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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF ACCELERATION CHARACTERISTICS OF A TURBOJET ENGINE INCLUDING REGIONS OF SURGE AND STALL FOR CONTROL APPLICATIONS

By Paul M. Stiglic, Ross D. Schmidt, and Gene J. Delio

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RESEARCH MEMORANDUM

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SUMMARY

The acceleration characteristics, in the regions of maximum acceleration and compressor stall and surge, of an axial-flow turbojet engine with a fixed-area exhaust nozzle were determined by subjecting the engine to fuel flow steps, ramps, and ramps with a sine wave superimposed. From the data obtained, the effectiveness of an optimalizer type of control for this engine was evaluated.

At all speeds above 40 percent of rated, a maximum acceleration was not obtained until the engine reached the point of stall or surge. A sharp drop, as high as 80 percent of maximum, in acceleration then occurred as the compressor entered surge or stall.

With the maximum acceleration occurring at the point of surge or stall, the optimalizer-type control could not prevent the engine from entering surge or stall. Effective operation of the control may still be possible by sensing the sharp drop in acceleration experienced at the point of stall or surge and using this signal to limit fuel flow. The success of this type of operation would depend on the magnitude of the stall-recovery hysteresis.

INTRODUCTION

The wide and rapid thrust changes required of a turbojet engine necessitate a control to prevent the engine from encountering surge or stall in addition to utilizing a maximum of the engines accelerating potential. Most present controls incorporate schedules, such as fuel flow or temperature with speed, to attempt to meet these needs. In practice, their use has proved difficult due to altitude correction. Also, schedules have certain basic shortcomings that do not assure maximum acceleration over a wide range of flight conditions. These shortcomings stem from lack of uniform performance among engines of the same design and manufacture, and the inability of the control to adjust for engine deterioration. Improvements over schedules could be made if some engine characteristic were detected that would warn of approaching surge or stall. One such characteristic would be the existence of a maximum engine acceleration just before the engine entered a surge or stalled condition. This signal could then be incorporated into a control to operate the engine at the point of maximum acceleration. The purpose of the present investigation was to determine whether the engine used possessed such a characteristic which could be incorporated into an optimalizing-type control.

A previous investigation (ref. 1) on an axial-flow turbojet engine indicated that a maximum acceleration did occur before surge or stall was encountered. This engine possessed acceleration characteristics suitable for an optimalizer control. By superimposing a test signal on the fuel flow, the control could automatically seek the optimum point by responding to the superimposed output signal generated by the engine. The principles of this type of control and its application to an internal combustion engine are reported in reference 2.

To determine whether or not an optimalizer control could be adapted to a modern turbojet engine of a different design and manufacture, a sea-level, zero-ram-ratio test was conducted. The program was carried out by imposing steps, ramps, and ramps with a superimposed sine wave on the fuel flows of the test engine and recording the desired engine parameters. All tests were run using the fixed, rated exhaust-nozzle area. The data are plotted to show the relation of acceleration with speed and fuel flow.

INSTRUMENTATION

The locations of all the pressure probes used during this investigation are shown in figure 1. The frequency response of a typical pressure transducer with its associated tubing and probe is presented in figure 2.

The fuel system, which was specially designed for this investigation, is shown in figure 3. A relief valve with a natural frequency of about 200 cycles per second was installed just before the engine throttle, and this relief valve maintained a constant pressure drop of approximately 100 pounds per square inch across the throttle. The throttle valve was positioned by the electrohydraulic servo to correspond to the input signal. The only parts of the original engine fuel system that were used were the flow divider and the nozzle networks. The fuel system was capable of supplying a change in actual fuel flow of 8000 pounds per hour within 15 milliseconds. The response of actual fuel flow through the nozzles to the throttle position should be flat to some frequency below the natural frequency of the flow divider, which is about 100 cycles per second. Actual fuel flow was determined by measuring the pressure differential between the small-slot pressure and the compressor-discharge pressure and calibrating this differential pressure against fuel flow during steady-state engine operation.

