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RESEARCH MEMORANDUM

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SOME EFFECTS OF RAPID INLET PRESSURE OSCILLATION ON THE OPERATION OF A TURBOJET ENGINE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

A program was conducted in an altitude facility at the NACA Lewis laboratory to investigate the effects of rapid inlet pressure oscillations on the operation of a current turbojet engine. These pressure oscillations were approximately sinusoidal in form and were generated to cover a frequency range of 2 to 75 cycles per second and an amplitude range of 10 to 70 percent of the free-stream total pressure.

As the oscillation progressed through the compressor, the amplitude was attenuated considerably and a relatively large phase shift (lag) occurred. Engine stall limits obtained during pressure oscillations differed from quasi-steady-state stall limits as defined by over-all compressor pressure ratio.

INTRODUCTION

The occurrence of compressor stall and/or combustor blowout, due to rapid oscillations in engine inlet conditions, has been observed in some flight installations of current turbojet engines. These transient inlet disturbances are due to the firing of armament near engine inlets, operation with variable-area inlet diffusers, or diffuser buzz (refs. 1 to 5). Of these, the armament firing problem is the most severe, since rapid changes in both inlet temperature and pressure are known to occur.

An experimental program was conducted at the NACA Lewis laboratory to investigate the effects of these rapid oscillations in inlet temperature and pressure on the operation of a current turbojet engine. The effects of rapid changes in inlet temperature on engine operation were investigated and are reported in reference 6; the effects of rapid inlet pressure oscillations are reported herein.

For that part of the investigation reported herein, a preliminary examination of flight experience and data indicated that the region of greatest significance would be covered by generating approximately sinusoidal pressure waves with frequencies varying from 2 to 75 cycles per second and amplitudes of 10 to 70 percent of inlet total pressure. Inlet total-pressure oscillations having amplitudes and frequencies in this range were generated by means of a rotary valve located upstream of the engine inlet.

Data were obtained for conditions simulating flight at a Mach number of 0.8 at an altitude of 50,000 feet. The effect of frequency on the amplitude and phase shift of the pressure oscillation as it passes through 4564
the engine is shown for a constant inlet amplitude. Maximum oscillation amplitudes that the engine will tolerate without stalling are presented in terms of amplitude and frequency of the inlet pressure oscillation. These maximum oscillation amplitudes are also presented in terms of maximum over-all compressor pressure ratio, which is compared with over-all compressor stall pressure ratio as obtained with quasi-steady-state engine operation.

APPARATUS

Engine and Installation

The investigation was conducted in an altitude facility where the pressure and temperature of the air supplied to the engine inlet and the ambient exhaust pressures were regulated to simulate the desired altitude flight condition. The basic test vehicle was a turbojet engine of the 10,000-pound-thrust class. The 15-stage, axial-flow compressor had progressively variable inlet guide vanes and a two-position interstage-acceleration bleed valve. All data were obtained with the inlet guide vanes open and the acceleration bleed valve closed. A photograph of the engine installed in the test facility is presented in figure 1.

Pressure Pulse Generator

The pulse generator was located just upstream of the engine inlet in the large duct which supplied the engine with ram air. A sketch of the pulse generator is presented in figure 2.

This pulse generator consisted of 40 small ducts, half of which were vented to high-pressure ram air. The remainder were vented to a large inner duct where the ram-air total pressure could be reduced by means of a butterfly valve. These ducts, which had wedge-shaped cross sections, were mounted side by side to form an annulus, with a low-pressure duct installed beside each high-pressure duct. The ducts were alternately opened and closed by means of the wedge-shaped spokes on a 20-spoke rotating valve. A nearly sinusoidal pressure oscillation could be generated by rotating the valve. Increasing the speed of rotation of the valve increased the frequency of the pressure oscillation, and the amplitude of the pressure oscillation was increased by closing the butterfly valve.

The range of operation possible with the pulse generator is indicated in figure 3. A gross indication of the frequency response of the pulse generator may be obtained from figure 3, in the region where the butterfly valve was fully closed. Typical inlet total-pressure oscillations obtained with the apparatus are presented in figure 4.

Instrumentation

Transient instrumentation stations were located throughout the engine as indicated by the following table:

Measured variable	Designation	Circumferential location (measured clockwise from top, looking downstream), deg
Compressor inlet total pressure	P_1	38
Compressor inlet total pressure	P_{1A}	225
1st-stage-stator total pressure	P_{1ss}	33
4th-stage-stator total pressure	P_{4ss}	45
7th-stage-stator total pressure	P_{7ss}	45
11th-stage-stator total pressure	P_{11ss}	45
14th-stage-stator total pressure	P_{14ss}	45
Compressor outlet total pressure	P_2	70
Compressor outlet total pressure	P_{2A}	165
Turbine inlet total pressure	P_3	41
Turbine outlet total pressure	P_4	75

Calibration of the transient instrumentation was accomplished by means of steady-state instrumentation, which was also installed at the preceding stations.

Pressure transducers used in this investigation were the variable-reluctance diaphragm type. The length of tubing used to connect the probe to the transducer was maintained at a minimum in order to obtain the best possible frequency response. The frequency response, determined from bench tests, was flat up to frequencies of 50 cycles per second.

The transient pressure variations were photographically recorded on a high-speed (50 in./sec) multiple-channel oscillograph.

PROCEDURE

Data were obtained for conditions simulating flight at a Mach number of 0.8 at an altitude of 50,000 feet. Engine stall limits during inlet pressure oscillation were obtained for corrected engine speeds of approximately 93, 100, and 110 percent of rated speed. At a given engine speed and frequency of inlet pressure oscillation, the amplitude was slowly increased until either engine stall occurred or the operating limit of the pulse generator was reached. In general, amplitudes at the highest frequencies were limited to about 25 percent by a performance limitation of the pulse generator, while amplitudes of the lowest frequencies were limited to approximately 60 percent by the occurrence of engine stall.

RESULTS AND DISCUSSION

The frequency-response characteristics, which were measured at various stations throughout the engine, are presented in figure 5. These data were obtained by varying the frequency of a constant amplitude (11 percent), approximately sinusoidal inlet total-pressure wave at approximately rated corrected engine speed.

The attenuation effect of the engine on the amplitude of the inlet total-pressure oscillation is shown in figure 5(a). Amplitude ratio is the ratio of the amplitude at each station to the inlet amplitude, divided by the same ratio for a frequency of 3 cycles per second. As the frequency was increased from 3 to approximately 60 cycles per second, amplitude ratio at each station became smaller. At a given frequency, amplitude ratio also decreased as the distance from the compressor inlet to each measuring station increased. For example, at a frequency of 15 cycles per second, the amplitude ratio of the pressure wave at the eleventh-stage stator dropped to 0.7; while, at the compressor outlet, the amplitude ratio decreased to approximately 0.5. At this frequency, the amplitude ratio at the turbine outlet was about 0.3.

These data also indicate that, for frequencies less than 30 cycles per second, no change in amplitude ratio across the combustor occurred at approximately rated corrected speed. For the same frequency range at a higher corrected speed (110 percent), an examination of the limited amount of data available also indicated no change in amplitude ratio across the combustor.

In figure 5(b), phase shift (lag) is presented as a function of the frequency of inlet total-pressure oscillation. The phase shift at any station became greater as frequency increased from 3 to 60 cycles per second and, at a given frequency, phase shift increased as the distance from the compressor inlet to each measuring station increased. At a frequency of 15 cycles per second, the phase lag of the pressure oscillation at the eleventh-stage stator was 36 degrees, and the phase lag at the compressor outlet and turbine inlet was about 80 degrees. It was not possible to read the phase shift at the first-stage stator, nor was it possible to read the phase shift at the turbine outlet above frequency of 10 cycles per second. These data indicate no phase shift across the combustor.

The transport time (time for pressure oscillations to proceed through compressor) was obtained from the compressor outlet phase-shift curve. These data indicated that transport time decreased from a value of 0.02 second at a frequency of 3 cycles per second to a value of 0.01 second at a frequency of 30 cycles per second. Although this trend was substantiated by means of the dynamical engine model of reference 7, the magnitude of the decrease in transport time is near the limit of accuracy of the measurement, and the indicated trend may not be valid.

