NASA TECHNICAL MEMORANDUM

NASA TM X-73438

A METHOD TO ACCOUNT FOR VARIATION OF AVERAGE COMPRESSOR INLET PRESSURE DURING INSTANTANEOUS DISTORTION ANALYSES

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TECHNICAL PAPER to be presented at Twelfth Propulsion Conference cosponsored by the American Institute of Aeronautics and Astronautics and the Society of Automotive Engineers
Palo Alto, California, July 26-29, 1976

A METHOD TO ACCOUNT FOR VARIATION OF AVERAGE COMPRESSOR INLET PRESSURE DURING INSTANTANEOUS DISTORTION ANALYSES

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E-8793

Abstract

Instantaneous distortion analyses compare a time-varying value of an index (or "surge margin used up") with a critical level (or "available surge margin" of the compressor) to determine inlet-engine compatibility. Unless freestream conditions or propulsion system controls are changing, it is generally assumed that the available surge margin of the compressor is accurately determined from the steady-state operating point. Results are presented which show that variations of average compressor inlet pressure may occur without changes in freestream conditions or propulsion system controls. The volume dynamics of the compressor will cause these pressure variations to be attenuated and delayed by the time they reach the exit. This will cause the compressor pressure ratio (and available surge margin) to vary with time. A method is presented to calculate the available surge margin as a function of time and incorporate it into an instantaneous distortion analysis. Results show that inlet pressure variations which cause only a small change at the compressor exit can cause a significant variation in the available surge margin.

Introduction

The problems associated with inlet-engine compatibility have received a great deal of attention in recent years (c.f. ref. 1). Wind tunnel and flight test programs have shown that losses in compressor surge margin cannot be predicted using only steady-state total-pressure measurements. Correlations between available compressor surge margin and various steady-state total-pressure distortion parameters have been obtained in engine tests where the magnitudes of the total-pressure fluctuations are small. Inlet-engine compatibility has been investigated by applying these steady-state distortion correlations to a set of fluctuating total-pressure measurements on a quasi-steady, or instantaneous, basis. Since the compressor does not appear to be sensitive to pressure fluctuations above a certain frequency (on the order of engine rev/sec), the total-pressures are normally filtered before instantaneous distortion values are calculated.

To apply the steady-state correlation at each instant in time, it is necessary to calculate both the distortion parameter and the available surge margin as functions of time. Unless freestream conditions or propulsion system controls are changing, it is generally assumed that the available surge margin of the compressor does not change with time and is accurately determined from the steady-state operating point.

Results are presented which show that variations of average compressor inlet pressure may occur without changes in freestream conditions or propulsion system controls. The volume dynamics of the compressor and its terminating volume cause these pressure variations to be attenuated and delayed by the time they reach the exit. The amount of attenuation and delay influence the variation of compressor pressure ratio (and available surge margin) with time.

The objective of this paper is to show that the use of the time-varying value of available surge margin can significantly change the results of an instantaneous distortion analysis. The distortion index used in this paper is of a general form and similar to many in use at the present time. Therefore, the results presented are expected to be indicative of those that would be obtained using many of the current indices.

Data from a supersonic wind tunnel test of an axisymmetric mixed compression inlet and J85-GE-13 turbojet engine are analyzed. Time-varying measurements of compressor-face total pressure are used to calculate exit total-pressure variations (using a compressor transfer function), because adequate exit pressure measurements were not available. Instantaneous values of a distortion index are calculated and compared with both the time-varying and steady-state levels of available surge margin. The differences between the two comparisons are examined to determine the effect of fluctuations in average inlet pressure.

Symbols

f(s)	transfer function
K	distortion index sensitivity coefficient
L^{-1}	inverse Laplace transform
M	Mach number
m	mass flow
N	engine speed
N*	rated engine speed (16 500 rpm)
$\frac{N\times100}{N^*\sqrt{\theta_2}}$	corrected engine speed
P	total-pressure
ΔP	fluctuating component of total-pressure
s	Laplace variable, sec^{-1}
t	time, sec
T	integration period such that $W(T) \approx .01$
W(t)	weighting factor, $L^{-1}[f(s)]$
θ	total-temperature ratio, T/288.2 K

Subscripts:

0	freestream
2	compressor inlet station
3	compressor discharge station
min.	minimum

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s.s steady-state

Superscripts:

— spatial average

Analysis and Procedure

The data to be analyzed were obtained during a test in the 10×10 Foot Supersonic Wind Tunnel at NASA-Lewis Research Center. An axisymmetric, mixed compression inlet was run with a J85-GE-13 turbojet engine at Mach numbers from 2.5 to 2.7. Reference 2 describes the details of the inlet, engine, instrumentation and data acquisition system used in the test.

Table I describes the four test points selected for analysis. In each case the compressor surged after a period of steady operation during which none of the inlet, engine or wind tunnel controls were varied. Fluctuating total-pressure data from 30 compressor face probes (6 rakes of 5 probes) were digitized for a time period up to and including surge. The analog pressure signals were filtered to 1600 hertz before being digitized at 8000 points/sec/channel. Steady-state total-pressure values were added to the fluctuating components to provide absolute pressures for use in the calculation of instantaneous distortion values.

A simple sliding window digital average was used to filter the individual pressure signals before instantaneous distortion values were calculated. An averaging period, or window width, of 2 milliseconds (about 1/2 rotor period) was used for the results presented in this paper.