Engine speed was recorded from a signal obtained by driving a high-frequency, engine-driven alternator coupled to a frequency meter that supplied a d-c signal to an amplifier containing appropriate zeroing and gain adjustments. The alternator also supplied a signal to a counter having a variable time base whose periodic display indicated true rpm when the engine was being run in steady state. A record of engine acceleration was obtained by differentiating the engine-speed d-c signal and supplying the resulting signal to an amplifier. The acceleration trace was not used for data-reduction purposes because of the large amount of noise contained in the signal. This noise probably resulted from play in gears and splined couplings which connected the alternator to the engine shaft.

As a result of a filter used on the engine speed signal, the speed and acceleration traces contain what amounts to "dead time". These two traces were shifted in time with respect to the other engine parameters as indicated on the oscillograph traces presented in this report.

The amplifier output signals of pressures, speed, acceleration, and fuel-valve position were used to drive the galvanometer elements of a multichannel oscillograph recorder.

TEST PROCEDURE

The speed range was divided into 400-rpm increments, and at each initial speed, starting from 3000 rpm, steps in fuel flow of successively increasing amplitude of approximately 300 pounds per hour were imposed up to the limit of the fuel system. For each fuel flow step, acceleration was allowed to continue until maximum turbine-discharge temperature, as indicated by a flight recorder, was reached. Because fairly large thermocouples were used, this procedure resulted in steps with an average duration of approximately 1.5 seconds. Although the fuel flow step was the disturbance most often used, fuel flow inputs of ramps and ramps with a superimposed sine wave were also introduced. The ramps were used for the purpose of comparing the fuel flow surge and stall limit so obtained with the limit obtained by using the step inputs. The fuel flow ramp with a superimposed sine wave was used to investigate how various engine parameters maximized in the region of surge or stall.

DATA REDUCTION

In order to determine the fuel flow at any instant, the small-slot pressure and the average compressor-discharge pressure were evaluated.

The difference between these two pressures was a measure of fuel flow, as shown by the calibration of fuel flow against differential pressure in figure 4. Because of the instruments used, this method of measuring fuel flow gave a frequency response which was flat to approximately 15 cycles per second.

The acceleration was not recorded at all times and therefore was determined by taking the slope of the speed trace. This method of evaluating acceleration gives the same effect as a filter in the acceleration circuit so that the acceleration-frequency response is probably flat to somewhat less than 10 cycles per second.

The sequence of points from any test run where the step-type fuel flow disturbance was used represents a line of constant fuel flow on the figures showing the variation of acceleration with speed. Data points were taken every 0.1 second, with each run yielding about 15 points. These figures were then cross-plotted to give the acceleration - fuel flow plots at constant speed, and finally a complete acceleration map of fuel flow against engine speed showing lines of constant acceleration was drawn.

RESULTS AND DISCUSSION

Typical oscillograph traces of engine response to a fuel flow step are presented in figure 5 for successively larger fuel flow steps. From a steady-state speed of 50 percent of rated, the fuel flow step shown in figure 5(a) caused the engine to accelerate in a normal manner. Oscillations in the compressor-discharge pressure of about 100 cycles per second are present both in steady state with a small amplitude and during the transient period with a much larger amplitude. These oscillations are referred to as "partial stall" (ref. 3) and were found to exist throughout the entire range of engine operation. Because no records were obtained without this partial stall, its effect on engine performance cannot be evaluated from this investigation.