The amplitude attenuation and phase shift that occur during an inlet pressure oscillation result in a change in the over-all compressor stall limits. This change in over-all compressor operating characteristics can be more clearly understood by considering the effect of a change in frequency on the operating characteristics of each compressor stage or small group of stages.

At a constant turbine inlet temperature, a very slow (frequency of 1 cps or less) sinusoidal variation in compressor inlet pressure would be expected to cause a sinusoidal variation in compressor discharge pressure. This variation in outlet pressure would compare with the inlet pressure variation in magnitude and phase and result in no change in over-all pressure ratio. As the frequency of the inlet pressure oscillation is increased, however, over-all pressure ratio should change as a result of amplitude attenuation and phase shift. Each stage or small group of compressor stages should retain its quasi-steady-state operating characteristics, however. The operating characteristics of small groups of compressor stages will not be in phase with the inlet pressure oscillation, due to the previously noted effects of amplitude attenuation and phase shift. As a consequence, compressor stage group and over-all pressure ratios depart from steady-state levels, setting up conditions that are conducive to stall somewhere within the compressor, even though the instantaneous over-all pressure ratio differs from the quasi-steady stall value.

The behavior of pressures through the engine, and stage pressure ratios during a typical rapid inlet pressure oscillation that resulted in compressor stall at approximately 93 percent of rated corrected engine speed is presented in figure 6.

A time history of the individual total pressures at each station is presented in figure 6(a). The occurrence of compressor stall is indicated by the sharp change in pressure level that occurs between 0.15 and 0.16 seconds. The approximate time of stall inception is indicated by a cross-hatched area on the figure. The stall apparently originated in a stage located between the compressor inlet and the seventh-stage stator, since all interstage pressures downstream of the seventh stage drop sharply (points A on fig.), while pressures upstream of the seventh-stage rise sharply (points B on fig.). Although the effect is slight, because of the compressed time scale, the time lag in these pressures (as flow proceeds through the compressor) is apparent in figure 6(a).

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A time history of compressor stage group and over-all pressure ratios, which were obtained from the individual pressures, is presented in figure 6(b). The variation of over-all pressure ratio (P_2/P_1), pressure ratio across the outlet or fourth group of stages (P_2/P_{11ss}), pressure ratio across the third-stage group (P_{11ss}/P_{7ss}), and pressure ratio across the first- and second-stage groups (P_{7ss}/P_1) are presented. In addition, the approximate quasi-steady-state stall limits for these stage groups are indicated on the figure by dashed horizontal lines. Because of the absence of a reliable pressure trace at the fourth-stage stator, the pressure ratios across the first two stage groups cannot be presented separately. The ratio P_{7ss}/P_1 is presented solely to give some indication of the behavior of the first half of the compressor, although such a large group of stages would not be expected to retain its over-all operating characteristics during an inlet pressure oscillation.

It is apparent from the pressure-ratio - time histories that the inlet group of stages, denoted in this instance by P_{7ss}/P_1, was oscillating near its stall limit, while the stall margin appears to increase progressively for the third- and fourth-stage groups. Maximum over-all compressor pressure ratio at the time of stall is lower than that shown by the quasi-steady stall limit line. This trend was substantiated by several other time histories of over-all compressor pressure ratio.

The duration of the stall was very short. Recovery was effected in approximately 0.04 second because of the sinusoidally varying compressor inlet pressure. Stall-free operation of the compressor then continued until the compressor inlet total pressure (P_1) again reached a minimum point in the succeeding cycle, at which time stall occurred again.

Operating the engine in this cyclic stalled condition for short periods of time (1 to 2 min) resulted in a small exhaust-gas temperature rise of about 30° F. In addition, no combustor blowout due to stall was experienced during the investigation. Operating with these inlet pressure oscillations did cause a low frequency engine vibration, however, which increased sharply in amplitude as stall occurred.

In order to show the effect of engine speed on the compressor stage-group stall limits, a time history of pressure and pressure ratio during
4664 a typical rapid inlet pressure oscillation at high corrected speed (110 percent) is presented in figure 7. The occurrence of compressor stall is indicated by the sharp change in pressure level (fig. 7(a)). The approximate time of stall inception is indicated by cross-hatched areas on the figure. Inspection of the individual interstage pressures (fig. 7(a)) shows that all interstage pressures upstream of the eleventh-stage stator increased sharply as the stall occurred (points B) while pressures downstream of this station dropped sharply (points A). This indicates that the stall originated somewhere between the eleventh- and fourteenth-stage stators. The pressure-ratio time histories (fig. 7(b)) indicate that the outlet-stage groups were oscillating near the quasi-steady stall limit, while the stall margin appears to increase progressively for the second- and inlet-stage groups. Maximum over-all compressor pressure ratio at this speed exceeds that indicated by the quasi-steady stall limit line.

Although compressor stall originated in an outlet-stage group at 110 percent of rated corrected engine speed, the characteristics were essentially those previously described for the stall that occurred in the inlet group of stages at a corrected speed of 93 percent.

The maximum oscillation amplitudes that the engine would tolerate without stalling are presented in figure 8 as a function of frequency for corrected engine speeds of 93, 100, and 110 percent. This figure indicates that, for a given frequency of oscillation, the inlet amplitude required for stall in the subject engine was highest at rated corrected engine speed and lowest at a corrected speed of 93 percent. The amplitude required for stall at the highest speed investigated (110 percent) fell between the amplitudes required for stall at the other two speeds. The occurrence of the highest amplitudes at 100-percent speed was probably the result of the better distribution of the loading of the compressor stage groups, which would be expected at design-point operation.

Increasing the frequency of oscillation at constant engine speed resulted in a significant reduction in the inlet amplitude required for stall. Thus, increasing frequency from 4 to 15 cycles per second at a corrected engine speed of 110 percent resulted in a 15-percent reduction in the inlet amplitude required for stall.

Figures 6 and 7 show that, during inlet pressure oscillations, compressor over-all pressure ratio at stall was lower than the quasi-steady stall limit at a corrected engine speed of 93 percent. Also, the compressor over-all pressure ratio at stall was higher than the quasi-steady stall limit at a corrected engine speed of 110 percent. Another illustration of this departure of compressor over-all pressure ratio from the quasi-steady stall limit during inlet pressure oscillation is provided by figure 9. Maximum over-all compressor pressure ratio as a function of corrected engine speed is presented for three frequencies of inlet total-pressure oscillation. The quasi-steady-state stall limit curve is included for comparison. The inlet amplitude of the pressure oscillations at these three frequencies is not constant but varies as indicated in figure 8.

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It is apparent from figure 9 that, as the frequency of the inlet pressure oscillation increases, the maximum over-all pressure ratio diverges from the quasi-steady stall limits. At the higher corrected engine speeds, maximum over-all pressure ratio was higher than the quasi-steady stall limit, while at the lower speeds maximum over-all pressure ratio was lower than the quasi-steady stall limit. This divergence in over-all pressure ratio can be attributed to the time lag that occurs in the interstage pressures. As flow proceeds through the compressor, the time lag increases and results in a mismatching of the compressor stages. At low corrected speeds, the loading of the inlet stages is normally high and the loading of the rear stages is relatively low. During an inlet pressure oscillation at low corrected speed, the loading of the inlet stages increases and stall occurs before the rear stages have time to assume their normal loading. The over-all compressor pressure ratio at the inception of stall will therefore be lower than normal. At high corrected speeds the loading of the rear stages is high, while the loading of the inlet stages is relatively light. During an inlet pressure oscillation at high corrected speed, the loading of the inlet stages increases to an above-normal value, as the rear-stage loading increases to the stall point. Over-all pressure ratio will therefore be higher than normal. Obviously, then, there should be combinations of loading distribution (corrected engine speed) and time lag (frequency of pressure oscillation) for which little or no divergence of over-all pressure ratio would result. For the engine used in this investigation there was little divergence in over-all pressure ratio between 95 and 96 percent of rated corrected speed.

