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**ANALYSIS OF DYNAMIC INLET DISTORTION
APPLIED TO A PARALLEL COMPRESSOR MODEL**

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ANALYSIS OF DYNAMIC INLET DISTORTION APPLIED TO A PARALLEL COMPRESSOR MODEL

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SUMMARY

An investigation of surge was conducted by using a parallel compressor model of the J85-13 compressor implemented on an analog computer. Surges were initiated by various types of dynamic disturbances in inlet pressure. The results provide insight into the sensitivity of the compressor to unsteady distortion and the manner in which inlet pressure data should be treated for experimental distortion analysis.

The compressor model was less sensitive to disturbances of short duration, high frequency, and long duration where the compressor discharge pressure could react. Adding steady distortion to dynamic disturbances reduced the amount of dynamic disturbance required to effect surge. Steady and unsteady distortions combined linearly to reduce surge margin.

The model was driven to surge by random fluctuations of varying frequency content. The root-mean-square value of the random noise required to surge the model increased as its frequency content was increased. Surge always occurred in response to a large negative pressure excursion.

The model was also surged by sinusoidal pressure fluctuations imposed over part or all of the compressor face. The amplitude required to cause surge varied over the frequency range and was a minimum at 100 hertz.

INTRODUCTION

In recent years inlet pressure distortion and its effect on compressor stability have received much attention. Great amounts of effort have been expended on distortion testing, correlation of distorted inlet conditions with compressor surge, development of indices or descriptors to quantify the distorted conditions, and evolution of models to predict the reaction of the compressor to distortion.

The models capable of handling distorted inlet conditions have generally been useful only for steady-state solutions. Parallel compressor models are most prominent in this class (e. g., refs. 1 to 3). In the studies of references 1 to 3 two or more similar compressor representations exhausted into a common plenum with a static-pressure balance and no flow redistribution. The inlet pressure to one of the parallel compressors was gradually lowered until the overall pressure ratio of that compressor exceeded the undistorted surge pressure ratio. That point was defined as surge; the operating points for the compressors were averaged, and the average represented the surge point of the distorted compressor. Distorted-compressor maps generated in this manner matched experimental data quite well, provided that the distorted area was large.

Compressors have also been represented by simulation of their internal flow processes. Reference 4 describes a model typical of this class. The single undistorted-compressor model includes stage by stage representation of pressure and temperature rise plus interstage dynamics. This model can predict surge when throttled rather than depending on violation of a predetermined surge line of an overall compressor map. Also, it can accommodate transient disturbances. To date, however, only one-dimensional flow can be handled.

Reference 5 extends the model to include two parallel compressors with interstage dynamics. This model predicts surge for steady-state circumferentially distorted inlet flow rather than depending on a predetermined undistorted surge line, as is done in parallel compressor theory. However, the model is implemented on the digital computer and has not been extended to include transient analysis because of the prohibitive computer time required.

This report presents the results of an investigation which combined the characteristics of the models of references 1 to 5. A second parallel compressor was added to the stage by stage compressor simulation described in reference 4. The resulting model had the ability to handle transient distorted inlet pressures. The reactions of the compressor to unsteady distortions of varying duration, type (single pulse, continuous sinusoid, or random noise), and circumferential extent and to the combination of steady and unsteady distortions were investigated. The effects of engine speed and compressor operating point were also examined.

The data resulting from these tests can be instructive in filtering inlet pressure data used to form distortion indices. Filter selection is presently by trial and error; various filter cutoff frequencies are tried to determine the best fit of the data. And filter cutoff characteristics are completely unspecified and arbitrary. Knowledge of the response of the compressor to dynamic distortion could lead to a more sophisticated filter design to correlate the data better.

DESCRIPTION OF MODEL

A parallel compressor representation of the J85-13 compressor was constructed on an analog computer. The two parallel compressors used were not modeled in the same manner. One side was the stage by stage model, which has been demonstrated to match experimental data well (ref. 4). In this model steady-state performance was represented by the pressure and temperature rise characteristics of each stage. The dynamic performance of the compressor was represented by momentum, continuity, and energy equations at each stage. Rotational speed was constant.

The stage by stage model required a large amount of analog computing equipment; the other parallel compressor was necessarily modeled more simply. An overall compressor map having performance equal to the steady-state behavior of the stage by stage model was used. Dynamic performance was not represented in this model.

The discharge flows from the two compressors were summed into a burner volume, which in turn discharged through a choked orifice. Burner volume dynamics were represented by the continuity equation. Pressures in the burner volume were assumed to be equal. This assumption is corroborated by experimental data given in figure 1. In this test, a J-85 engine was run at 100 percent of rated speed with (1) no inlet distortion, (2) a 180° circumferential screen on the right side of the inlet (0° - 90° - 180°), and (3) a 180° circumferential screen on the left side of the inlet (180° - 270° - 360°). The distortion index for the screen DIST was 0.12. (Symbols are defined in the appendix.) Total and static pressures were measured at four circumferential positions at the compressor discharge and were normalized by the average pressure. Maximum deviations of the distorted cases from the undistorted case were within approximately 1 percent. Since the compressor discharge pressures remained nearly equal in the presence of circumferential distortion, the constant burner pressure assumption can be reasoned to be valid. A sketch of the model is shown in figure 2.

Various extents of distortion were accommodated by varying the relative contributions of the discharge flows from the two compressors to the burner volume.

The dynamic behavior of the stage by stage model has been partially verified. Reference 6 presents the results of experimental frequency response testing of a J85-13 engine and compares these data to stage by stage model results. The results are in reasonable agreement up to the experimental limit of 100 hertz, with the exception of an unexplained resonance in the experimental data at about 35 hertz. Above 100 hertz the stage by stage model is unverified.

PROCEDURE

Throughout the study the same procedure was used. The parallel compressor model was operated at steady state with an inlet pressure of 1 atmosphere and with the desired values of speed, extent of distortion, and level of steady distortion. A dynamic disturbance was then introduced to the stage by stage compressor. The amplitude of the disturbance was adjusted in successive tests until a boundary between surge and no surge was established.