Engine response to a larger step in fuel flow at about the same engine speed is shown in figure 5(b). For the first 0.2 second, acceleration of the engine proceeded in a manner similar to that in figure 5(a) until stall was encountered. Stall (ref. 3), sometimes referred to as "hard stall," "complete stall," or "total stall," was encountered at all speeds above 40 percent of rated with large fuel flow inputs. The onset of stall can always be detected in the compressor-discharge trace by a sudden drop in the mean pressure level followed by a large-amplitude oscillation of 35 to 40 cycles per second. The stall in figure 5(b) caused the acceleration to drop to about 80 percent of its previous value, which can be seen from the change in slope of the speed trace. Upon reducing the fuel flow to the initial value, the engine did not immediately recover from stall, but encountered a hysterisis condition which caused it to remain stalled for approximately 0.2 second. After the compressor came out of stall, the engine still continued to accelerate for 0.15 second, at which time a deceleration involving a very large time constant was begun.

A clearer demonstration of this continued acceleration effect after a cut-back in fuel flow is shown in figure 5(c). This transient was initiated at approximately the same engine speed as that of figure 5(a), but the amplitude of the fuel flow step was larger. After the fuel flow was reduced, the compressor again encountered hysterisis and remained stalled for about 0.2 second. When the compressor recovered from stall, the engine acceleration increased. The deceleration which followed was again characterized by a large time constant.

At engine speeds below 50 percent of rated and at maximum fuel flows, stall was no longer experienced. As shown in figure 6, an excessive post-turbine burning resulting in screech was encountered. During screech and at a constant value of fuel flow, the engine reached a peak speed and then began to decelerate. The high-frequency oscillation of about 900 cycles per second on the turbine-discharge pressure trace was probably caused by the transducer being forced to resonate at its natural frequency. The 200-cycle-per-second oscillation on the throttle-discharge pressure trace was probably caused by the relief valve used in the fuel system. After fuel flow had been cut back, the engine again began to accelerate.

Above 60 percent of rated speed, a large increase in fuel flow caused the engine to operate in a surged condition, then pass into a state of total stall as shown in figure 7. Surge is characterized by a much greater amplitude fluctuation in compressor-discharge pressure than stall, and the frequency is lower (10 to 15 cps). Although the average accelerating ability of the engine was quite good under surge conditions, as indicated by the slope of the engine-speed trace, large positive and negative values of acceleration were obtained because of the surging state of the compressor. These values were much greater numerically than any that could be realized in a normal transient. As engine speed increased during the transient, surge oscillations ceased, the compressor entered a stall region, and the engine acceleration was reduced to approximately zero. Upon reduction of fuel flow, the engine remained in a stalled condition, but the engine speed responded to fuel flow with a relatively short time constant when compared with the previous low-speed deceleration time constants. At point A, the engine had come to the initial steady-state fuel flow and engine speed but remained in a stalled condition and decelerated. The engine recovered from stall a short time later when fuel was further reduced.

The location of these regions of stall, surge, and screech is shown in figure 8. This plot of fuel flow against engine speed illustrates an overlapping of the regions as seen from the percent-rated-speed axis. At engine speeds of 40 to 50 percent, stall or screech may be encountered, depending on the magnitude of the imposed fuel flow increase. From engine speeds of 55 to 80 percent, stall or surge regions can be penetrated. It will be noted that figure 8 holds only for fuel flow increases, and the engine cannot pass from stall to surge by changing the engine speed. When the shaded area designated surge is encountered, the engine will first complete a few cycles of surge, then operate in a stall condition. When this area is not directly encountered (i.e., penetrated on a change in engine speed), stall only is experienced. The area below the stall line and above the steady-state line is the region of normal acceleration and will be discussed later in this section.

The response of the engine to a fuel flow ramp with a superimposed sine wave is presented in figure 9(a). This type of fuel flow input was used to determine how the various engine parameters maximized. A smooth maximum would be evidenced by a frequency doubling followed by a 180° shift in phase of the parameter that so maximized (ref. 2). As seen on the trace of figure 9(a), acceleration did not maximize in this manner. Just before stall, the response of acceleration to fuel flow was attenuated, demonstrating that the accelerating potential of the engine increases only slightly with larger increases in fuel flow. The transient presented in figure 9(b) was initiated at about 600 rpm higher engine speed. Acceleration at this higher speed does not attenuate as much just before stall as that in figure 9(a), showing that at the higher speeds acceleration tends to have a more linear relation with fuel flow.