The important point illustrated by figure 9 is that quasi-steady stall limits, in terms of over-all compressor pressure ratio, cannot be used to describe accurately the stall limits of an engine that is subjected to rapid inlet pressure oscillations. Thus, a prediction of the quasi-steady compressor stall limits, which is based solely on steady-state compressor performance, will not be valid for operation with inlet pressure oscillations. Since the trends and magnitudes of the effects of inlet pressure oscillations on compressor operation were shown to be dependent on the distribution of the stage loading and stage stall margins, widely different results may be obtained with other engines. Therefore, the experimental results presented in this report can serve only to explain the differences in over-all compressor stall limits that result from inlet pressure oscillations. However, the compressor stall limits for any engine can be predicted by means of an analytical method that combines a knowledge of the steady-state operating characteristics of each small group of compressor stages with an assumed dynamical engine model. This method of analysis is discussed in reference 7.

SUMMARY OF RESULTS

An experimental investigation was conducted to determine the effect of rapid inlet pressure oscillations on the operation of a current turbojet engine.

The amplitude of the approximately sinusoidal total-pressure wave, which was generated at the compressor inlet, was attenuated considerably as the wave passed through the compressor, and a large phase shift (lag) also occurred. Although the operating characteristics of each small group of compressor stages did not deviate appreciably from steady-state characteristics, the amplitude attenuation and phase shift resulted in a mismatching of the compressor stage groups and a consequent change in over-all compressor performance.

The inlet amplitude required to stall the engine was greatest at approximately rated corrected speed. As the operating point moved either above or below rated corrected speed, the amplitude required to stall the engine became smaller.

The change in over-all compressor stall limits, as defined by the maximum over-all compressor pressure ratio, was clearly indicated by comparison with the quasi-steady-state compressor stall limits. At the higher corrected engine speeds investigated, maximum over-all compressor pressure ratio was higher than the quasi-steady stall limit curve; while at the lower speeds the over-all pressure ratio was below the quasi-steady stall limit curve. Thus, a prediction of the engine stall limits that is based solely on steady-state compressor performance, will not be valid for operation with inlet pressure oscillations.

Trends and magnitudes of the effects of pressure oscillations on over-all compressor operation will vary from one engine to another, because they depend on the stage loading distribution and stage stall margins. However, a method for predicting the compressor stall limits during inlet pressure oscillations exists in the reference literature.

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National Advisory Committee for Aeronautics
Cleveland, Ohio, January 7, 1958

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REFERENCES

1. Childs, J. Howard, Kochendorfer, Fred D., Lubick, Robert J., and Friedman, Robert: Stall and Flame-Out Resulting from Firing of Armament. NACA RM E55E25, 1955.

2. Anon.: Investigation of Conditions Conducive to Compressor Stall. AFAC TR-54-15, Air Force Armament Center, Air Res. and Dev. Command, Elgin Air Force Base (Florida), June, 1954.

3. Beke, Andrew, Englert, Gerald, and Beheim, Milton: Effect of Air Adjustable Supersonic Inlet on the Performance up to Mach Number 2.0 of a J34 Turbojet Engine. NACA RM E55I27, 1956.

4. Dangle, E. E., Cervenka, A. J., and Perchonok, Eugene: Effect of Mechanically Induced Sinusoidal Air-Flow Oscillations on Operation of A Ram-Jet Engine. NACA RM E54D01, 1954.

5. Sterbentz, William H., and Davids, Joseph: Amplitude of Supersonic Diffuser Flow Pulsations. NACA TN 3572, 1955. (Supersedes NACA RM E52I24.)

6. Wallner, Lewis E., Useller, James W., and Saari, Martin J.: A Study of Temperature Transients at the Inlet of a Turbojet Engine. NACA RM E57C22, 1957.

7. Gabriel, David S., Wallner, Lewis E., Lubick, Robert J., and Vasu, George: Some Effects of Inlet Pressure and Temperature Transients on Turbojet Engine. Aero. Eng. Rev., vol. 16, no. 9, Sept. 1957, pp. 54-59.

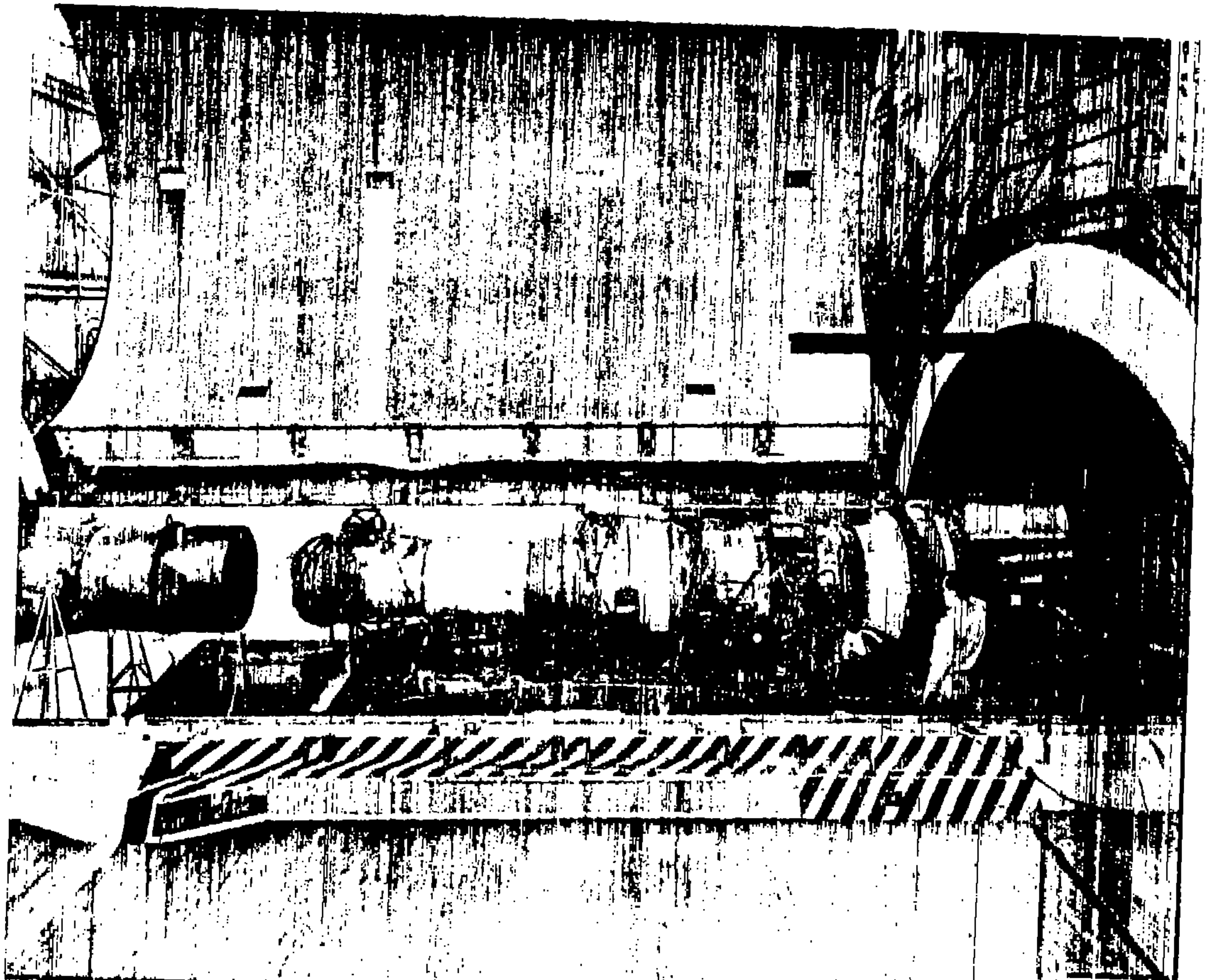

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Figure 1. - Engine installed in test facility.

