defined as

$$\%\text{rms}_{\text{diff}} = \left\{ \frac{1}{n-1} \sum \left[\frac{\Delta P_{Ti}}{P_{T0}} - \frac{\Delta \bar{P}_T}{P_{T0}} \right]^2 \right\}^{1/2} \times 100\% \tag{4}$$

where ΔP_T is the difference between predicted and measured pressures. The percent rms difference for the 40 probes is 3.34.

From an analysis of the cases examined in Ref. 10, it appears that a statistical prediction model's ability to predict the maximum distortion level accurately may have little to do with providing an accurate distortion map. A distortion parameter can provide some averaging that minimizes the effect of the differences between predicted and measured probe recoveries. For example, the PWA circumferential distortion parameter, K_θ, uses a Fourier curve fit of the pressure distribution about a ring, and, consequently, may be affected less by differences between predicted vs measured pressure values. On the other hand, the GE circumferential distortion parameter, *IDC*, uses the minimum pressure probe value in defining the distortion level. If that minimum value is in error, it has a significant effect on the prediction of total distortion.

Histograms for the 49 cases investigated have shown that, as turbulence increases, there is a flattening and spreading of the distribution with large differences between predicted and measured probe pressures.

Improved Statistical Model Description

A schematic of the improved model is shown in Fig. 2. The method consists of three elements: the generation of the compressor face dynamic total pressures, the determination of the maximum distortion level and pressure contour map, and the map averaging that provides the most probable maximum distortion level and pressure contour map.

The rms turbulence and random numbers are combined, as was done in the basic method. However, these synthesized pressures are now input into the two digital filters added to the basic model. The first filter is a nonrecursive filter that provides a slight rolloff over the entire power spectrum and the second filter, the recursive filter, accounts for engine sensitivity. The second filter's output is the filtered synthesized fluctuating pressure component that is added to the steady-state pressure to form the dynamic total pressure. The dynamic total pressures are input to the distortion parameter equation where the distortion level is determined. Forty new random numbers are generated, providing 40 filtered dynamic pressures for another equivalent time slice. The distortion level is then computed and compared to the current maximum value. The larger value is retained, as well as the pressures for the distortion map. The sequence is repeated until a desired sample size is reached which is based on cutoff filter frequency. The entire solution is then restarted with another set of random numbers, another maximum distortion map is generated, and this sequence is repeated several times. The pressure recoveries of each probe for all of the generated maximum maps are summed and averaged to develop the most probable maximum distortion map.

The concept of map averaging is presented. A different random number set will generate a somewhat different but equally valid predicted distortion contour map and level. The impact is small for probes with low turbulence levels, but can be significant for probes with high turbulence levels. Therefore, for each probe, the predicted pressure is considered to be part of a distribution. The average maximum distortion map is achieved by repeating the solution several times with different sets of random numbers to generate several maximum distortion maps. Individual probe pressures are summed and averaged so that the resulting 40 pressures represent the data for the most probable or average maximum pressure distortion map. For the cases presented, the pressures for six maximum distortion maps were summed and averaged.

Digital Filter Development

The power spectral density for inlet pressure data used in a dynamic distortion analysis exhibits two characteristics. First, the spectrum exhibits a decreasing amplitude as frequency increases as more energy is usually present at lower frequencies. Second, the spectrum has a sharp rolloff above some frequency due to the use of a filter defining engine sensitivity. Digital filters are added to the basic prediction model to impose the additional condition that the power spectral density for the generated random numbers will have a shape approximating that of inlet pressure data.

A normally distributed, uncorrelated set of random numbers is equivalent to white noise which has a flat power spectrum. The psd function for low-pass white noise is defined as

$$G_x(f) = a, \quad 0 < f \leq B; \quad 0 \text{ otherwise} \tag{5}$$

A nonrecursive filter is used to satisfy the general observation that more energy is contained in the lower portion of the spectrum. Nonrecursive filters represent a data-averaging technique that uses variable weighting coefficients. The formula[1] for this type of filter is

$$Y_n = h_0 X_n + \sum_{k=1}^{M} h_k (X_{n-k} + X_{n+k}) \tag{6}$$

A filter with three coefficients was selected to minimize nodal points in the power spectrum. The shape of the spectrum is dictated by the values of h_k and h_0 used. As the values of h_k increase and h_0 decrease, the spectrum exhibits a progressively steeper rolloff characteristic. The influence of this filter on the predicted maximum distortion level and pressure contour map is affected by the cutoff filter frequency describing engine sensitivity. If the cutoff filter frequency is in the lower portion of the spectrum, where it is essentially flat, the effect of the nonrecursive filter is very small. Thus, the nonrecursive filter has a secondary effect on the predicted maximum distortion level with small values of h_k and cutoff filter frequencies in the lower portion of the spectrum.