For this study surge was defined as a nonrecovering computer overload. For surge-producing disturbances, divergent oscillations which grew without bound were triggered within the model. Overloads occurred when flows became negative. Smaller disturbances were damped out, and the model returned to steady state.

Generally, steady and dynamic distortions were imposed on the compressor with the stage by stage representation. In a few cases pulses were simultaneously imposed on both compressors in such a manner as to maintain a constant average inlet pressure over the entire compressor face.

RESULTS AND DISCUSSION

The parallel compressor model was tested for the following types of dynamic disturbances:

- (1) Single pulses
 - (a) Inlet effects
 - (1) Pulse duration
 - (2) Pulse shape
 - (3) Extent of distortion
 - (4) Added steady distortion
 - (b) Engine effects
 - (1) Rotational speed
 - (2) Operating point
- (2) Random noise
- (3) Sinusoidal perturbations

This list includes the parameters which were expected to have an impact on the response of the compressor to inlet distortion. Single pulses were chosen since they were analytic and readily allowed comparison of different durations and magnitudes. Random noise was used because it would be representative of the inlet pressure environment experienced by a real compressor. Sinusoidal perturbations were used because they could be duplicated in an experimental test to verify the model.

Pulse-Induced Surges

Effect of duration and shape. - Single negative pulses in inlet pressure were applied to the stage by stage side of the model to establish the sensitivity of the compressor to transient distortion. Three pulse shapes were used, triangular, square, and half-sine.

The pulse amplitudes required to effect surge as a function of pulse duration and shape are presented in figure 3. For these data, rotor speed was 100 percent of rated; there was no steady distortion; and the extent of the distortion was 180° . The curves in this figure represent boundaries between surge regions above the curves and nonsurge regions below the curves.

For pulse durations below 0.002 second, pulse amplitudes for all pulse shapes increased as pulse duration was decreased. This effect occurred because the interstage volumes and fluid momentum attenuated the short pulses and reduced their effect on the compressor. At long pulse durations, the half-sine and triangular pulse amplitudes also increased. These increases were due to the ability of the burner pressure to follow or track the slowly changing inlet pressure, which reduced the compressor pressure ratio. This phenomenon is discussed more thoroughly in the next section.

For square pulses at durations longer than 0.002 second, surge was triggered by early portions of the pulse. Hence, pulse amplitude did not change at the longer durations.

For pulse durations from 0.0001 to 0.001 second, the curves have similar shapes and the spacing between the curves is approximately constant. Since the ordinate is logarithmic, this means that the ratios of the amplitudes of the curves are approximately constant over this range of durations. For the five durations tested in this range, the averages of the ratios of pulse amplitudes required to cause surge are given by

$$\left(\frac{\Delta P_{2, \text{triangle}}}{\Delta P_{2, \text{square}}} \right)_{\Delta t = \text{constant}} = 1.73$$

$$\left(\frac{\Delta P_{2, \text{triangle}}}{\Delta P_{2, \text{half-sine}}} \right)_{\Delta t = \text{constant}} = 1.26$$

Figure 4 shows the three types of pulses used. The areas of the pulses, defined as

$$\text{area} = \left| \int_{\text{duration}} \text{pulse amplitude (t) dt} \right|$$

are indicated. The ratios of the pulse areas for constant duration are

$$\frac{\text{area}_{\text{triangle}}}{\text{area}_{\text{square}}} = \frac{\Delta P_{2, \text{triangle}}}{2\Delta P_{2, \text{square}}}$$

$$\frac{\text{area}_{\text{triangle}}}{\text{area}_{\text{half-sine}}} = \frac{\pi \Delta P_{2, \text{triangle}}}{4 \Delta P_{2, \text{half-sine}}}$$

Substituting the average surging pulse amplitude ratios into these area relations gives

$$\left(\frac{\text{area}_{\text{triangle}}}{\text{area}_{\text{square}}} \right) = 0.87$$

$$\left(\frac{\text{area}_{\text{triangle}}}{\text{area}_{\text{half-sine}}} \right) = 0.99$$

for the range of pulse durations from 0.0001 to 0.001 second. The values given here resulted from tests at 100 percent of rated speed. Similar results were achieved at 80 percent of rated speed.

The implication which can be drawn is that at small durations the compressor is more sensitive to pulse area than pulse shape. For disturbances in this time regime, that is, 0.001 second or less, these pulse amplitudes can be reduced to a nearly constant value by using a first-order lag with a 0.01-second time constant followed by a peak reading device.

A transient recording of a typical surge is presented in figure 5. For this test corrected speed was 100 percent of rated, and the extent of the distortion was 180°. Flows and pressures throughout the compressor are shown as they responded to a 0.001-second triangular pulse. The data were not reliable after the flows become negative, which occurred about 0.0018 second after the initiation of the pulse.

Effect of extent of distortion. - In addition to the magnitude and duration of the dynamic distortion, the portion of the compressor face over which the distortion extends is important. Triangular pulses were imposed over varying circumferential angles at the compressor face to investigate this effect. Figure 2 shows how this was accomplished. The relative contributions of the compressor discharge flows to the pressure computation in the burner volume were adjusted according to the coefficients shown.

The results are shown in figure 6. Triangular pulse amplitudes required to cause surge for 90° and 270° are compared with those for 180° for a range of pulse durations.

For pulse durations less than 0.001 second, the extent of the distortion had no effect. This was true because in these short times the burner pressure did not have an

opportunity to react significantly and remained essentially constant. In other words, the stage by stage compressor experienced nearly identical inlet and exit conditions and surged for the same disturbance regardless of its extent.

As pulse duration was increased above 0.001 second, the effect of extent of distortion became more pronounced. For the longer pulses the pressure in the burner volume was able to respond to the inlet pressure perturbation and effectively tracked it. Thus, the pressure ratio across the compressor was reduced, and larger pulse amplitudes were required to cause surge.

The degree to which the burner pressure tracked the inlet pressure perturbation depended on the extent of the distortion, which set the relative amount of perturbed flow to the burner volume. As shown in figure 6, the increasing pulse amplitudes required to cause surge were more pronounced at the larger angles.