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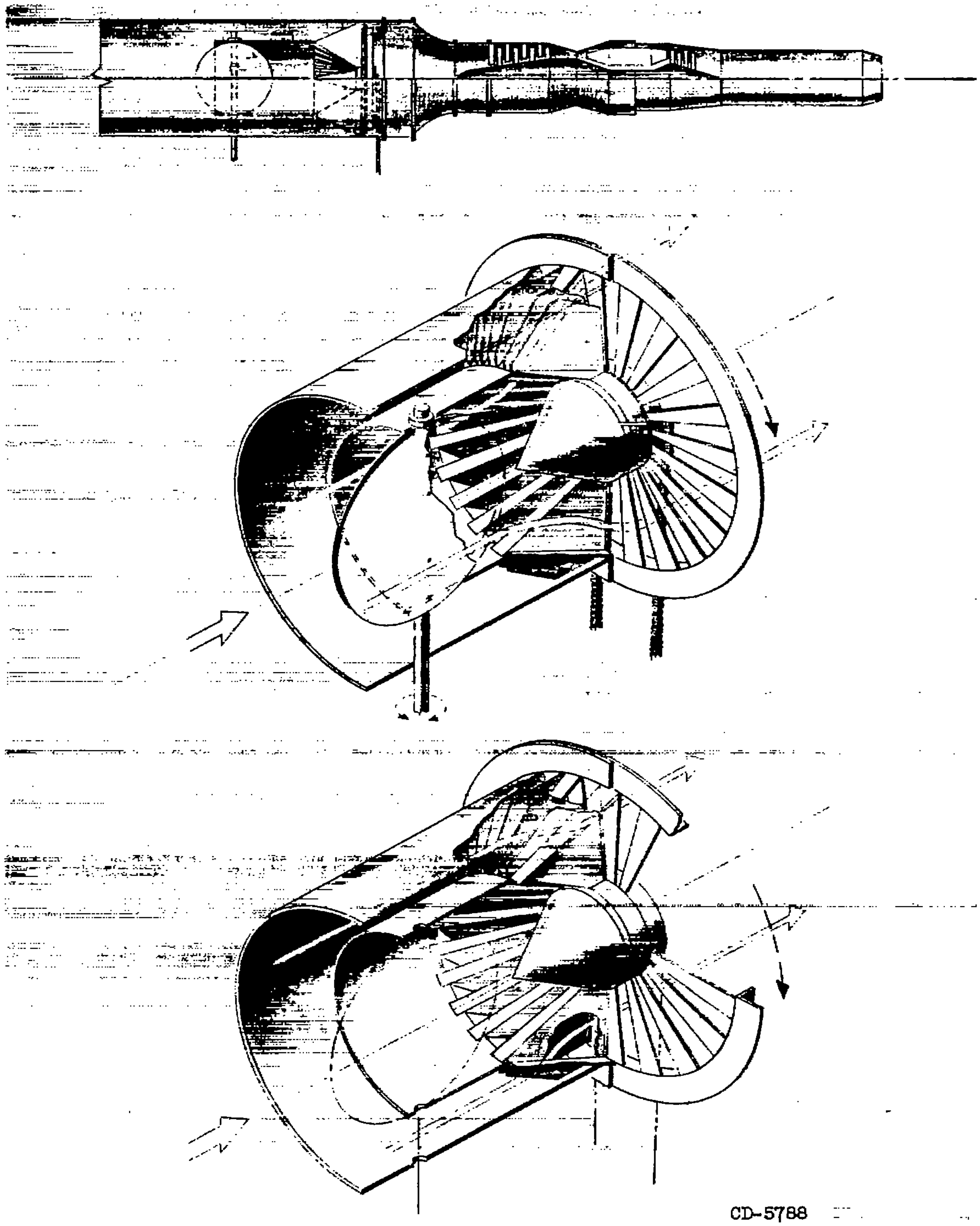

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Figure 2. - Pressure pulse generator.

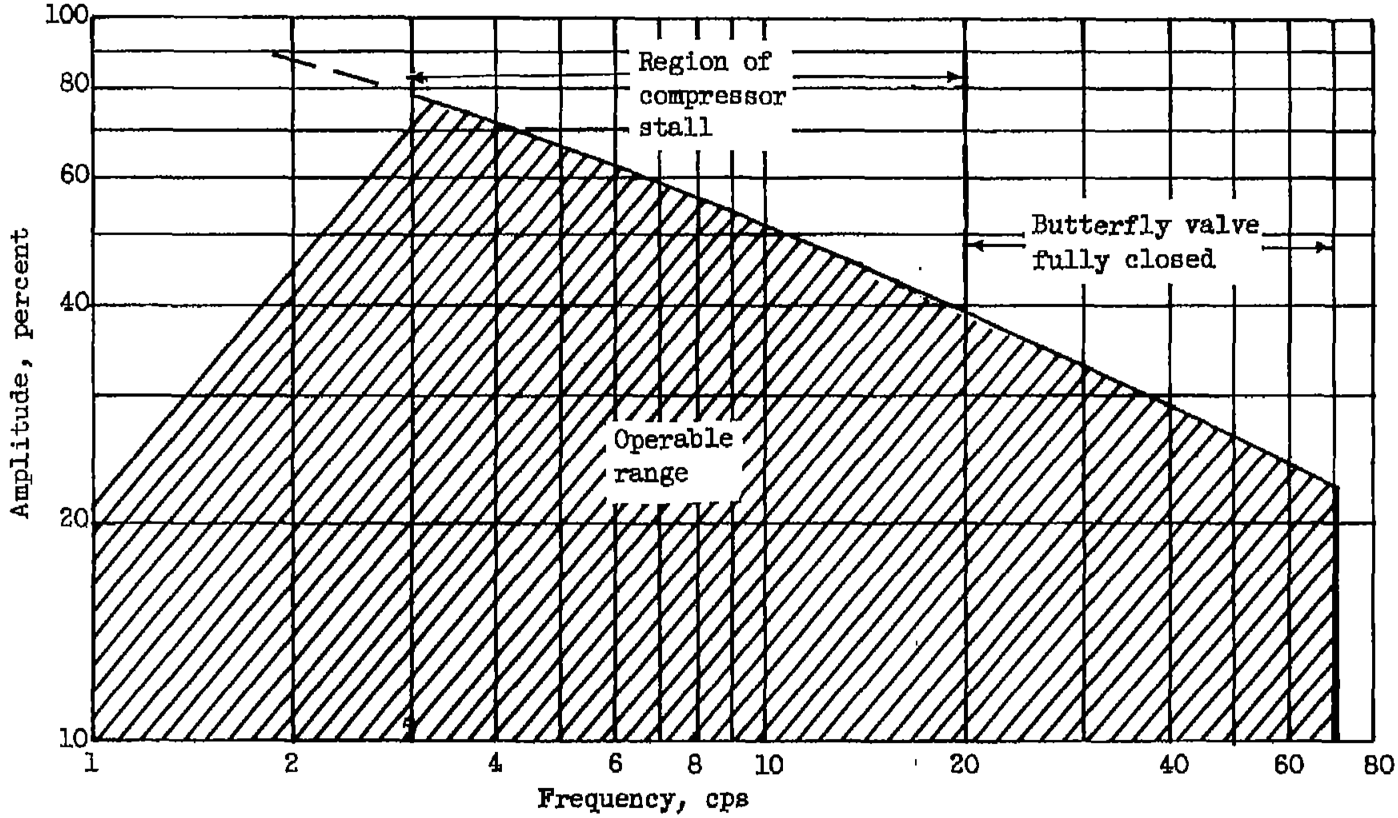

Figure 3. - Operational limits of inlet pressure pulse generator engine combination. Corrected engine speed, 100 percent of rated.