The distortion index used in this report is based on parallel compressor theory and is described in Ref. 3. Available surge margin is defined at constant corrected speed as

$$\left[1 - \frac{(\overline{P}_3/\overline{P}_2)_{distorted}}{(\overline{P}_3/\overline{P}_2)_{clean\ surge}}\right]_{N/\sqrt{\theta_2} = const.}$$

When spatial distortion of exit total-pressure is negligible, parallel compressor theory indicates that

$$(\overline{P}_3/P_{2,min})_{\substack{distorted\\surge}} = (\overline{P}_3/\overline{P}_2)_{\substack{clean.\\surge}}$$

This means that the following identity should hold at surge:

$$\left(1 - \frac{P_{2,min}}{\overline{P}_2}\right)_{distorted} \equiv \left[1 - \frac{(\overline{P}_3/\overline{P}_2)_{distorted}}{(\overline{P}_3/\overline{P}_2)_{clean\ surge}}\right]_{N/\sqrt{\theta_2} = const.} \quad (1)$$

The left side of the identity is a distortion index which can be interpreted as "surge margin used up," or how far the distorted surge line has decreased from the clean surge line. When the "margin used up" equals the "margin available," surge is expected, as shown in Fig. 1.

Instantaneous distortion analysis should calculate the terms of Eq. (1) as a function of time. Then surge would be expected whenever,

$$\left[1 - \frac{KP_{2,min}(t)}{\overline{P}_2(t)}\right] \geq \left[1 - \frac{(\overline{P}_3(t)/\overline{P}_2(t))_{distorted}}{(\overline{P}_3/\overline{P}_2)_{clean\ surge}}\right]_{N/\sqrt{\theta_2} = const.} \quad (2)$$

where K is an empirical sensitivity coefficient that allows radial distortion patterns to be treated using parallel compressor theory.

Available surge margin as a function of time is given by the right hand side of Eq. (2). Since the dynamic measurements of compressor exit total-pressure did not provide adequate information below about 20 hertz, they could not be used to determine the time-varying pressure ratio. Compressor exit pressure was calculated from compressor face pressure measurements using a transfer function which represented the dynamic behavior of the compressor. The transfer function was determined from an analog computer model of the J-85 compressor. In this model, steady state performance was represented by each stage's pressure and temperature rise characteristics. The compressor's dynamic performance was represented by momentum, continuity, and energy equations at each stage. Rotational speed was constant. This model is described fully in Ref. 4.

Frequency response data from the analog simulation of the compressor were expressed as transfer functions by using a computer program described in Ref. 5. The transfer functions were transformed to the time domain and used as weighting factors in a digital integration of the compressor face total-pressure data. Figure 2 shows the amplitude and phase variations of the compressor transfer functions. The equations of the transfer functions and the expressions for the associated weighting factors are shown in table II, along with the equation used to compute compressor exit total-pressure.

Measurements of unsteady compressor exit pressure would avoid the use of a compressor transfer function, and would also account for changes which are not caused by inlet pressure variations.

Results and Discussion

Effect of Full-Face Pressure Pulses

Consider the case of uniform total pressure at the compressor face (i.e. no spatial distortion). When the total-pressure across the compressor face varies simultaneously with time (a full-face pulse), the disturbance does not "use up" surge margin because it does not generate distortion. However, a full-face pulse may reduce the amount of available surge margin if there is a lag between the compressor inlet and exit pressures. When the pulse frequency is very low, the pressure in the large diffuser and combustor volume at the compressor exit changes almost simultaneously with the inlet pressure. Therefore, the lag between inlet and exit pressure variations is negligible, so the compressor pressure ratio and available surge margin do not change with time.

When the pulse frequency is high, the large exit volume causes the amplitude of the exit pressure variations to be negligible, so pressure ratio (and available surge margin) variation is due only to changes in inlet pressure.

For pulses of intermediate frequency (the range considered in Fig. 2), the inlet and exit pressures of the compressor will be out of phase. Also, the amplitude of the pressure changes in the exit volume will be attenuated. This case is shown in Fig. 3 for a 20 hertz sinusoidal variation of inlet pressure. Available surge margin (or compressor pressure ratio) depends on both inlet and exit pressure variations, so it is not in phase with either of these variations. Since the distortion level (or margin used up) is zero, an instantaneous distortion analysis would predict surge if the available margin reached zero.

The measured inlet pressure variations and compressor response are generally a random combination of the low, medium and high frequency cases discussed above, or a single frequency component may predominate. Figure 4 presents the variation of compressor inlet pressure, $\overline{P}_2(t)$, for test point 103, and the exit pressure variation, $\overline{P}_3(t)$, computed by using the compressor transfer function of Fig. 2(a). The figure also includes a plot of the available surge margin (right-hand side of Eq.(2)). This test point contains a cyclic variation of inlet pressure $\overline{P}_2(t)$ at a frequency of approximately 70 hertz and the delayed, attenuated response to this disturbance at the exit is apparent.

Since compressor transfer functions were only determined for two corrected engine speeds, the wind tunnel data presented in the figures were analyzed with the function for the corrected speed (80 or 100 percent) closest to the value listed in table I. As a check, all data were examined using both 80 and 100 percent speed transfer functions. The two available surge margin variations determined (but not shown) for each test point were quite similar, indicating that changes in attenuation and phase lag between Figs. 2(a) and (b) combine in such a way that the pressure ratio $\overline{P}_3(t)/\overline{P}_2(t)$ does not change very much.

Variations of the average total-pressure at the inlet and exit of the compressor were not as large for the other test points as those shown in Fig. 4, and did not contain large discrete frequency components. Figure 5 is typical of the other test points. It presents the inlet and exit pressures and available surge margin for test point 154 and shows that small pressure variations (about ±2.5 percent in $\overline{P}_2(t)$ and .75 percent in $\overline{P}_3(t)$) combine to produce significant changes (about ±10 percent of .16) in available surge margin.

Instantaneous Distortion Time-Histories

Plots of the surge margin available and surge margin used up (right and left sides of Eq. (2)) as a function of time are presented in Fig. 6 for the test points described in table I. The steady-state level of available surge margin (normally used in a conventional instantaneous distortion analysis) is included for purposes of comparison. The conventional analysis will be valid only when the average inlet pressure variations are of low enough frequency to allow the inlet and exit pressures to change simultaneously. This allows the pressure ratio and available surge margin to remain constant.