The burner pressure variation can be minimized by holding the average inlet pressure constant through introduction of a coincident compensating pulse into the compressor with the overall map. The compensating pulse was of opposite polarity and was sized to give the net effect of no change in average inlet pressure. Although the compressor with the overall map was not modeled dynamically, this test was expected to yield the proper trends, particularly for long durations.

The results of this study are presented in figure 7. The variation in pulse amplitude required to cause surge at long pulse durations for extents from 90° to 270° was reduced for constant average inlet pressure. Varying average inlet pressure was responsible for the extent effect in figure 6. Thus, for inlet perturbations with low frequency content, average inlet pressure should be considered in distortion analysis.

Effect of added steady distortion. - The effect of combined steady and dynamic distortion was also investigated. Steady distortion was created by reducing the mean inlet pressure to the stage by stage side of the model.

In all cases the addition of steady distortion reduced the amplitude of the dynamic disturbance required to effect surge. Typical results are presented in figure 8 for triangular pulses of 180° extent at 100 percent of rated speed. Pulse amplitudes are given as a function of duration and steady distortion. Steady distortion index DIST is defined as the difference between the average inlet pressure and the steady inlet pressure to the stage by stage side of the model divided by the average inlet pressure.

It is important to note that the spacing between the curves in figure 8 is approximately constant over the range of durations tested. Since the ordinate is logarithmic, this means that the amplitudes differ by an approximately constant ratio which is not sensitive to pulse duration. Similar results were obtained at 80 percent of rated speed with triangular pulses and at 100 percent of rated speed with noise-induced surges.

A plot of these data is presented in figure 9. The ordinate is the average dynamic distortion parameter required to effect surge with steady distortion present, normalized by the dynamic distortion parameter required to effect surge with no steady distortion.

The abscissa is the steady distortion index with dynamic disturbances present, normalized by the steady distortion index required to effect surge with no dynamic disturbance. The data indicate that there exists a linear relation of the form normalized dynamic distortion plus normalized steady distortion equals 1. This relation holds for the triangular pulse and noise disturbances tested and for the two corrected speeds tested.

The information contained in figures 8 and 9 is the essence of the formulation of a distortion index. The fact that disturbance amplitudes differ by a nearly constant ratio, independent of disturbance duration, implies that it is not necessary to sense duration to form an index. Steady and filtered dynamic distortions can be combined to form a single-valued index if a filter can be constructed which has characteristics that are the inverse of those of the compressor. It should be noted that the sensitivity of the compressor to single pulses as a function of pulse duration (e. g. , fig. 3) may require a filter more complex than a simple low-pass filter.

Effect of engine speed. - Most of the investigation was conducted at 100 percent of rated engine speed. Tests with triangular pulses of 180° extent were repeated at 80 percent of rated speed to check the effect of speed. No steady distortion was added. The results of these tests are presented in figure 10. Triangular pulse amplitudes required to surge the compressor are given as a function of pulse duration.

The shapes of the curves for the two speeds are similar. Smaller pulse amplitudes were required to cause surge at 80 percent of rated speed. This was true because the operating point was closer to the clean surge line at this speed than at 100 percent of rated speed.

Also, the 80-percent-speed curve is shifted to the left, toward smaller pulse durations. This effect is attributed to higher frequency response exhibited at 80 percent of rated speed by interstage pressures in response to inlet pressure perturbations, primarily in the front stages. This observation was made on data for frequency response of interstage pressures to sinusoidal perturbations in inlet pressure. These data are not presented in this report.

Effect of operating point. - The sensitivity of the pulse amplitude required to cause surge to the proximity of the operating point to the clean surge line was investigated. These results are presented in figure 11 for triangular pulses with no steady distortion at 100 percent of rated speed for three operating points. The operating point was manipulated by varying the area of the orifice at the discharge of the burner volume.

The curves for the three operating points are similar in shape. The spacing between the curves (i. e. , the ratios of the pulse amplitudes at a given duration) is approximately proportional to the available surge margin at the respective operating points. Surge margin is defined in this report as the difference between the clean surge pressure ratio (7.33) and the operating point pressure ratio at constant speed.

Noise-Induced Surges

The parallel compressor model was surged by imposing random pressure fluctuations on its stage by stage side. This type of disturbance is representative of distortion experienced by a real engine.

The output of a white noise generator was recorded on magnetic tape to allow test to test comparison. The recording was replayed as the disturbance. On another tape channel, a starting signal was recorded. This arrangement allowed use of the identical disturbance for repeated tests.

The noise signal was passed through a first-order filter of variable time constant and a gain before being introduced into the model. The frequency content of the unfiltered noise signal was flat from 16 to 3000 hertz. A schematic diagram of this arrangement is shown in figure 12.

The test procedure was to select a filter time constant and gain setting and then to play the noise signal into the compressor model for 1 second. If no surge occurred, the gain was increased and the noise signal replayed. This process was repeated until a boundary between surge and no surge was identified. A calculation of the root-mean-square value of the noise signal was made concurrently with each test, so that the average root-mean-square value from start to surge

$$\left[\frac{1}{t_{\text{surge}}} \int_0^{t_{\text{surge}}} (\Delta P_{2, \text{rms}})^2 dt \right]^{1/2}$$

would be known.

The results presented in figure 13 show that, as the frequency content of the noise signal was decreased below 3000 hertz, the gain necessary to effect surge increased. The trend was toward constant power, especially at low frequencies. This trend is verified by the data presented in figure 14, which shows that the root-mean-square value of the noise signal was relatively flat in the lower frequency range. As frequency was increased, the gain leveled off, and the root-mean-square values increased. This effect occurred because the compressor was less sensitive to disturbances at these frequencies.

The surges observed occurred at a few discrete instants during the 1-second tests. An oscillograph record of the noise signal revealed large negative pressure excursions at these times, which indicated that the surges were due to discrete peaks.

Sinusoidal Oscillations

Surges were also induced by imposing sinusoidal oscillations on all or portions of the compressor face. These oscillations were continuous in contrast with previously discussed single pulses. For these tests the procedure was to increase the sinusoidal oscillation amplitude gradually from zero to that value which effected surge.

In figure 15 the results of these tests are given as the oscillation amplitude required to cause surge when imposed on one-fourth, one-half, and all of the compressor face. Engine speed was again 100 percent of rated.