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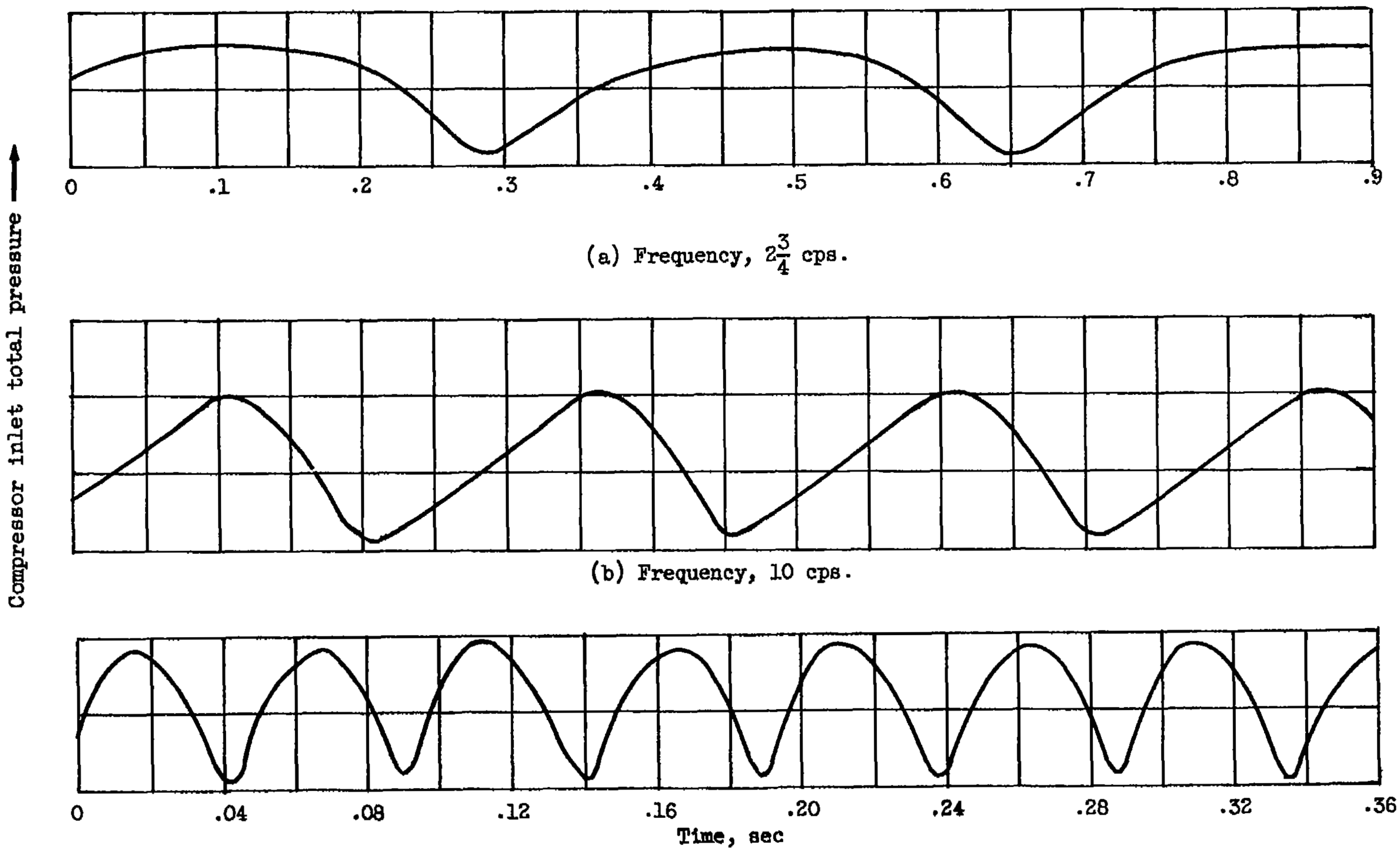

(a) Frequency, $2\frac{3}{4}$ cps.

(b) Frequency, 10 cps.

(c) Frequency, 21 cps.

Figure 4. - Typical inlet total-pressure oscillations obtained with pulse generator.

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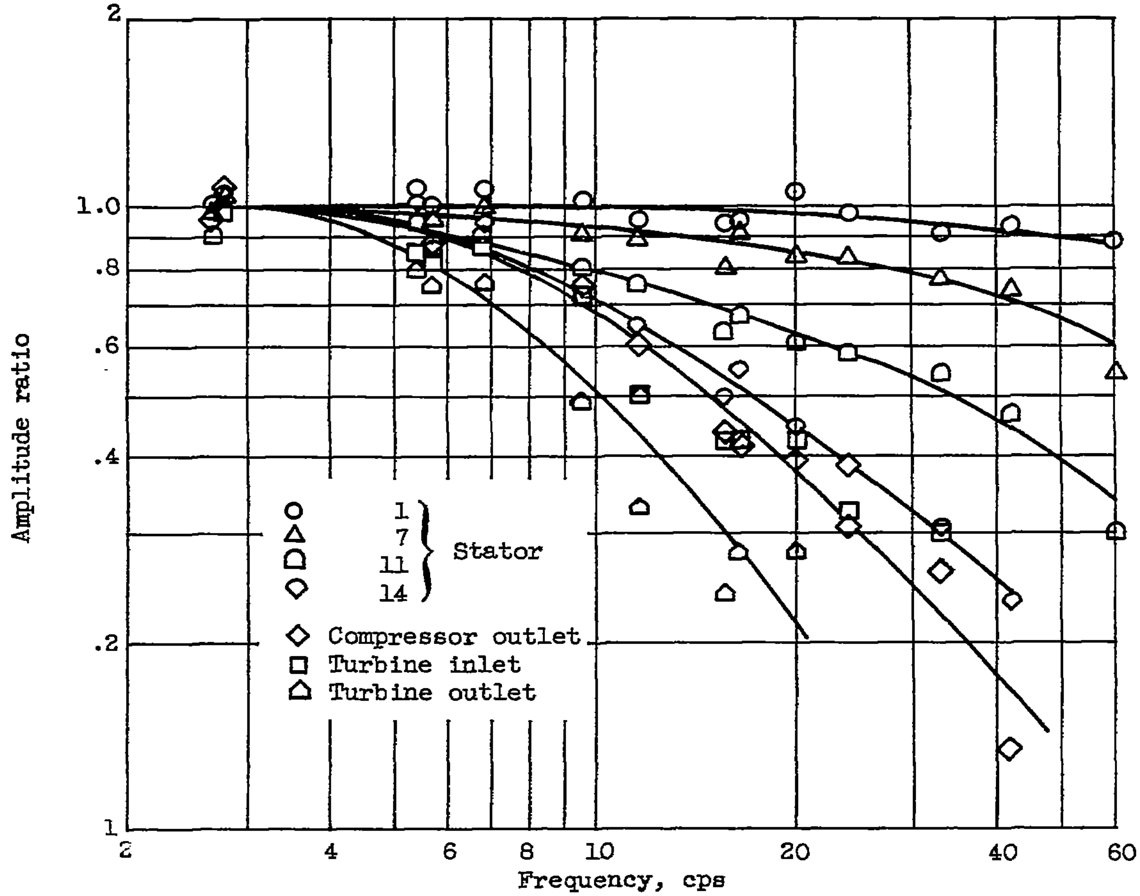
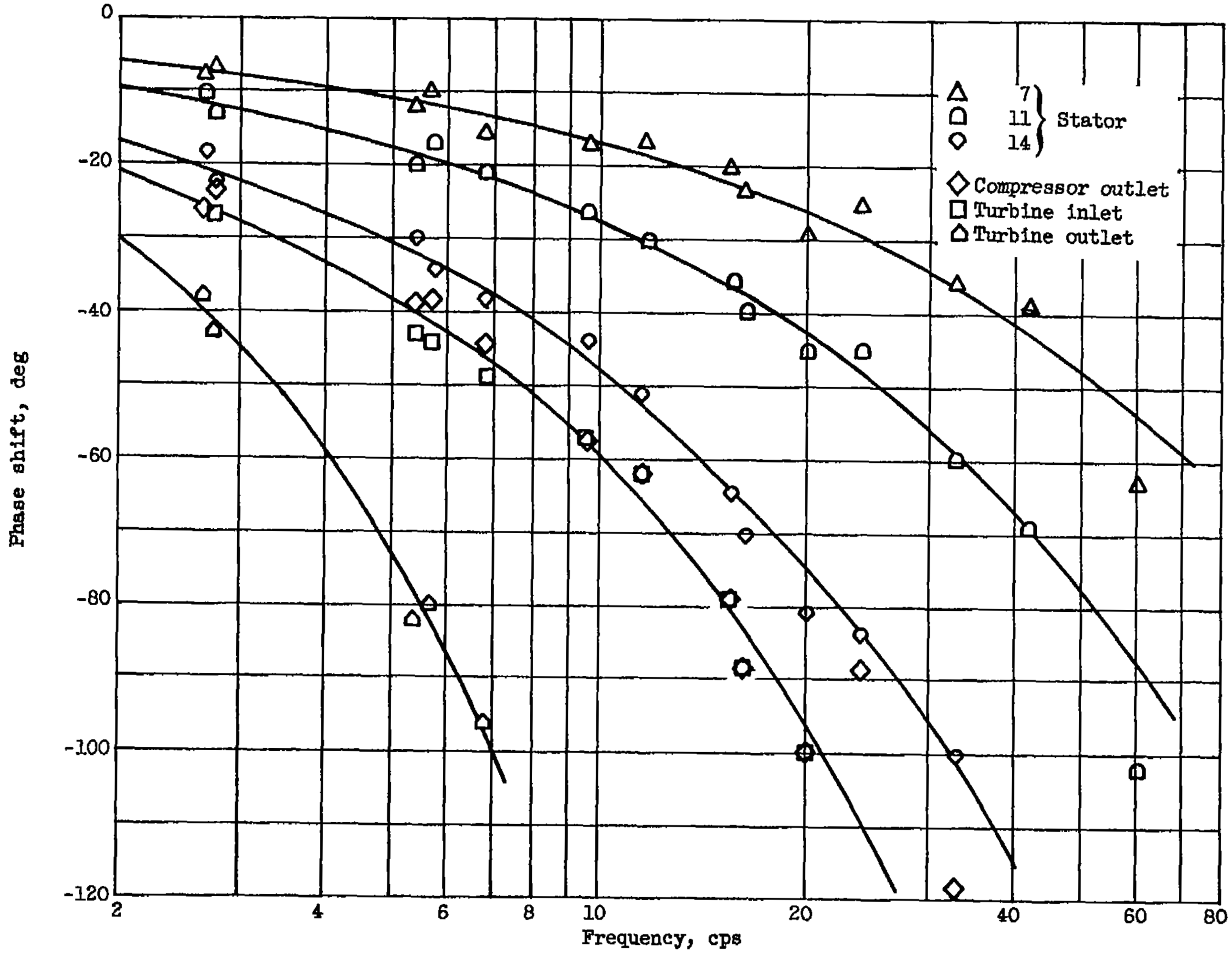