The filter used to describe engine sensitivity has the greatest effect on predicted levels of distortion. Engine manufacturers have specified three- or four-pole linear phase (Bessel) and constant-amplitude (Butterworth) filters to describe critical engine frequencies.[12] Butterworth filters exhibit a sharper rolloff characteristic beyond the cutoff frequency, while Bessel filters minimize in-phase relationships with frequency. Three-pole Butterworth filters are used, for example, to filter the pressure data used in the DYNADEC analysis.

A recursive filter was selected to represent a three-pole analog Butterworth filter. Whereas the output of a nonrecursive filter is a function of the input only, the recursive filter output is a function of previous output as well as input. This recursive filter[13] uses a bilinear transformation of a continuous filter function, defined as

$$S = (Z-1)/(Z+1) \tag{7}$$

where S is a complex variable and Z a rational function that maps the imaginary axis of the S-plane onto the unit circle of the Z-plane. The desired digital filter is obtained by substituting the bilinear transform into the analog transfer function $H(S)$, defined for a three-pole Butterworth filter as

$$H(S) = \frac{\omega_A^3}{S^3 + 2\omega_A S^2 + 2\omega_A^2 S + \omega_A^3} \tag{8}$$

ω_A is an analog frequency variable defined as

$$\omega_A = \tan \frac{\pi f_c}{\text{sampling rate}} \tag{9}$$

By expanding the equation and combining certain terms, the filter output can be expressed as

$$Y_0 = B_0 X_i + B_1 Z^{-1} X_i + B_2 Z^{-2} X_i + B_3 Z^{-3} X_i$$
$$+ C_1 Z^{-1} Y_0 + C_2 Z^{-2} Y_0 + C_3 Z^{-3} Y_0 \tag{10}$$

where X_i and $Z^{-1}X_i$, $Z^{-2}X_i$, and $Z^{-3}X_i$ are the current and past three input values of X_i, respectively, and $Z^{-1}Y_0$, $Z^{-2}Y_0$, and $Z^{-3}Y_0$ are the past three output values.

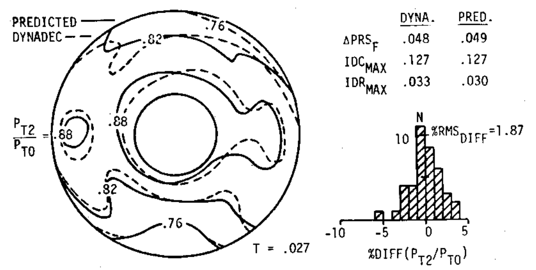

Fig. 3 Pressure contour map and histogram, moderate turbulence, 40 turbulence measurements.

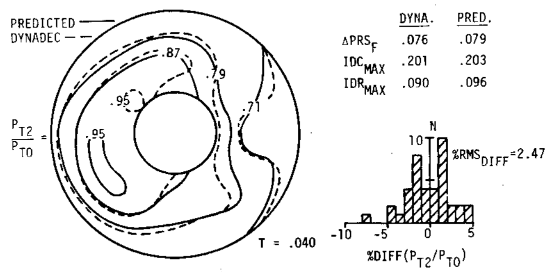

Fig. 4 Pressure contour map and histogram, high turbulence, 40 turbulence measurements.

By defining the Butterworth filter in this manner, the coefficients can be expressed in terms of the cutoff frequency and sampling rate. Based on experience, the sampling rate should be at least four times the cutoff frequency. Lower sampling rates were found to introduce instabilities in the filter algorithm.

Statistical Model Results

The improved method's capabilities are shown by presenting predicted pressure contour maps and distortion levels for representative moderate and high-turbulence level cases. For the examples presented, the nonrecursive filter is not included since the cutoff filter frequency ($f_c = 500$ Hz) used with the GE distortion parameters is in the flat portion of the shaped spectrum.