At low frequencies, which correspond to long pulses, the curves fan out because the pressure in the burner volume followed the inlet pressure, as discussed in the section Effect of extent of distortion.

In the middle of the frequency range, there was little difference in the surging amplitude for the three extents. At high frequencies, however, the curves separate again and show behavior differing from that previously noted for short pulses. This can be attributed to nonlinearities in the stage by stage compressor. The nonlinearity was such that the average value of discharge flow from the stage by stage compressor was lower with sinusoidal inlet perturbations present than if there were no perturbations. The nonlinearity was more pronounced at higher perturbation amplitudes.

The effect of the decrease in average discharge flow was a decrease in burner pressure. This decrease lowered the operating point and provided more surge margin, so that a still greater inlet pressure perturbation was required to effect surge. This effect was, of course, more pronounced at the larger perturbed extents, where the contribution of flow from the stage by stage compressor was greater.

CONCLUDING REMARKS

The results presented in this report are indicative of the types and time regimes of inlet pressure disturbances to which the compressor was sensitive and should have bearing on the manner in which inlet pressure data are treated. If a filter is constructed which gives weighting complementary to the response of the compressor, the correlation between inlet pressure distortion and loss in surge pressure ratio should be improved.

The analytical results presented in this report will be difficult to verify because of their high frequency content. A disturbance device capable of periodic pressure perturbations up to several hundred hertz has been tested (ref. 7). A similar device would be useful in verification of part of the present results.

SUMMARY OF RESULTS

The responses of a parallel compressor model to several types of dynamic distortion were investigated. The model was implemented on an analog computer. One compressor was dynamically modeled by using stage stacking and lumped volume techniques. The other compressor was represented by an overall compressor map and included no dynamics. Among the findings given in this report which have impact on the design of a filter for inlet pressure signals are the following:

1. The compressor model was less sensitive to single pulses shorter than 0.002 second.
2. For pulse durations less than 0.001 second, the pulse area for various pulse shapes was nearly constant at a given duration.
3. For square pulses the amplitude at surge was constant for durations of 0.002 second and longer.
4. Pulse amplitudes at surge for long durations increased, since burner pressure was able to follow inlet pressure.
5. Average inlet pressure had to be considered for inlet pressure perturbations having low frequency content.
6. Steady and dynamic distortions combined linearly to reduce surge margin.
7. The proximity of the operating point to the surge line had a profound effect on disturbance amplitude at surge.
8. Rotational speed had a second-order effect on tolerance to distortion.
9. When perturbed by random noise, surge was always initiated by a large negative pressure excursion.
10. The root-mean-square value of the random noise signal at surge increased as the frequency content of the signal was increased.

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505-05.

APPENDIX - SYMBOLS

DIST	distortion index, $\frac{P_{2,av} - P_{2,min}}{P_{2,av}}$
f	frequency, Hz
f_0	filter cutoff frequency, Hz
N_c	corrected rotational speed, rpm
P_B	pressure in burner volume, N/cm^2 ; psia
P_{vx}	pressure in volume after inlet guide vanes, N/cm^2 ; psia
$P_{v1}, P_{v2}, P_{v3}, P_{v4},$ P_{v5}, P_{v6}, P_{v7}	pressure in volume after first to seventh stages, respectively, N/cm^2 ; psia
P_2	inlet pressure, N/cm^2 ; psia
ΔP_2	perturbation in inlet pressure, N/cm^2 ; psi
P_3	pressure in volume after exit guide vanes, N/cm^2 ; psia
P_3/P_2	compressor pressure ratio
t	time, sec
Δt	disturbance duration, sec
\dot{W}_B	flow out of burner volume, kg/sec; lbm/sec
\dot{W}_{dx}	flow through inlet guide vanes, kg/sec; lbm/sec
$\dot{W}_{d1}, \dot{W}_{d2}, \dot{W}_{d3}, \dot{W}_{d4},$ $\dot{W}_{d5}, \dot{W}_{d6}, \dot{W}_{d7}, \dot{W}_{d8}$	flow through first to eighth stages, respectively, kg/sec; lbm/sec
θ^-	extent of distortion, deg
Subscripts:	
av	average
min	minimum
rms	root mean square
s	static
ss	steady state
surge	occurrence of surge
Superscript:	
-	average

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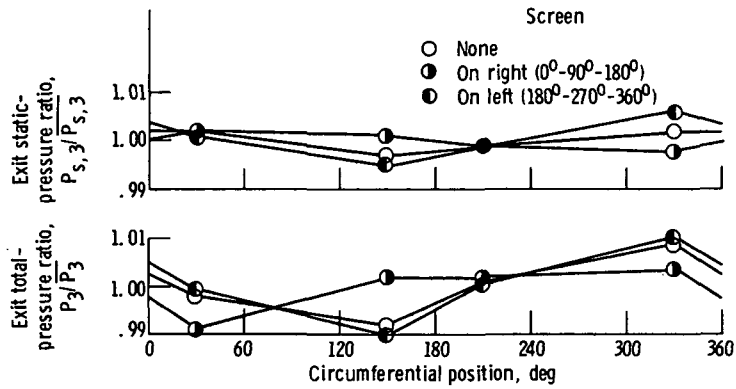


Figure 1. - Experimental data giving influence of circumferential distortion on total and static pressures at compressor discharge.

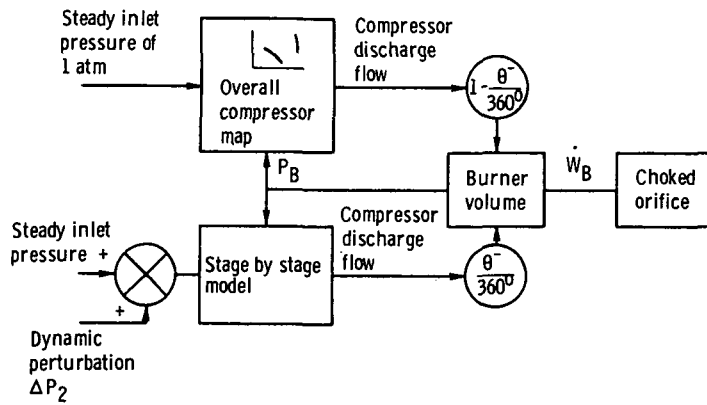


Figure 2. - Parallel compressor model.