(a) Amplitude ratio.

Figure 5. - Frequency response at various stations throughout engine. Inlet total-pressure amplitude, 11 percent; corrected engine speed, 100 percent of rated.



(b) Phase shift.

Figure 5. - Concluded. Frequency response at various stations throughout engine. Inlet total-pressure amplitude, 11 percent; corrected engine speed, 100 percent of rated.

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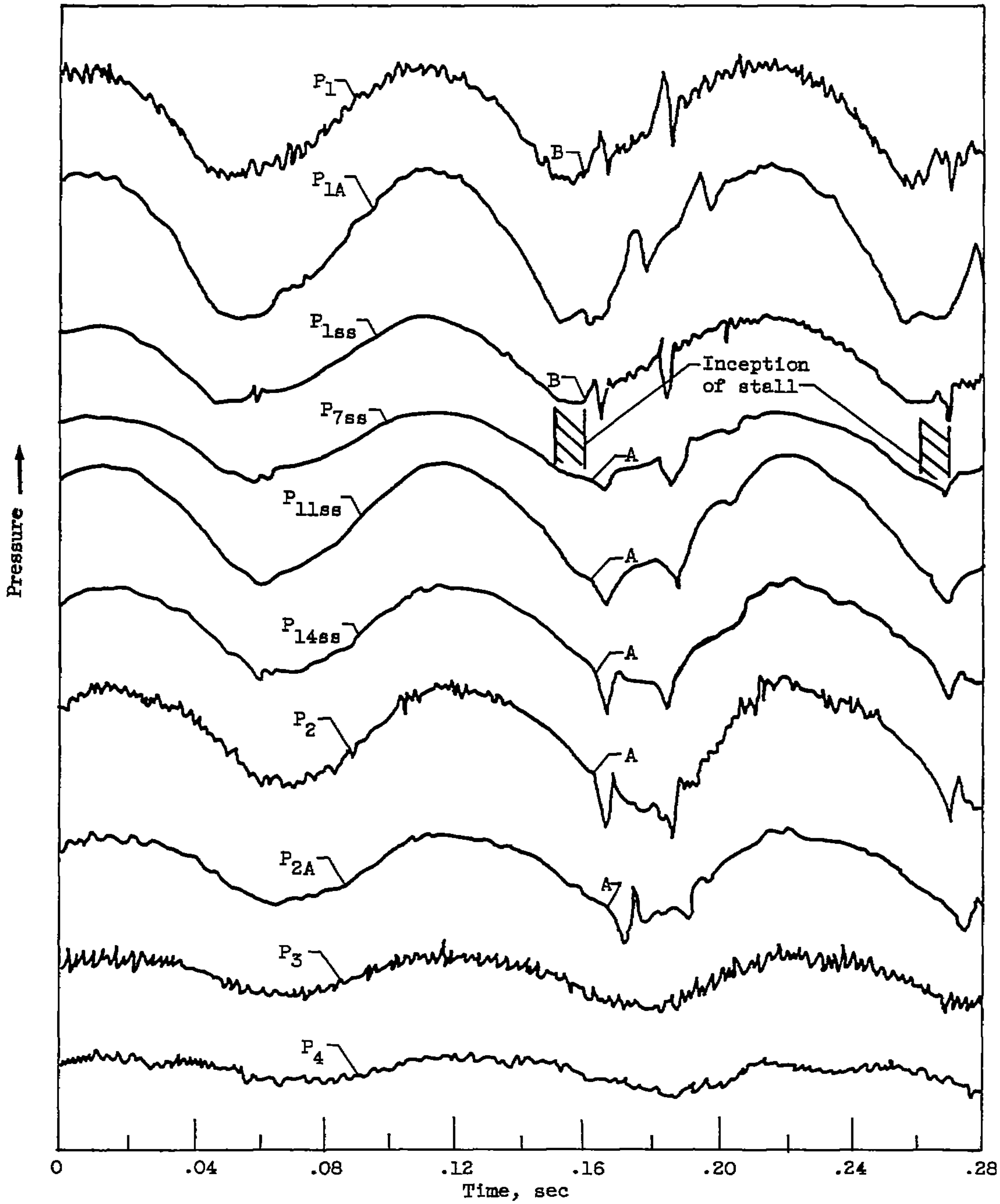

(a) Individual total pressures.

Figure 6. - Time history of typical inlet total-pressure oscillation. Corrected engine speed, 93 percent; frequency, $9\frac{1}{2}$ cycles per second; inlet total-pressure amplitude, 37 percent.

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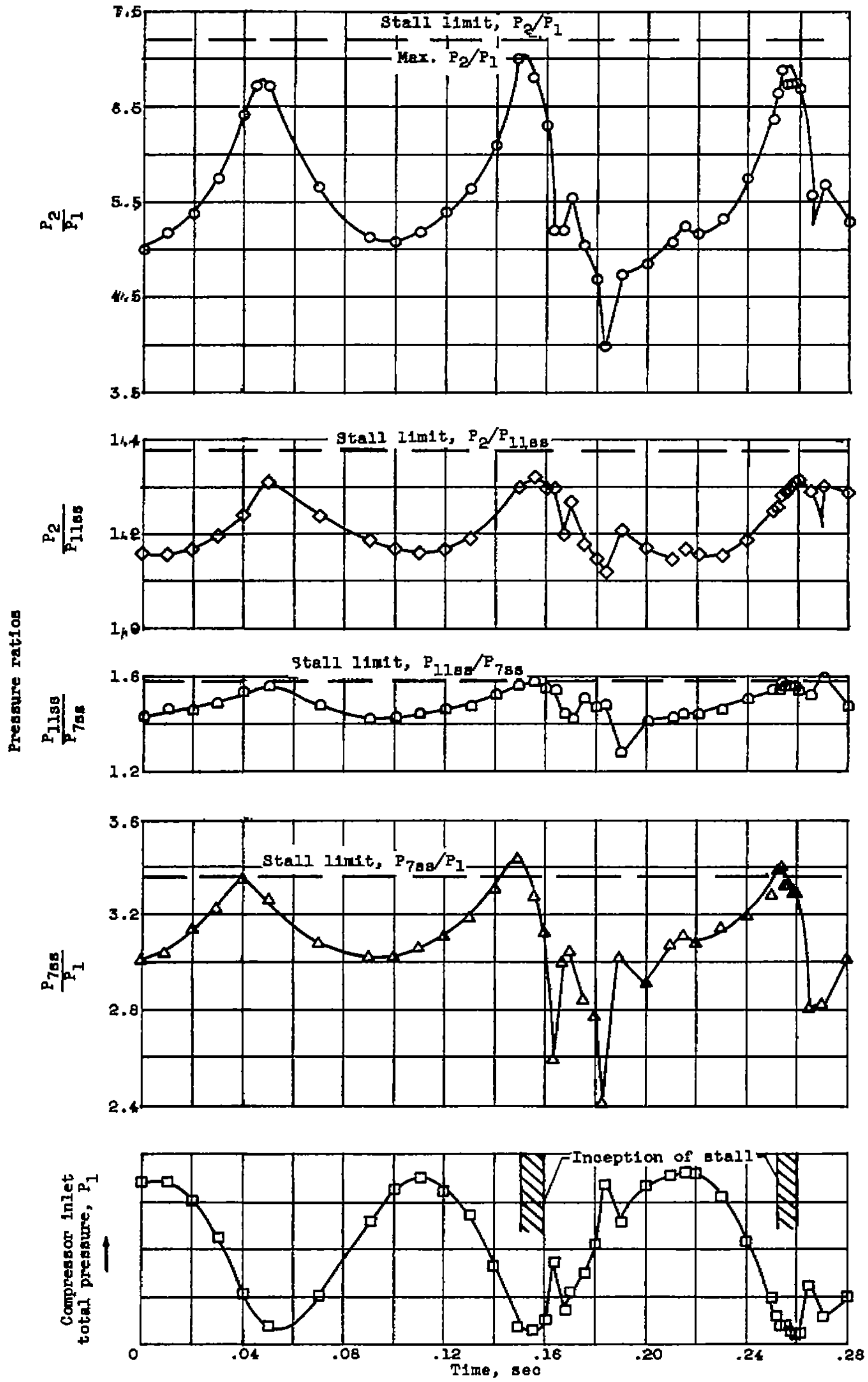