Instantaneous distortion analyses assume engine surge will occur when the level of margin used up equals or exceeds the level of margin available. Although surge may not always occur at these points, they serve as an obvious point of comparison for different analyses. The magnitude of the difference between margin used up and margin available is a function of time and depends on which value of available surge margin (steady or unsteady) is considered. Figure 6 shows that when a distortion index (margin used up) of the form $1 - [KP_{2,min}(t)/\overline{P}_2(t)]$ is compared with both the steady and unsteady values of available surge margin, the predictions of engine surge may be significantly different. Some locations where the use of unsteady available margin would predict surge, and the steady-state value would not, are marked by arrows in Figs. 6(a), (b), and (c). For all the plots shown in Fig. 6, many instances are apparent where the unsteady margin available is much closer to the margin used up than the steady-state value.

When the average total-pressure variations at the compressor inlet are of small enough amplitude and/or high enough frequency, the variation of exit pressure will be negligible. In cases of this type, changes in the available surge margin will be due only to the inlet pressure, $\overline{P}_2(t)$. Then the equality of Eq. (2) can be rewritten as;

$$\left[1 - \frac{KP_{2,min}(t)}{\overline{P}_{2_{s.s}}}\right] = \left[1 - \frac{\left(\overline{P}_{3_{s.s}}/\overline{P}_{2_{s.s}}\right)_{distorted}}{(\overline{P}_3/\overline{P}_2)_{clean\ surge}}\right]_{N/\sqrt{\theta_2} = const.} \qquad (3)$$

$\overline{P}_3(t)$ has been replaced by $\overline{P}_{3_{s.s}}$, and instead of eliminating $\overline{P}_2(t)$ from both sides, it has been replaced with its steady-state value. This causes the available surge margin (right side) to assume a steady-state value. If the exit pressure variation, $\overline{P}_3(t)$, is negligible, the equalities of Eq. (2) and (3) will occur simultaneously for a given set of data, and the simplified expression can be used to predict surge. This can be seen by rewriting Eq. (3) as;

$$\frac{-\overline{P}_{3_{s.s}}\Big/(\overline{P}_3/\overline{P}_2)_{\substack{clean\\surge}} + KP_{2,min}(t)}{\overline{P}_{2_{s.s}}} = 0 \qquad (4)$$

This says that, at surge, the difference between margin used up and margin available is zero, and the use of $\overline{P}_{2_{s.s}}$ in place of $\overline{P}_2(t)$ does not influence this result. When this margin difference is not zero, its magnitude depends on $\overline{P}_{2_{s.s}}$. Therefore, even when $\overline{P}_3(t) = \overline{P}_{3_{s.s}}$, finite values of the difference between the margin terms of Eq. (3) and those of Eq. (2) will only be the same when $\overline{P}_2(t) = \overline{P}_{2_{s.s}}$.

The surge margin terms of Eq. (3) are plotted in Fig. 7 for the same test points that were shown in Fig. 6. Arrows that were used as event markers in Fig. 6 are duplicated in Fig. 7.

Test point 154 had a small variation of exit total pressure (Fig. 5), but the assumption that this variation is negligible (Fig. 7(a)) does not give results comparable with those shown in Fig. 6, because the equality marked by the arrow near 12 milliseconds in Fig. 6(a) did not occur in Fig. 7(a).

In Fig. 7(b), the first arrow (near 12 msec) marks another location where Eq. (3) does not predict surge and Eq. (2) (Fig. 6(b)) does. The $\overline{P}_3$ variation is not negligible at that point. However, the second arrow in Fig. 7(b) (near 20 msec) indicates a point where the $\overline{P}_3$ variation is ngeligible. The equality of margin used up and margin available shown in Fig. 6(b) is essentially duplicated in Fig. 7(b). Figure 7(c) presents results, similar to those of Fig. 7(b), marked by two arrows near 50 milliseconds.

Results for test point 261 are presented in Fig. 7(d). The simplified analysis of Eq. (3) compares quite well with the results of Fig. 6(d) for peak values of margin used up. This indicates that both $\overline{P}_3(t)$ and $\overline{P}_2(t)$ are about equal to their steady-state values at those points.

The comparison of Figs. 6 and 7 demonstrates that the average total-pressure variations at the compressor face are not of small enough amplitude or high enough frequency for the exit pressure variations to be negligible.

The simplified analysis (Eq. (3)) fails to match the surge predictions of the full instantaneous analysis (Eq. (2)). This occurs even when $\overline{P}_3(t)$ changes by less than 1 percent (Fig. 5).

Summary of Results

A method was developed to account for the variation of average compressor inlet pressure during instantaneous distortion analyses. The pressure ratio and surge margin of the J85-13 compressor were determined as a function of time. Compressor discharge total-pressure was calculated by applying a transfer function to the measured inlet total-pressure. Supersonic wind tunnel test data from an inlet-engine combination were used to determine the influence of a time variation in available surge margin on an instantaneous distortion analysis. These data were recorded while freestream conditions and propulsion system controls were not changing. An instantaneous distortion index (surge margin used up) was compared with both the steady state and time-varying values of available surge margin.

The following conclusions were drawn:

1. Small variations of the average compressor inlet total-pressure can have a significant effect on available surge margin. Compressor inlet total-pressure variations of ±2.5 percent caused exit total-pressure variations of ±0.75 percent which combined to produce ±10 percent changes about a 0.16 level of available surge margin.

2. The effect of full-face pulses of compressor inlet total-pressure can be accounted for by an instantaneous distortion analysis which includes the time-variation of available surge margin. In the limiting case of zero distortion, the analysis would predict surge when the available surge margin decreased to zero.

3. When a steady-state distortion correlation is applied to time-varying data on a quasi-steady or instantaneous basis, both the distortion index (margin used up) and the available surge margin should be determined as functions of time. The available surge margin is generally assumed to remain constant when freestream conditions and propulsion system controls are not changing. The wind tunnel data that were examined did not support this assumption. This caused the results of an instantaneous distortion analysis using the unsteady level of available surge margin to be significantly different from the results of an analysis using the steady state level of available surge margin.