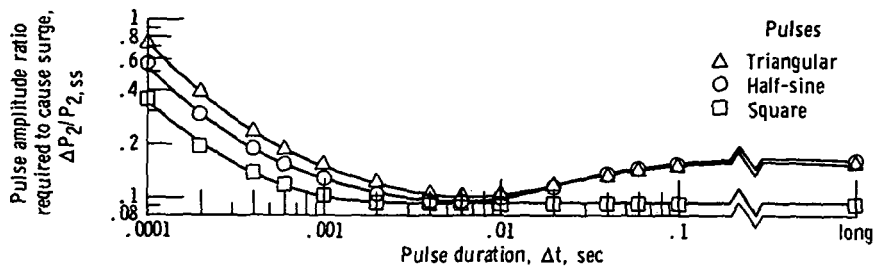


Figure 3. - Effect of pulse shape on compressor surge. Speed, 100 percent of rated; extent of distortion, 180°.

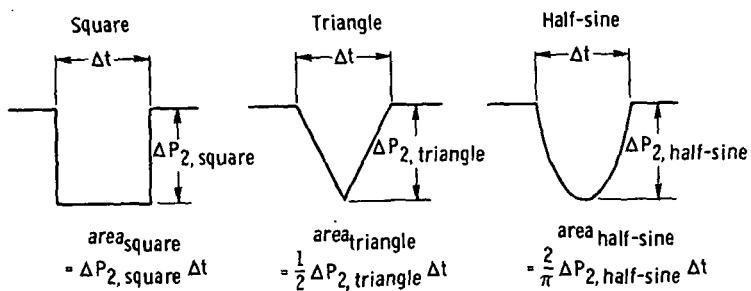


Figure 4. - Pulse shapes tested and their area relations.

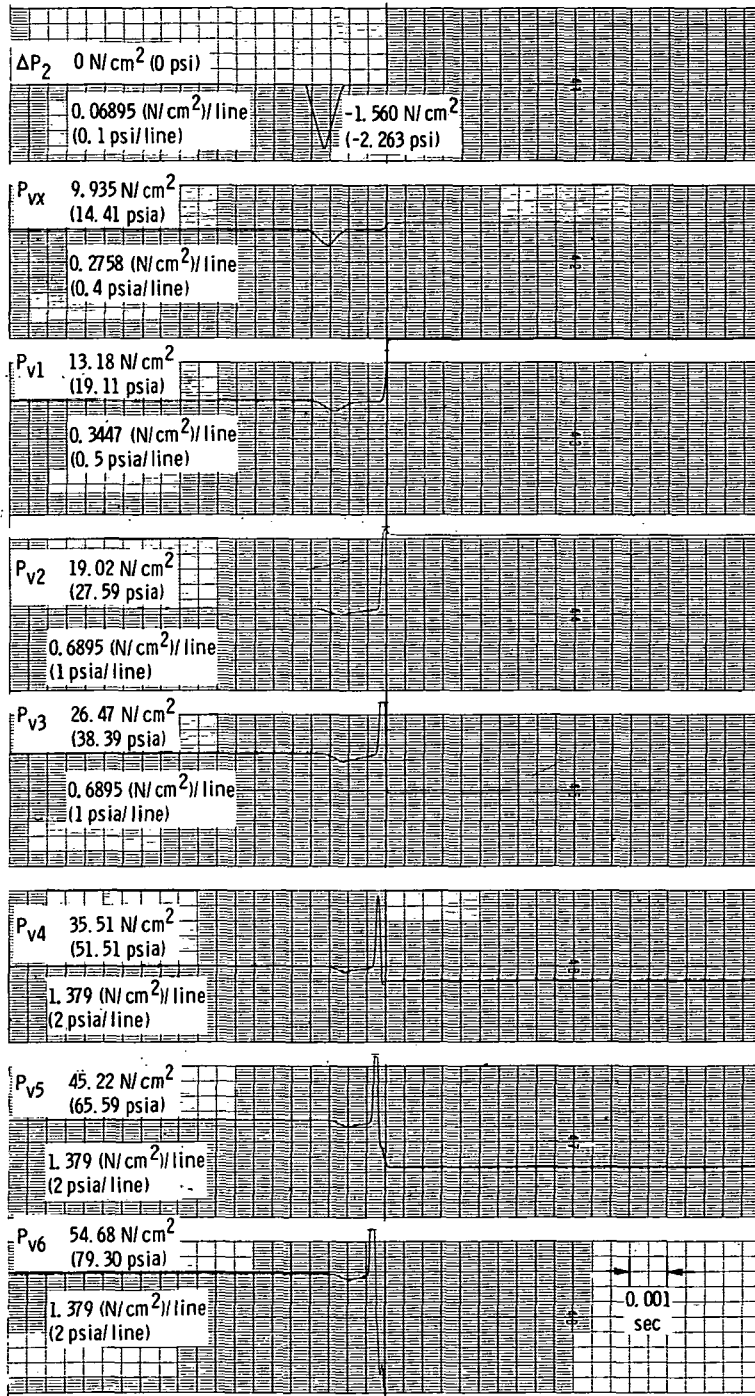


Figure 5. - Transient recording of pulse-induced compressor surge. Speed, 100 percent of rated; inlet steady-state pressure, 10.14 newtons per square centimeter (14.7 psia); pulse duration, 0.001 second; extent of distortion, 180°.