(b) Pressure ratio.

Figure 6. - Concluded. Time history of a typical inlet total-pressure oscillation. Corrected engine speed, 93 percent; frequency, $9\frac{1}{2}$ cycles per second; inlet total-pressure amplitude, 37 percent.

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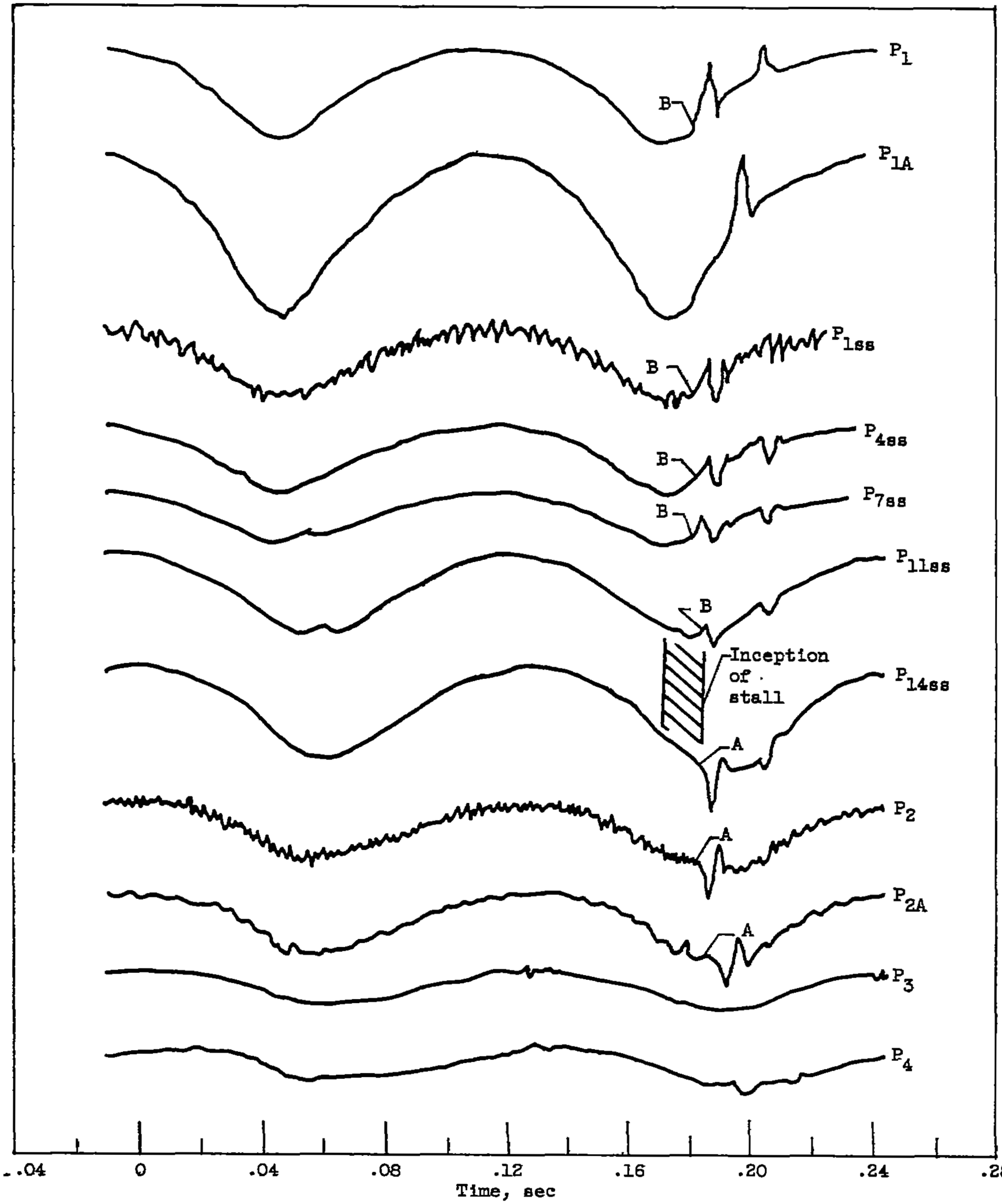

(a) Individual total pressures.

Figure 7. - Time history of typical inlet pressure oscillation. Corrected engine ed speed, 110 percent of rated; frequency, 8 cycles per second; inlet total-pressure amplitude, 45 percent.

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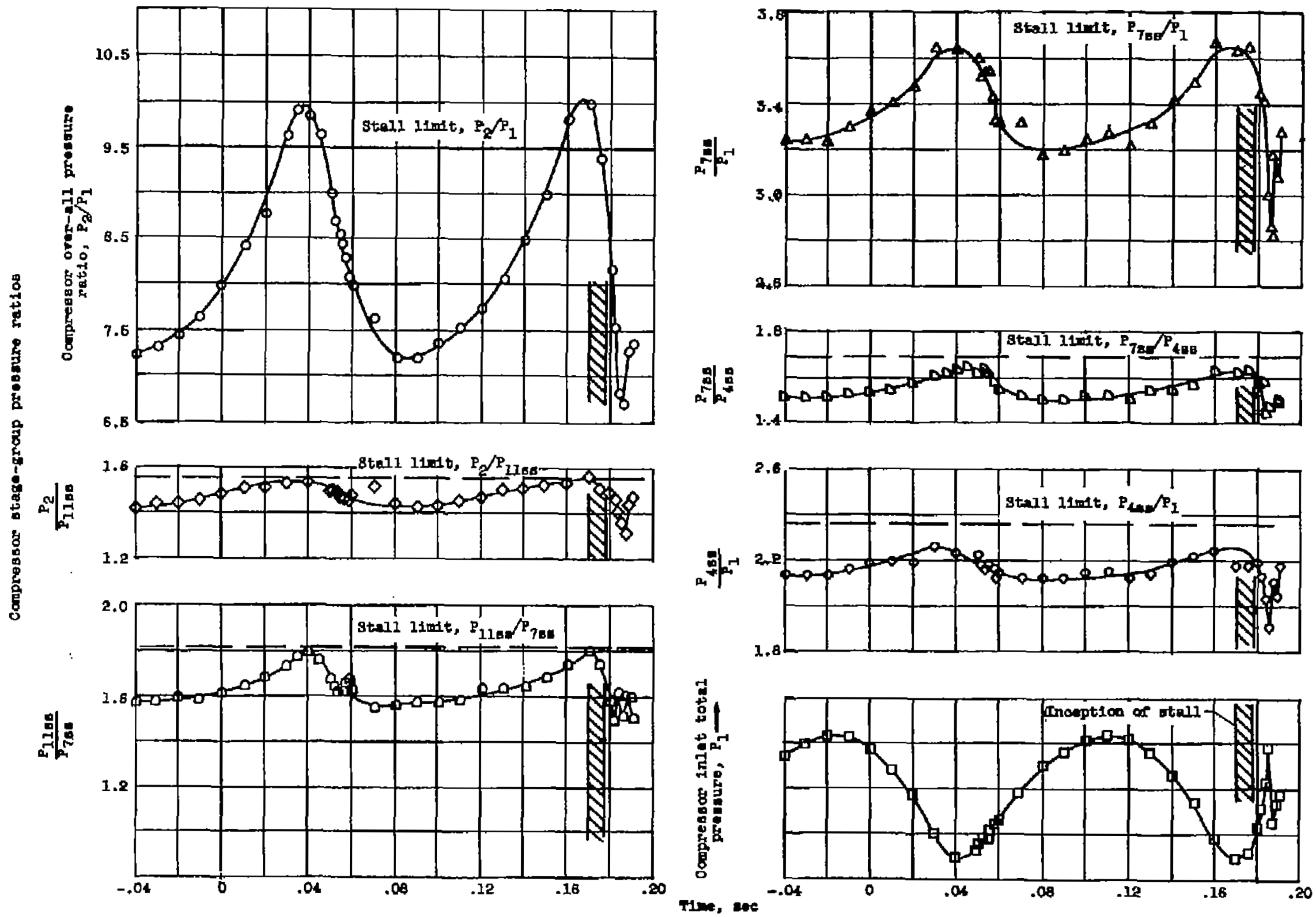