4. If the average inlet pressure variations are of small enough amplitude and/or high enough frequency, the compressor exit pressure changes will be negligible. In this case, the simplified expression

$$\left[1 - \frac{P_{2,min}(t)}{\overline{P}_{2_{s.s}}} = \text{s.s available surge margin}\right]$$

will be satisfied at the same time surge is predicted by the complete time-dependent distortion analysis. At times when surge is not predicted, the simplified analysis will not accurately express the difference between margin used up and margin available, unless the inlet pressure variations, $\overline{P}_2(t)$, are also negligible.

Results show that exit pressure variations, $\overline{P}_3(t)$, as small as 0.75 percent will cause the simplified expression to fail to predict surge.

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3. Calogeras, J. E., and Burstadt, P. L., "Formulation of a Distortion Index Based on Peak Compressor Pressure Ratios," Proceedings of the Eleventh National Conference on Environmental Effects on Aircraft and Propulsion Systems, U.S. Naval Air Propulsion Test Center, N.J., 1974, pp. 9-1 to 9-8.

4. Willoh, R. G. and Seldner, K., "Multistage Compressor Simulation Applied to the Prediction of Axial Flow Instabilities," NASA TM X-1880, Sept. 1969.

5. Seidel, R. C., "Transfer-Function-Parameter Estimation from Frequency Response Data: A Fortran Program. NASA TM X-3286, Sept. 1975.

TABLE I. - INLET-ENGINE CONDITIONS FOR WIND TUNNEL STALL POINTS

Test point	Mach number, M_0	Angle of attack, degrees	Inlet recovery, $\overline{P}_{2_{s.s}}/P_0$	Inlet mass flow ratio, m_2/m_0	Corrected engine speed, $\frac{N\times100}{N^*\sqrt{\theta_2}}$	Compressor pressure ratio at surge, $\overline{P}_{3_{s.s}}/\overline{P}_{2_{s.s}}$	Available surge margin,[a] steady-state
154	2.50	0	.799	.834	92.25	5.240	.158
148	2.50	0	.788	.704	86.88	4.601	.135
103	2.68	0	.736	.840	86.42	4.684	.110
261	2.58	6	.783	.851	87.00	4.355	.184

[a]Defined at constant corrected speed.

TABLE II. - EQUATIONS FOR COMPRESSOR TRANSFER FUNCTIONS AND WEIGHTING FACTORS

	$\frac{N\times100}{N^*\sqrt{\theta_2}} = 80\%$	$\frac{N\times100}{N^*\sqrt{\theta_2}} = 100\%$
Transfer function, f(s)	$\dfrac{(\overline{P}_3/\overline{P}_2)_{s.s}\exp\left(\frac{-.00166\ s}{2\pi}\right)}{\left(\frac{s}{68.25\times2\pi}+1\right)\left(\frac{s}{67.93\times2\pi}+1\right)}$	$\dfrac{(\overline{P}_3/\overline{P}_2)_{s.s}\exp\left(\frac{-.00199\ s}{2\pi}\right)}{\left(\frac{s}{28.54\times2\pi}+1\right)\left(\frac{s}{92.63\times2\pi}+1\right)}$
Weighting factor, W(t)	$= 91032.(\overline{P}_3/\overline{P}_2)_{s.s}\{\exp[-426.8(t-.00026)] - \exp[-428.8(t-.00026)]\}$ when $t > .00026$; $= 0$ when $t \leq .00026$	$= 259.1(\overline{P}_3/\overline{P}_2)_{s.s}\{\exp[-179.3(t-.00032)] - \exp[-582.0(t-.00032)]\}$ when $t > .00032$; $= 0$ when $t \leq .00032$

Then: $\Delta\overline{P}_3(t) = \int_0^T \Delta\overline{P}_2(t-\xi)W(\xi)d\xi$

and $\overline{P}_3(t) = \overline{P}_{3_{s.s}} + \Delta\overline{P}_3(t)$

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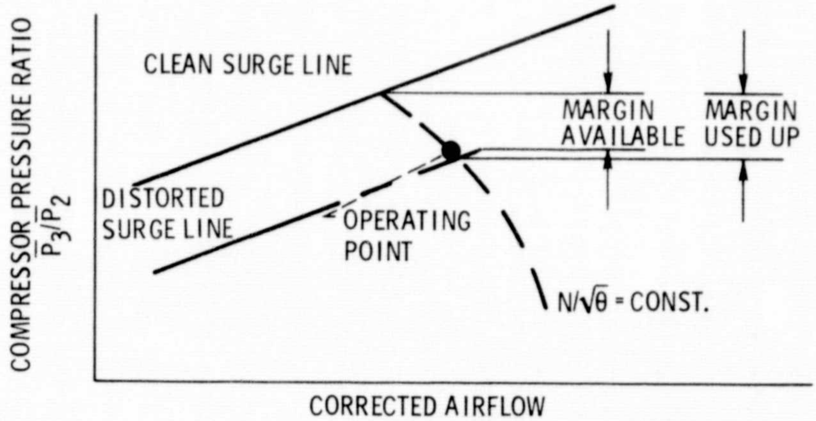
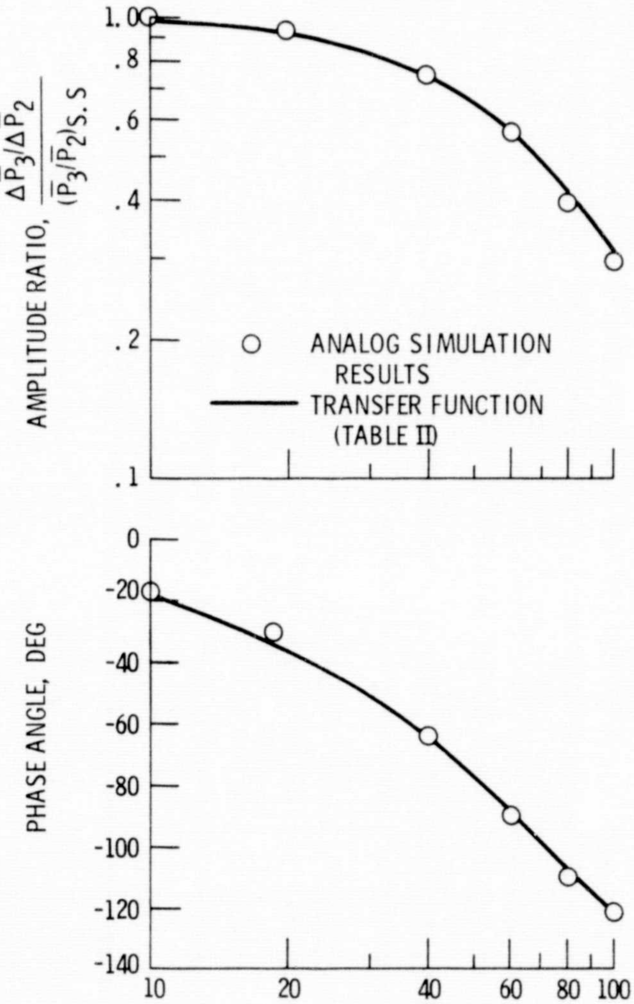