Plots of acceleration as a function of engine speed for lines of constant fuel flow are shown in figure 10. When acceleration was initiated from 67 percent rated speed (fig. 10(a)), the acceleration rate increased with increasing fuel flow until a flow of 4245 pounds per hour was reached. This value represents the highest fuel flow which may be used at this particular speed without encountering stall. The next larger fuel flow forced the engine into stall, with the acceleration rate dropping to approximately one-fourth of the rate achieved just before stall. In the higher-speed region, as shown by figure 10(b), where the initial speed was 78 percent of rated, an increase in fuel flow to as high as 6410 pounds per hour was not sufficient to penetrate the stall or surge region.

The results at an initial engine speed of 53 percent rated are presented in figure 11(a). Although for each of the transients shown the engine entered into a stall condition, the transient represented by a fuel flow of 4520 pounds per hour did not cause stall until the engine had increased its speed by approximately 200 rpm. This indicates that the stall line has a negative slope referred to the engine parameters of fuel flow and engine speed. In all cases after the engine entered a stall condition, acceleration fell to approximately a constant value of 60 percent of the acceleration reached before stall occurred.

Accelerations into stall and surge regions initiated from approximately 74.0 percent rated speed are shown in figure 11(b). For the cases shown, the engine encountered stall, directly at the lower fuel flows and following a few cycles of surge at higher ones. The acceleration in stall is less than 20 percent of that before stall, while the acceleration in surge dropped to about 50 percent of that before surge. When stall was encountered at higher speeds, even larger acceleration drops were experienced. The data for accelerations during surge plotted in figure 11(b) are the average accelerations encountered during surge. The peak accelerations occurring in surge were found to be as high as ±1500 rpm per second.

A cross plot of the acceleration-speed plots at 40 percent rated speed is shown in figure 12(a). This plot exhibits an ideal type of maximization of acceleration with fuel flow for control application. A control operating with a superimposed sine wave on the fuel flow and with a phase detector to compare fuel flow and acceleration could operate at the peak acceleration at all times with this type of an acceleration characteristic. The phase detector would indicate the peak when the 180° phase shift was encountered. This was the only region of engine operation that exhibited the ideal maximization of acceleration.

A similar cross plot at 60 percent rated engine speed is presented in figure 12(b). In this higher-speed range, the point of stall is clearly defined by the very large (about 60 percent) abrupt drop in the engine acceleration. Stall, at this speed, has a frequency of approximately 35 cycles per second and is probably composed of one rotating stall pattern. At the very high fuel flows, acceleration exhibits another abrupt drop, which may represent the onset of post-turbine burning. While the transition to stall was abrupt, the acceleration characteristic did exhibit a maximum at the stall point; and an optimalizer control, if fast enough, could maintain an average acceleration close to the peak acceleration. Its operation would, however, be affected by a hysteresis condition that makes it necessary to reduce fuel flow below the stall limit to recover from stall. On the traces of figure 5(b), where the fuel flow was reduced to the initial value, there is a hysteresis effect amounting to 0.2 second before the flow can be reestablished to enable the engine to recover from stall. Figure 7, where the engine operated in a stalled condition for a greater length of time, shows that an even longer period, in addition to a second fuel flow cut-back, was required for the engine to recover. Although no data are presently available to verify it, an extremely short time in stall may yield correspondingly small hysteresis. If this is proved correct, the optimalizer control could operate even though the maximum point were on the stall line.