(b) Pressure ratio.

Figure 7. - Concluded. Time history of typical inlet pressure oscillation. Corrected engine speed, 110 percent of rated; frequency, 8 cycles per second; inlet total-pressure amplitude, 45 percent.

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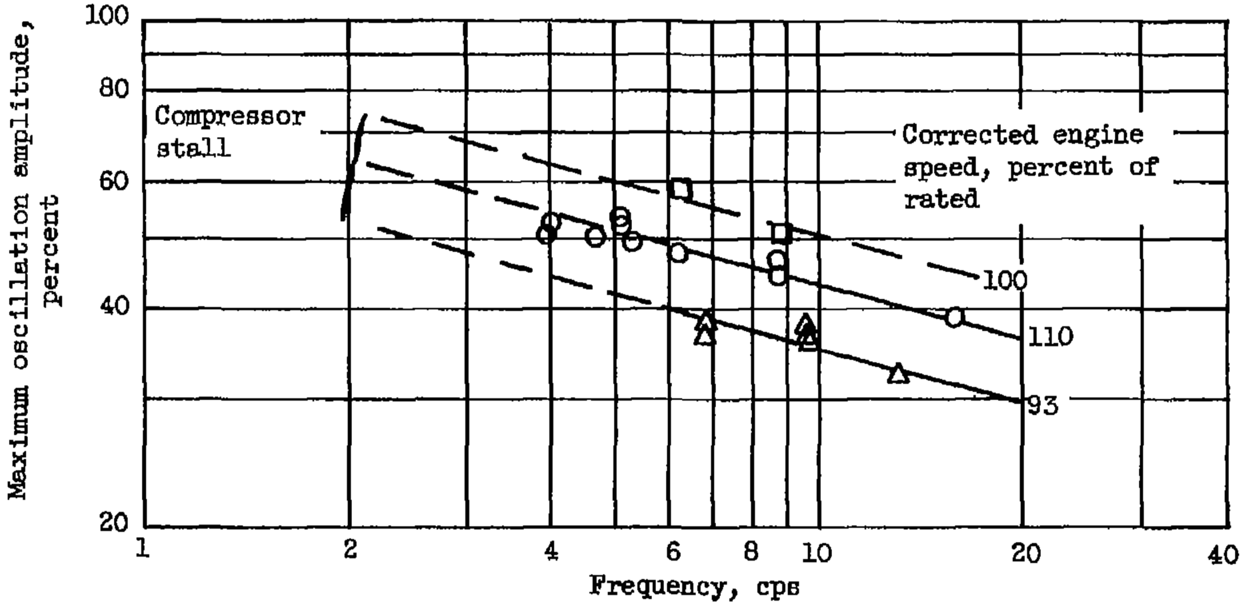

Figure 8. - Maximum oscillation amplitude at stall as function of frequency of oscillation.

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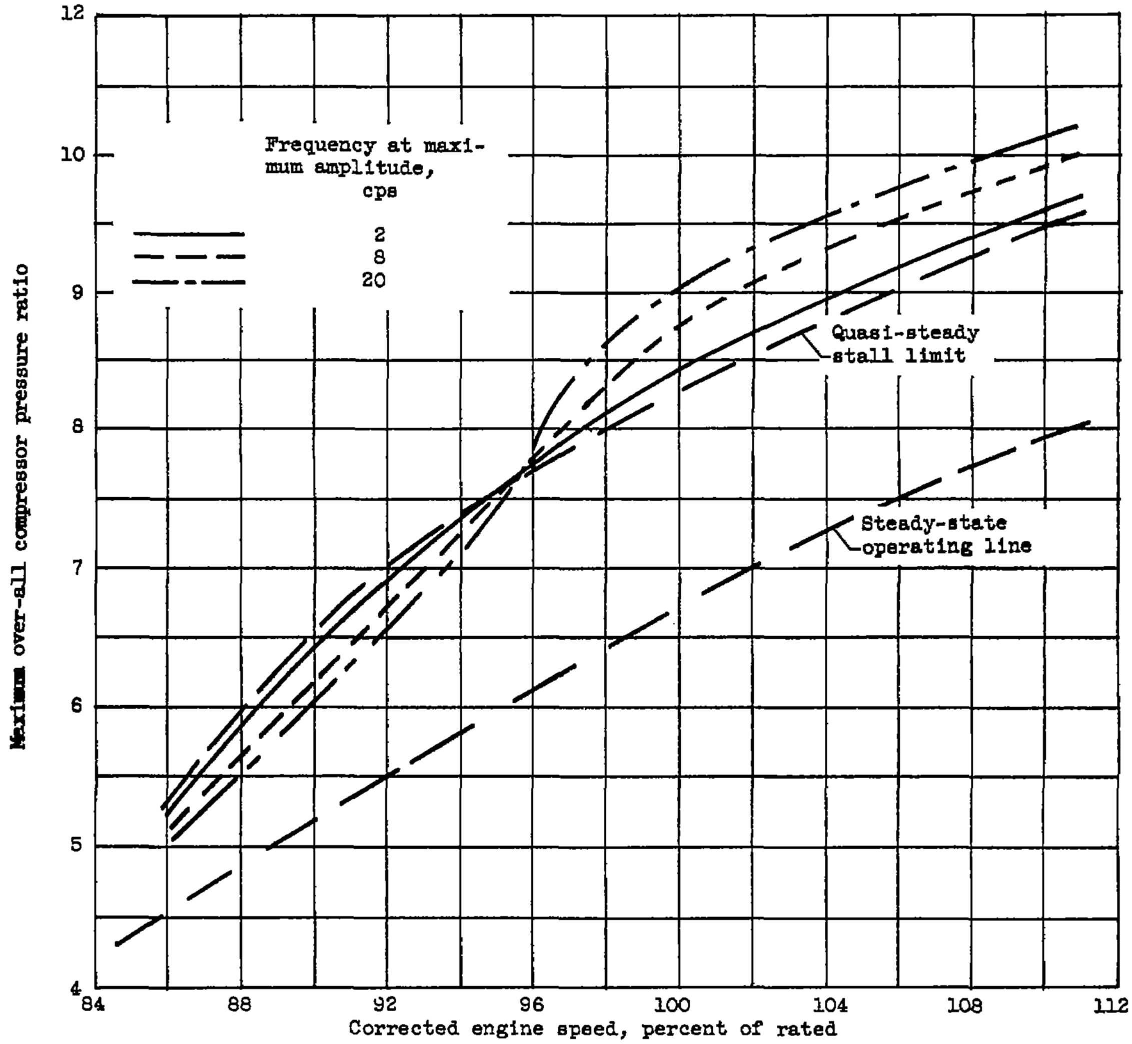

Figure 9. - Over-all compressor pressure ratio as function of frequency at maximum amplitude.

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