Figure 1. - Sketch of terms used in equation (1).



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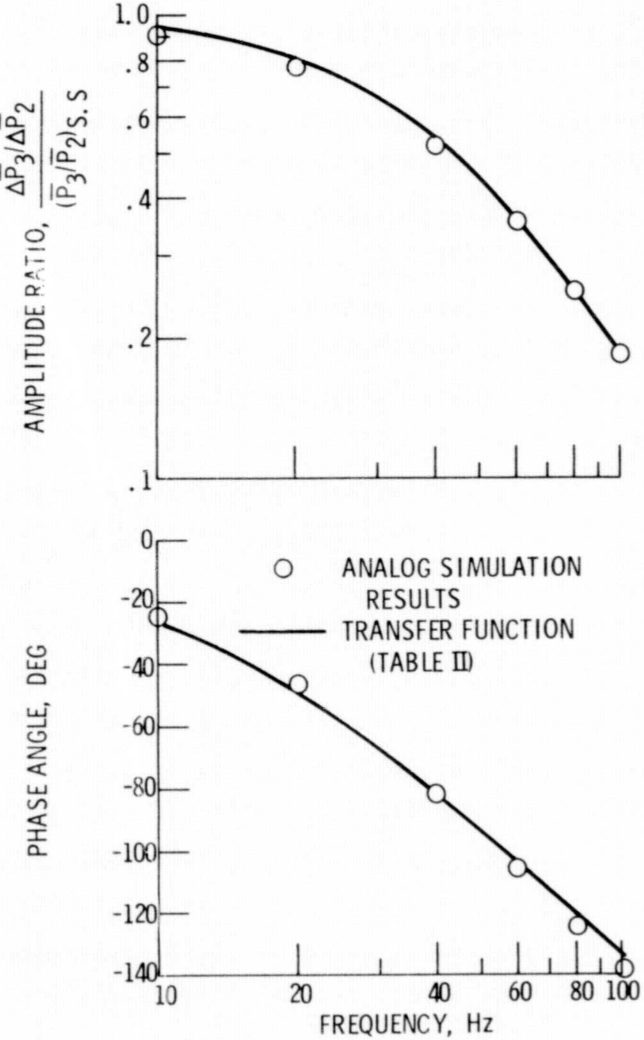
(a) $\frac{N \times 100}{N^{*}\sqrt{\theta_2}}$ = 80%, $(\bar{P}_3/\bar{P}_2)_{S.S}$ = 3.80.

Figure 2. - Frequency response of J85-13 compressor.



(b) $\frac{N \times 100}{N^* \sqrt{\theta_2}} = 100\%$, $(\bar{P}_3/\bar{P}_2)_{S.S} = 7.00$.

Figure 2. - Concluded.