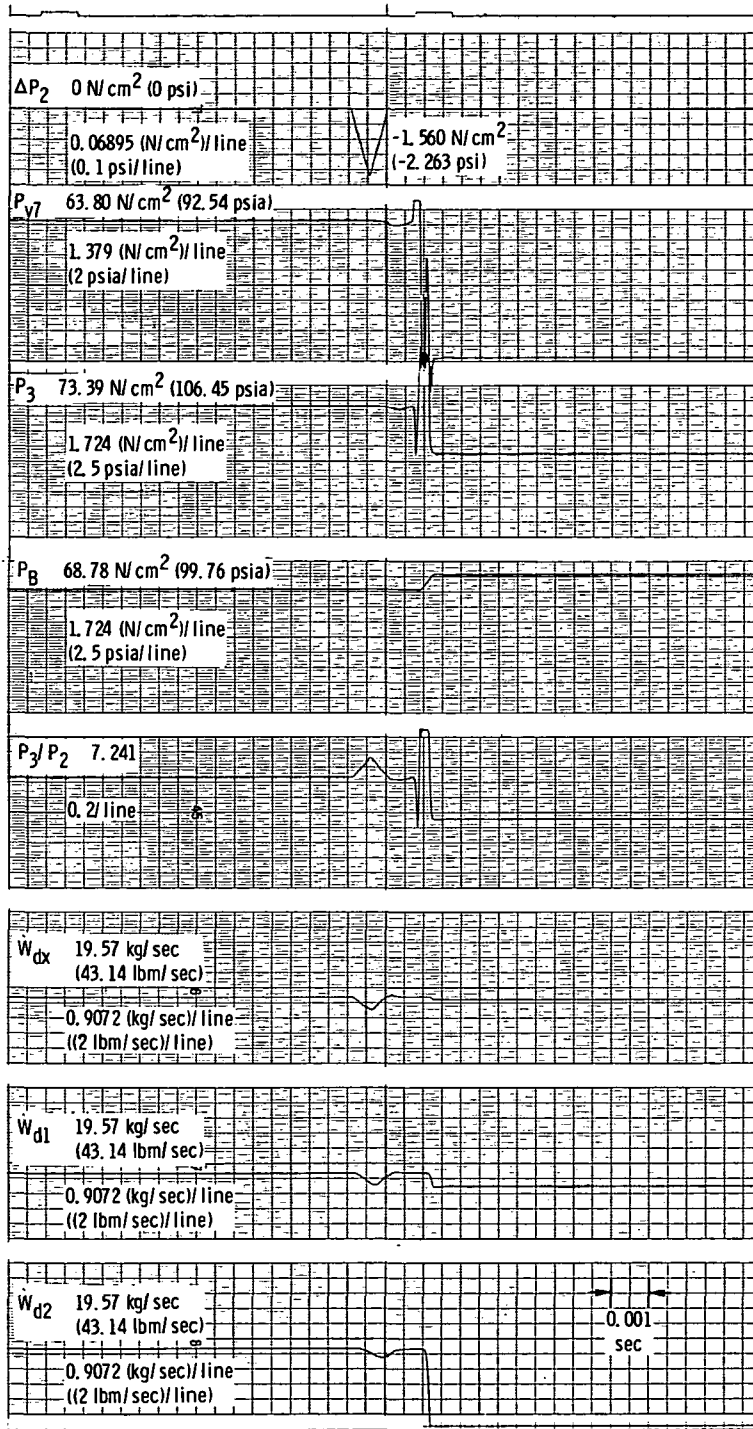


Figure 5. - Continued.

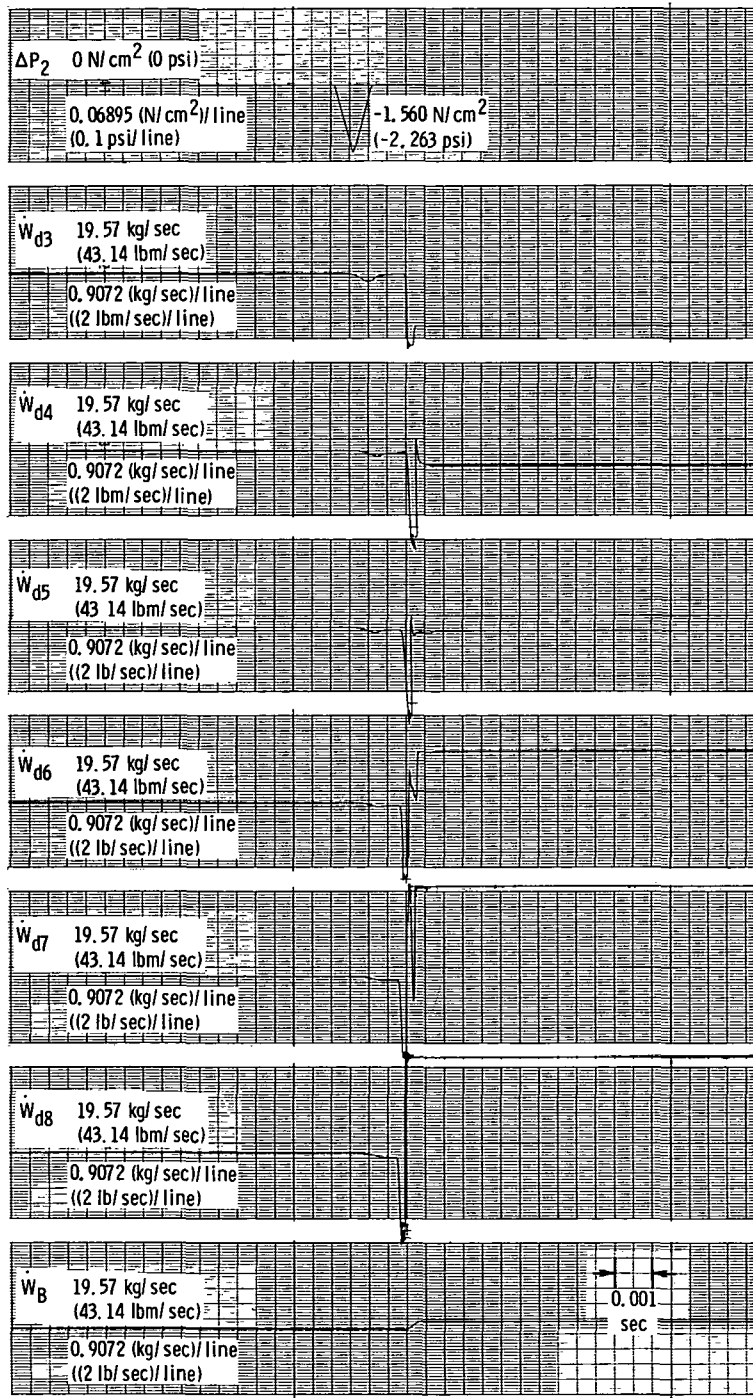


Figure 5. - Concluded.