The predicted maximum distortion level and most probable maximum pressure contour map are presented in Fig. 3 for the moderate turbulence level case presented earlier. Both the experimental and synthesized fluctuating pressure data are based on filtering the raw data at a frequency of 500 Hz. Excellent agreement has been achieved between the predicted and measured contour map and total distortion levels, including the circumferential and radial components. The distribution of probe recovery difference (the histogram) shows that 29 probe pressures are within ±2% of their measured values, while the range has decreased from 17% for the basic model to 10% for the improved model. The rms difference for the 40 probes is 1.87%, a 44% improvement over results from the basic model.

A high-turbulence case is presented in Fig. 4 to further demonstrate the capabilities of the model. The pressure contours of the predicted map show excellent agreement with the measured map with the exception of the pressure recovery contour of 0.95. Predicted and measured distortion levels exhibit excellent agreement. The number of probes within ±2% of their measured values is 26, a 73% improvement over the results with the basic method (not shown). The range of difference decreased 56% and the rms_{diff} decreased 46% compared to results with the basic model.

The improvement over the basic model is summarized in the next two figures using two measures of goodness, the percent rms difference, $\%\text{rms}_{\text{diff}}$, between predicted and measured probe pressure recoveries, and the number of probes with predicted recoveries within ±2% of their measured values.

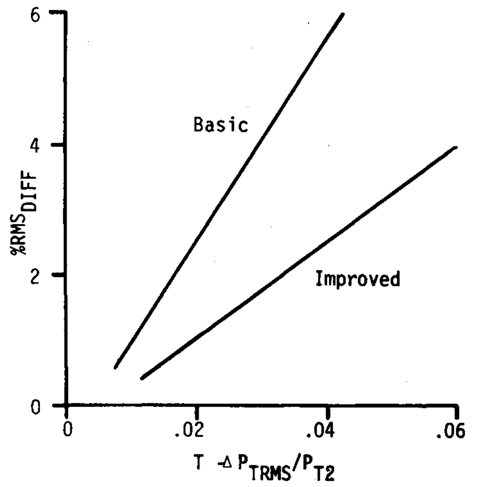

Fig. 5 Percent rms difference.

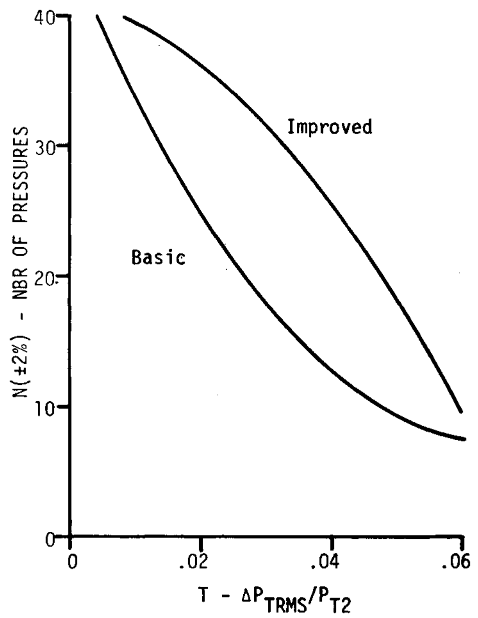

Fig. 6 Predicted pressures within $\pm 2\%$ measured P_{Ti}.

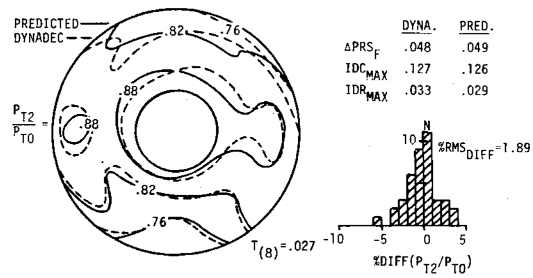

Fig. 7 Pressure contour map and histogram, moderate turbulence, 8 turbulence measurements.

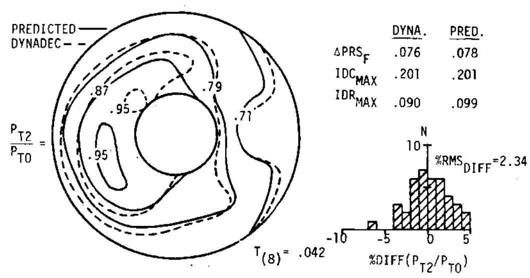

Fig. 8 Pressure contour map and histogram, high turbulence, 8 turbulence measurements.