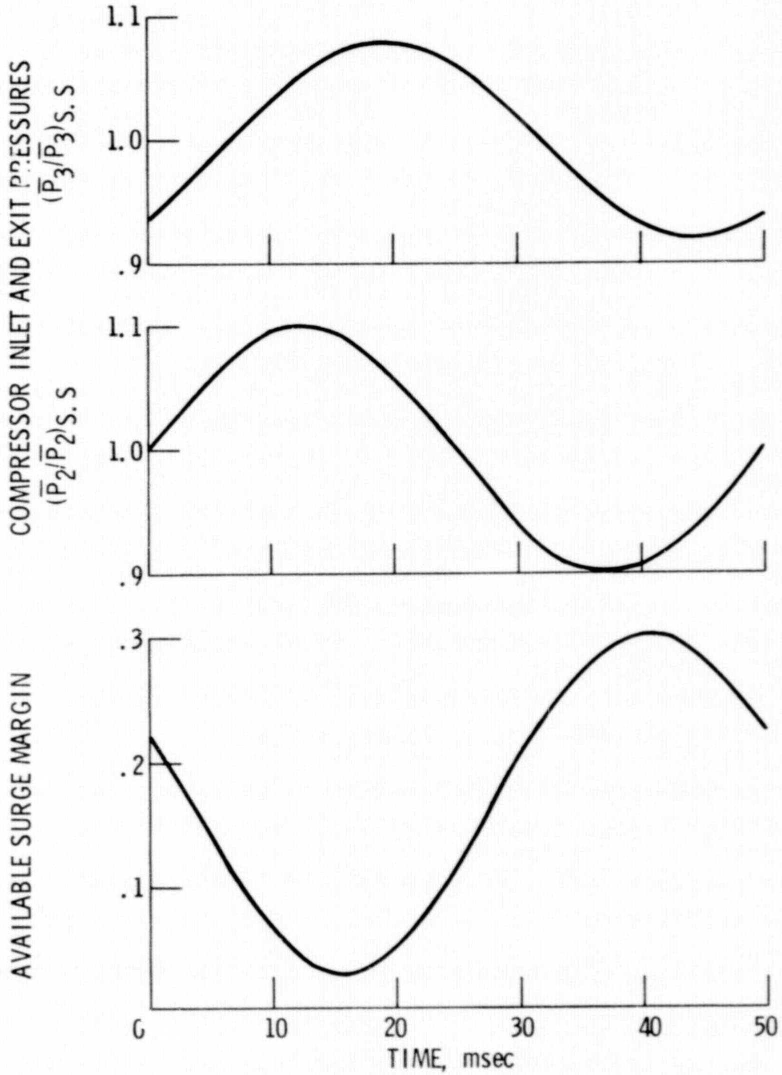


Figure 3. - Compressor response to a full-face inlet pressure variation: $\bar{P}_{3_{S.S}}/\bar{P}_{2_{S.S}} = 5.29$; fig. 2(b) transfer function.

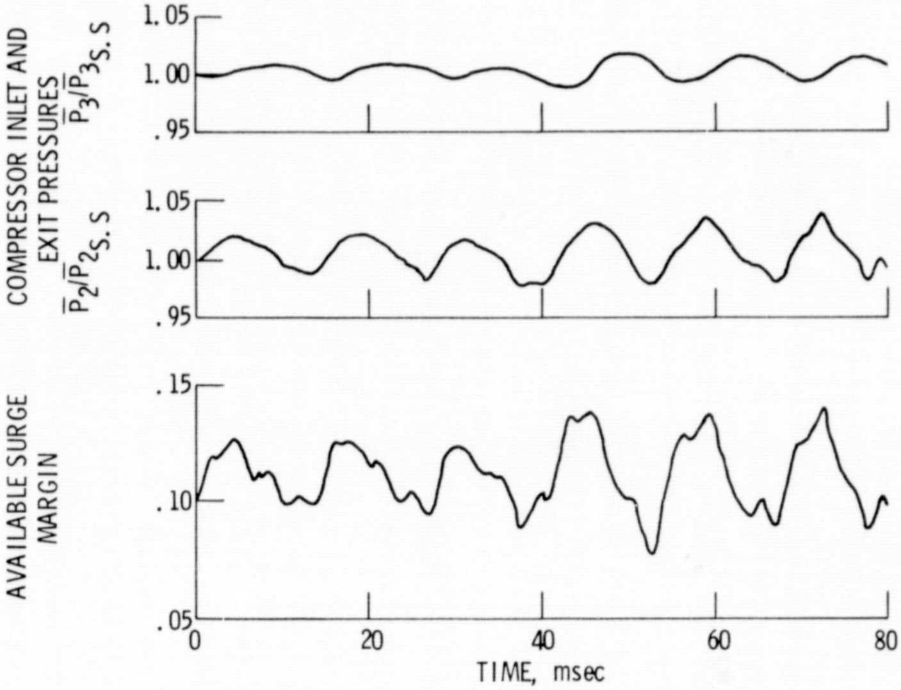


Figure 4. - Time-History of compressor pressures and available surge margin; test point 103; transfer function of fig. 2(a).

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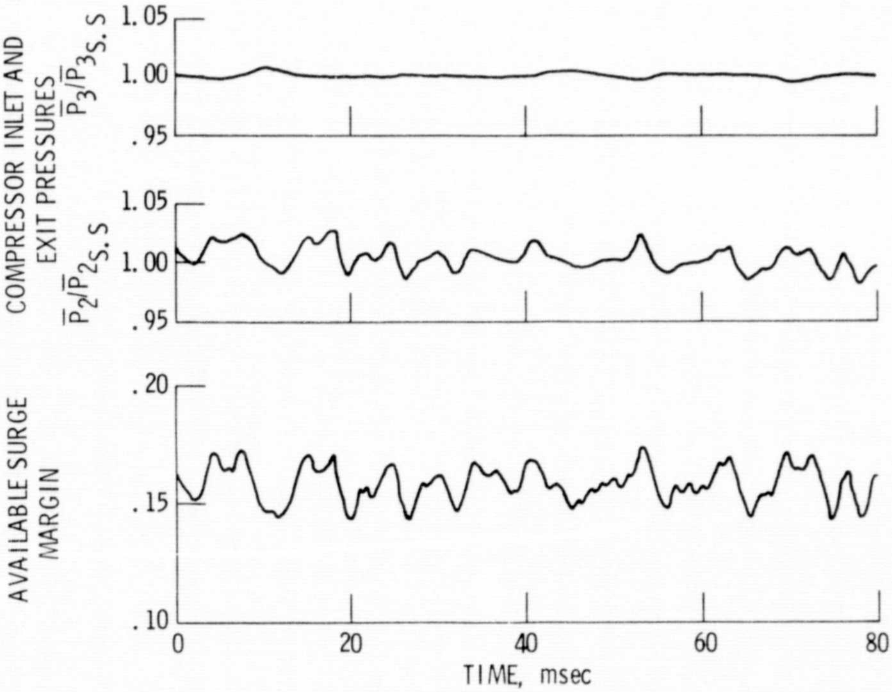
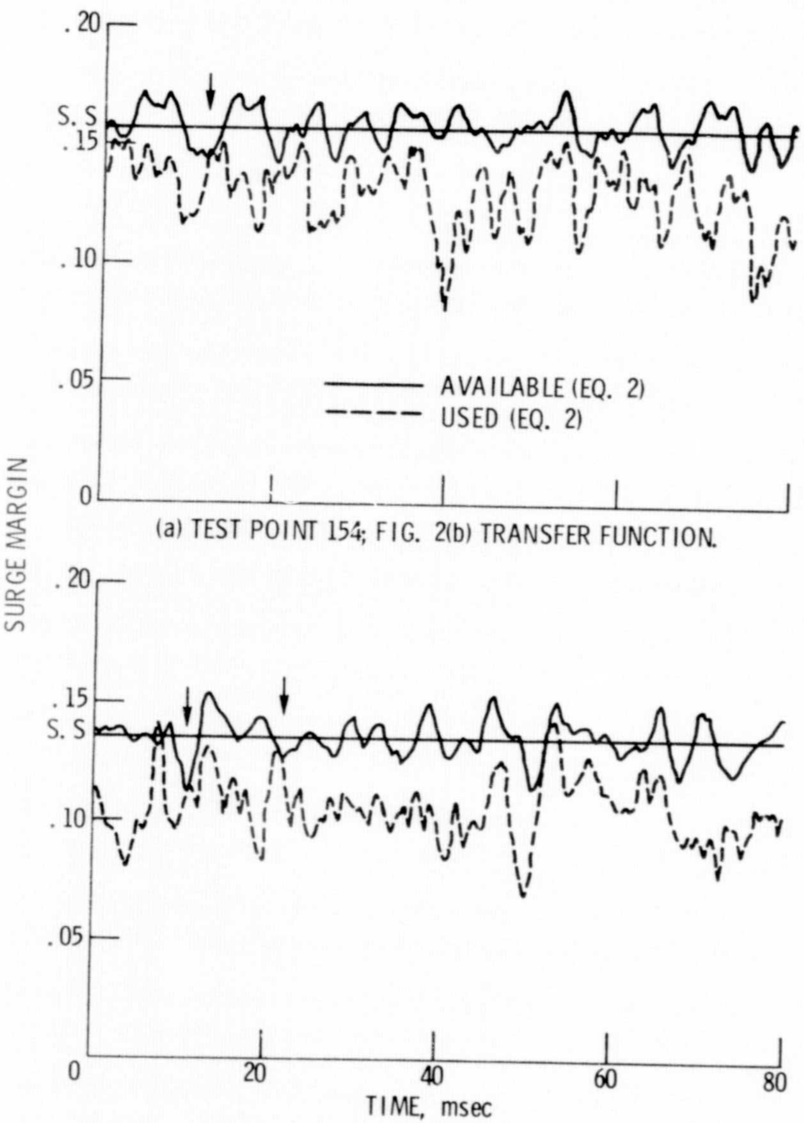