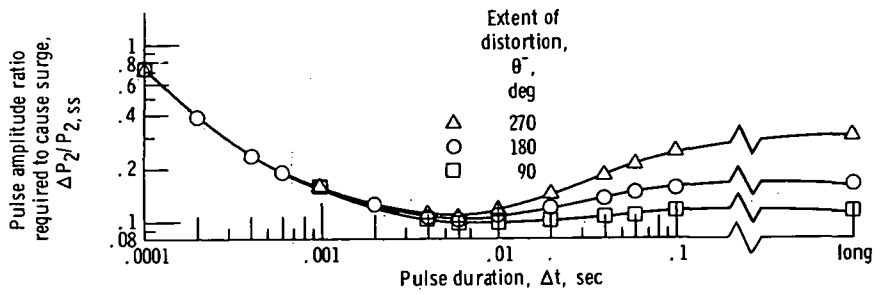


Figure 6. - Effect of circumferential extent of distortion on compressor surge with average inlet pressure not constant. Speed, 100 percent of rated; triangular pulses.

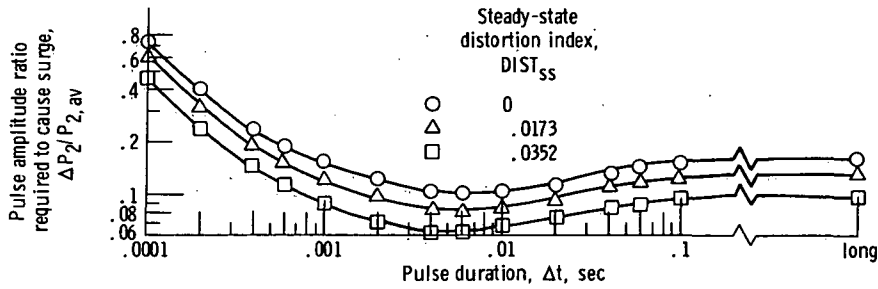


Figure 8. - Effect of added steady distortion on compressor surge. Speed, 100 percent of rated; extent of distortion, 180°; triangular pulses.

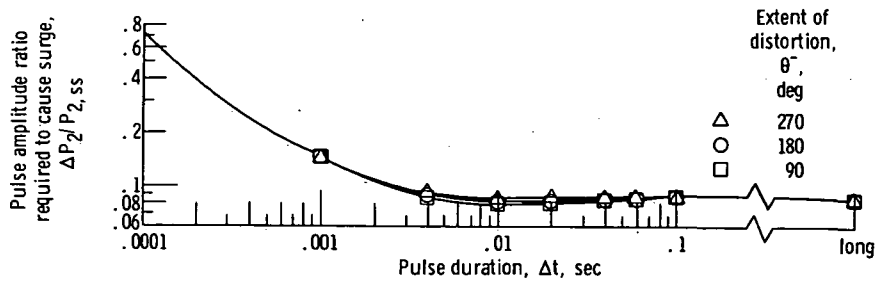


Figure 7. - Effect of circumferential extent of distortion on compressor surge with average inlet pressure constant. Speed, 100 percent of rated; triangular pulses.

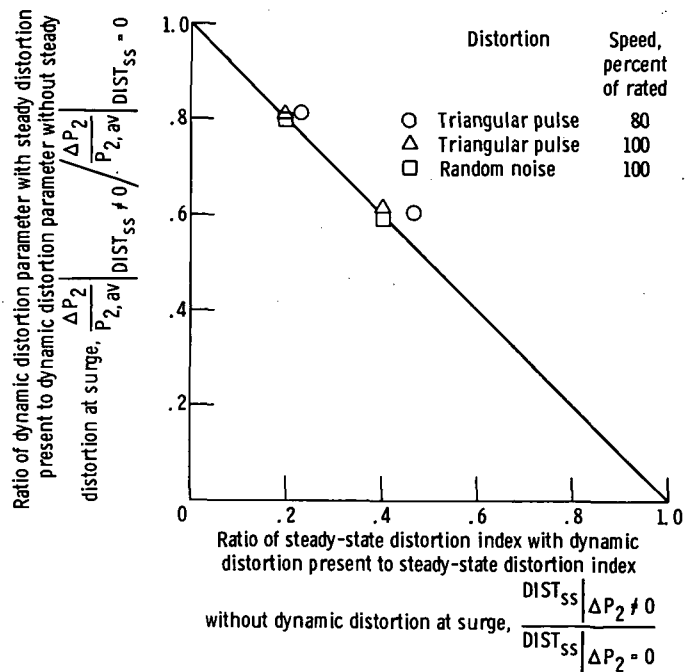


Figure 9. - Additive properties of steady and dynamic distortions.

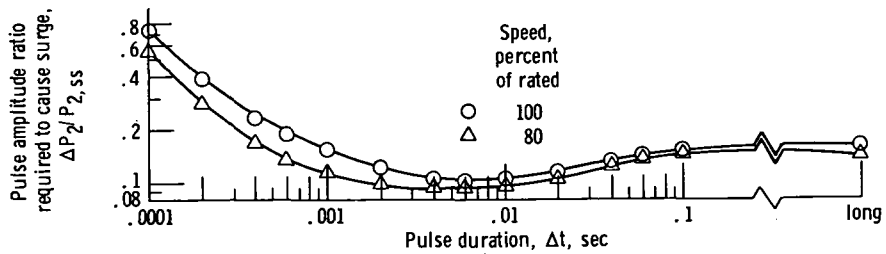


Figure 10. - Effect of engine speed on compressor surge. Extent of distortion, 180°; triangular pulses.