The linear regression lines, Fig. 5, illustrate the reduction in $\%\text{rms}_{\text{diff}}$ using filtering and map averaging with the GE distortion parameter methodology for cases having average turbulence levels of 0.01-0.06. With the exception at low-turbulence levels where there is little difference between the models, the filtering of the synthesized pressures in combination with map averaging provides a substantial reduction in the percent rms difference between predicted and measured pressures. For example, at an average compressor face turbulence level of 0.04, the %rms difference with map averaging filtering is 2.5, a reduction of 56% compared to the basic model. The regression curves in Fig. 6 present the other indicator of goodness, the number of pressures agreeing within $\pm 2\%$ of their measured value using the GE methodology. In terms of this parameter, there is little difference between the basic and improved models for turbulence levels of less than 0.01 and for levels greater than 0.06. [The improved model is significantly better than the basic model for turbulence levels above 0.06 as shown in Fig. 5. $N(\pm 2\%)$ is not the appropriate indicator.] Maximum benefits from the improved model are in the 0.02-0.04 turbulence range. For a turbulence level of 0.03, the combined filtering and map averaging offers a substantial improvement in the number of probes predicted to be within $\pm 2\%$ of their measured value. Thirty-two pressures are within $\pm 2\%$ of their measured value for the improved model, compared to only 18 pressures for the basic method.

Thus far, the analysis has been based on 40 measured turbulence values. Comparisons are now presented using eight measured values. The turbulence distribution for each ring is assumed to be the same as that for the third ring of the eight-rake by five-ring array.

The predicted pressure contour map for the moderate-turbulence case, based on eight measurements, is shown in Fig. 7. The only difference between the results presented here and those based on 40 measurements, Fig. 3, is the slightly different distribution in the histogram depicting the difference between predicted measured probe recoveries. Otherwise, there is excellent agreement between predicted and measured pressure contours and the distortion parameter components, with no difference in the number of pressures within $\pm 2\%$ of their measured values. Essentially the same quality of results is obtained for the high-turbulence case, Fig. 8. All of the indicators of goodness—the pressure contours, the distortion levels, and the distribution of the difference in probe recovery—show virtually identical results to those based on 40 turbulence measurements. For the cases examined in Ref. 10, the effect of using fewer measured turbulence values on the average percent rms difference between predicted and measured probe recoveries and on the average number of predicted pressures within $\pm 2\%$ of their measured values was small.

An examination of the magnitude of the terms of the equation defining dynamic total pressure recovery, Eq. (1), in particular the fluctuating pressure component term, would suggest that the recovery term and the random number dominate the turbulence value. Consequently, only a reasonable estimate of probe turbulence is required to predict the most probable maximum distortion pressure contour map. Previous investigators[5-8] have shown that the maximum distortion level is predicted just as well with fewer turbulence measurements as with 40 values. This study has shown that a good estimate of the pressure contour map is possible with fewer turbulence measurements as well.

Summary

A prediction method that uses the inlet total pressure statistical properties and a random number generator has been developed to predict the most probable maximum distortion and pressure contour map. The model incorporates two digital filters to shape the random number power spectrum to approximate that of inlet pressure data and a map-averaging approach that provides the most probable maximum distortion.

Several measures of goodness have been used to assess the capability of the model. Those factors include the predicted pressure contour map and distortion level, the distribution of the difference and the standard deviation of the difference between predicted and measured pressures, and the number of pressures agreeing to within ±2% of their measured values.

The results indicate that the model can be applied to inlet pressure data having average turbulence levels up to 0.04. The assumption that the pressures have a normal distribution may preclude its application to those situations where there is substantial separation or planar wave phenomena.

While not illustrated here, a conclusion from the basic study indicated that the relative benefits of filtering is a function of cutoff filter frequency. As cutoff filter frequency increases, the standard deviation of the difference (%rms_{diff}) between predicted and measured pressures increases and the number of pressures agreeing within ±2% of their measured values decreases. The application of the method, including map averaging, may be limited to cutoff filter frequencies of less than 1500 Hz.

The improved method has been shown to provide predicted pressure contour maps that are in substantial agreement with measured contour maps based on both 40 and 8 measured turbulence values.

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