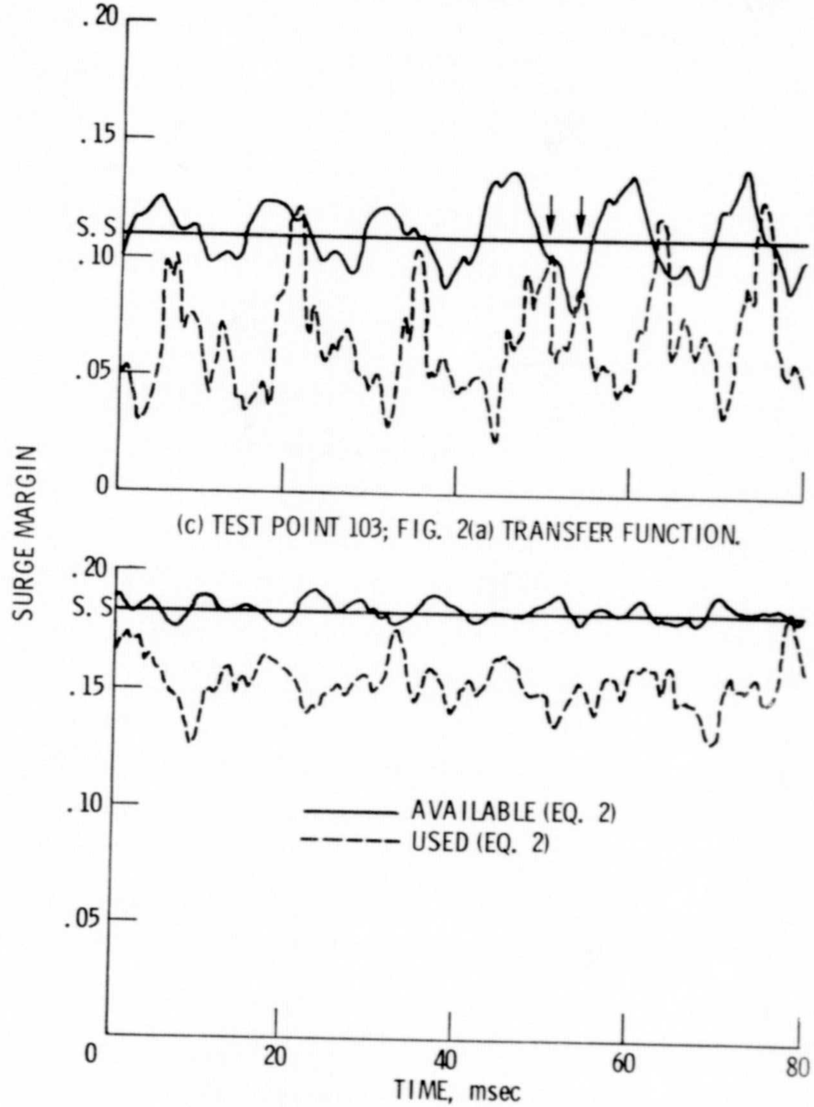
Figure 5. - Time-History of compressor pressures and available surge margin; test point 154; transfer function of fig. 2(b).



(a) TEST POINT 154; FIG. 2(b) TRANSFER FUNCTION.

(b) TEST POINT 148; FIG. 2(a) TRANSFER FUNCTION.