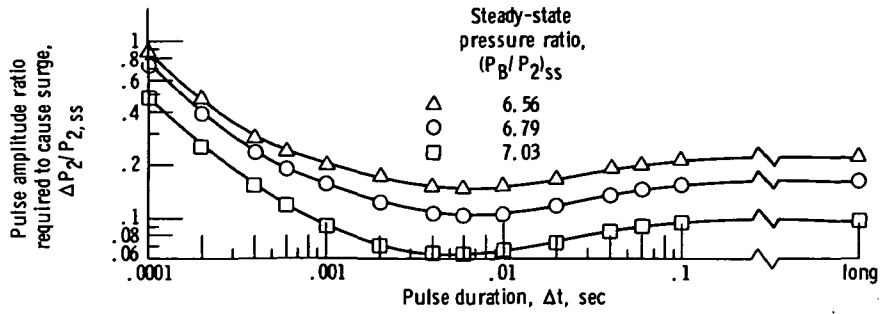


Figure 11. - Effect of overall compressor operating point on compressor surge. Speed, 100 percent of rated; extent of distortion, 180°; triangular pulses.

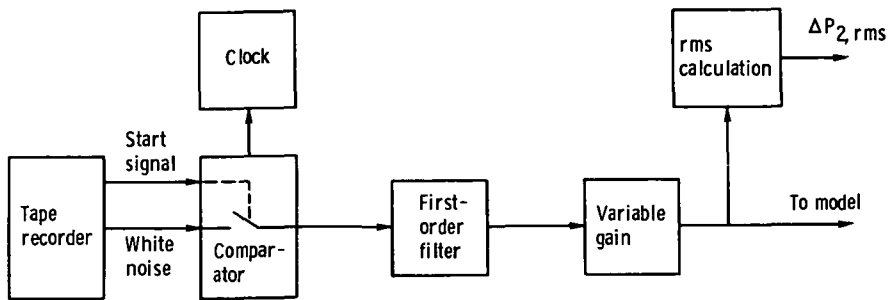


Figure 12. - Schematic diagram of system used to perturb parallel compressor model with random noise.

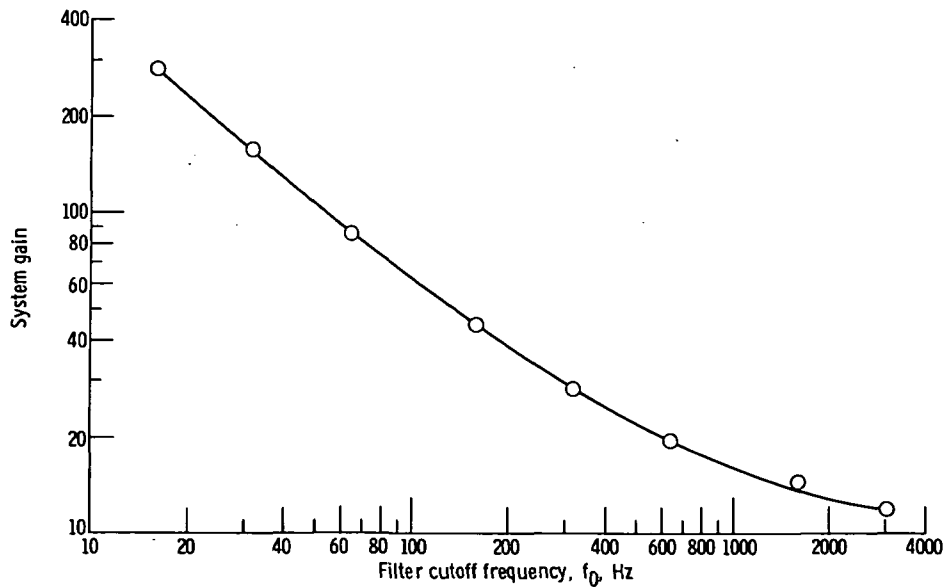


Figure 13. - System gain required to cause surge as function of filter cutoff frequency. Speed, 100 percent of rated; extent of distortion, 180°.

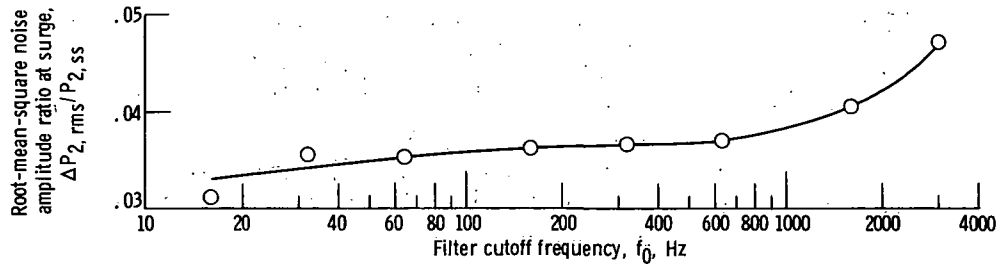


Figure 14. - Root-mean-square amplitude ratio of noise signal at surge as function of filter cutoff frequency. Speed, 100 percent of rated; extent of distortion, 180° .

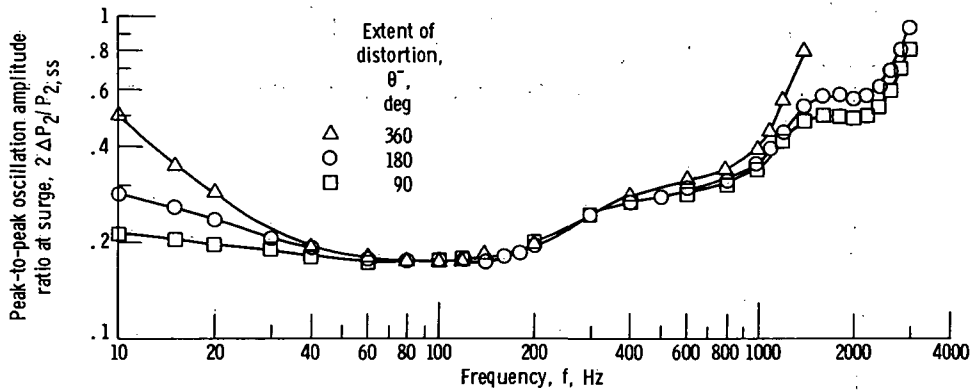


Figure 15. - Effect of circumferential extent of distortion on sinusoidal oscillation amplitude ratio required to cause surge. Speed, 100 percent of rated.



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