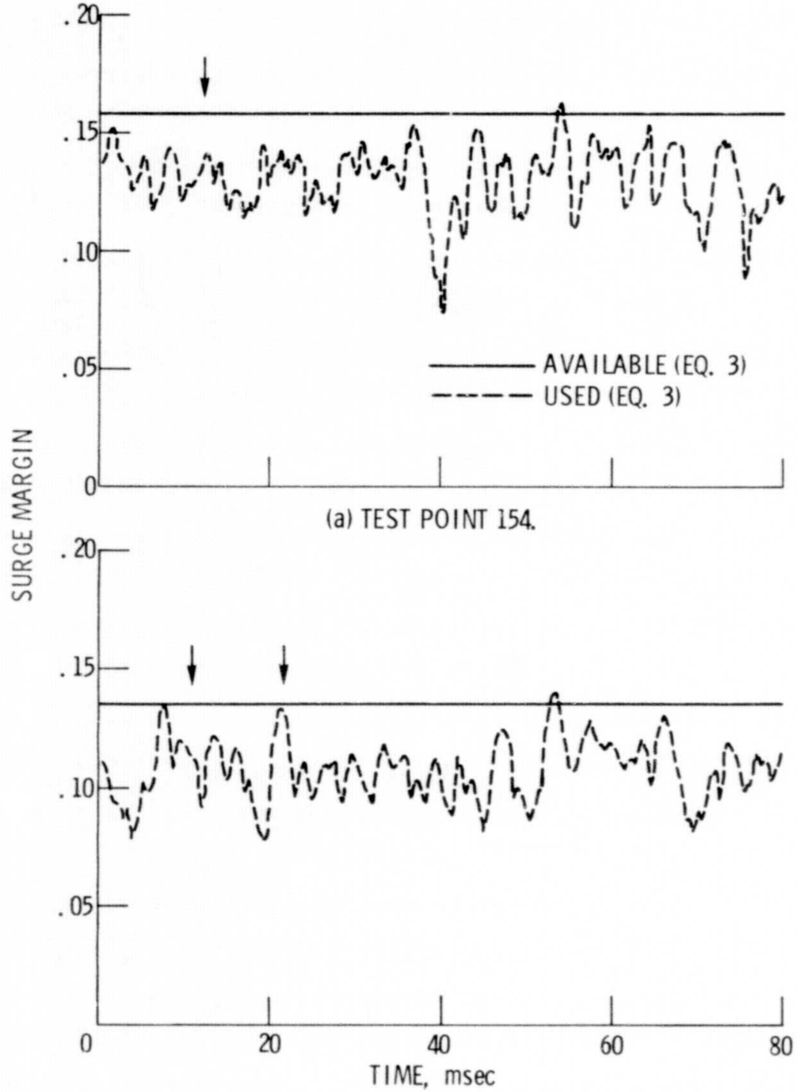
Figure 6. - Instantaneous distortion time - histories.



(c) TEST POINT 103; FIG. 2(a) TRANSFER FUNCTION.

(d) TEST POINT 261; FIG. 2(a) TRANSFER FUNCTION.

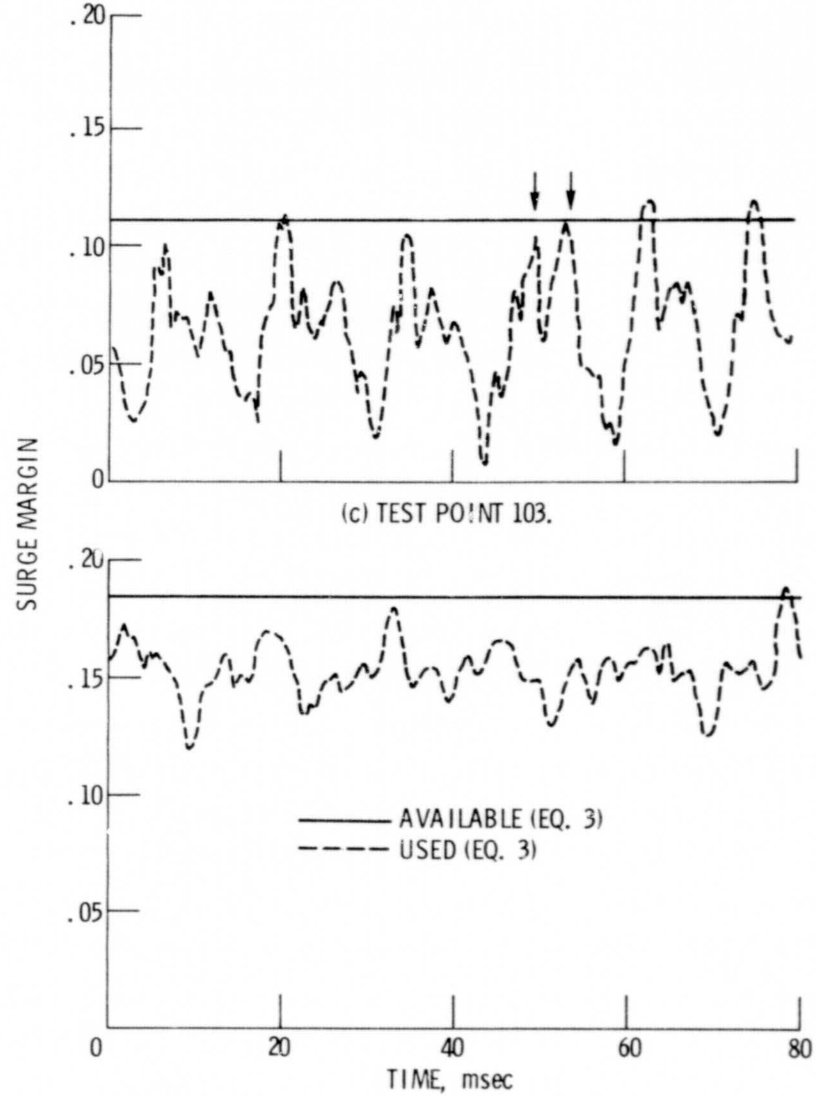
Figure 6. - Concluded.



(a) TEST POINT 154.

(b) TEST POINT 148.

Figure 7. - Time-Histories from simplified instantaneous distortion analysis.



(c) TEST PO!NT 103.

(d) TEST POINT 261.

Figure 7. - Concluded.