The acceleration - fuel flow characteristic at 70 percent rated engine speed is presented in figure 12(c). In this speed range, the acceleration in the normal operating region tends to become more linear with fuel flow. Upon entering stall, the acceleration dropped and remained at approximately a constant value of 20 percent of the stall limit for further increases in fuel flow. This value is about 20 percent of that obtained at a 10-percent lower engine speed. Although surge was experienced at this speed, only the stall and normal acceleration data are shown on figure 12(c).

At 74 percent rated engine speed (fig. 12(d)) the engine encountered either surge or stall, depending on the size of the fuel flow input. As fuel flow was increased, the engine acceleration increased until stall was attained. Then with larger steps in fuel flow the engine first entered a surge region and then passed into a stalled state. Sometimes, however, at the very high fuel flows, the engine would enter stall or surge (this variation is shown in fig. 11(b)). Whether the engine enters stall or surge in the 6000-pound-per-hour fuel flow range may depend on the immediate previous history of the engine transients. Figure 12(d) shows that the acceleration in surge is over twice that found in stall in this speed range.

The acceleration - fuel flow map for increasing values of constant-speed lines is found in figure 13. This figure shows that near peak acceleration may be obtained up to 70 percent rated engine speed by holding a constant value of fuel flow of 4400 pounds per hour. Only in the very-low-speed range, at 40 percent of rated, does the acceleration attain a smooth maximum before stall is encountered.

A complete acceleration map throughout the engine operating range is presented in figure 8. Lines and regions of constant acceleration above the steady-state line are shown on this plot. Lines of constant acceleration shown in the surge region are values obtained only when the engine is operating in a stall condition in this area. It will be noted that, once stall is encountered, acceleration is fairly constant at approximately 200 to 250 rpm per second except at the higher speeds, where stall acceleration drops to 50 rpm per second. Acceleration values for surge are not shown in figure 8 but maintain an average value of 200 to 250 rpm per second. The bending over of the constant-acceleration lines in the vicinity of 40 percent rated speed illustrates that acceleration reached a maximum prior to stall. Accelerations in the screech region were very small or even negative in some instances.

Figure 8 was plotted from data obtained only by fuel flow increases, and an entirely different map may exist for fuel flow decreases. Effects such as those shown on figure 5(b), where speed increases after fuel flow has been cut back, indicate that positive accelerations may exist below the steady-state line with decreasing fuel flow.

A number of ramp increases in fuel flow were compared at the stall line with the results obtained by using the step disturbances in fuel flow. These points compared very well with the step stall line, lying slightly above but varying at the most by only about 200 pounds per hour.

The minimum time to accelerate from any speed to maximum speed was calculated, and the results are presented in figure 14. The acceleration used at each speed was the maximum obtained at that speed. Overtemperature conditions, which would be of prime importance in the actual control, were not considered.

SUMMARY OF RESULTS

A turbojet engine with a fixed-area exhaust nozzle was run on a sea-level test stand to determine its acceleration characteristics in the regions of maximum acceleration and during surge and stall. The results of these tests were used to determine the effectiveness of an optimalizing-type control for this engine.

At all speeds above 40 percent of rated, a maximum acceleration was not obtained until the engine reached the point of surge or stall. A smooth maximum prior to stall or surge occurred only around 40 percent rated speed. At low speeds and maximum fuel flows, burning past the turbine resulted in very low acceleration and an audible screech.

At speeds above 40 percent of rated, a sharp drop in acceleration, as severe as 80 percent of maximum, occurred if the compressor encountered stall. A similar drop of about 50 percent occurred if the compressor surged. Hysteresis effects were noted in recovering from stall.

Because of the lack of a smooth maximum acceleration prior to surge or stall, the optimalizer control could not prevent this engine from encountering surge or stall. However, the maximum acceleration which exists at the point of surge or stall may possibly be satisfactory for the operation of the optimalizer, depending on the magnitude of the stall-recovery hysteresis.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, September 3, 1954

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2. Draper, C. S., and Li, Y. T.: Principles of Optimalizing Control Systems and Application to the Internal Combustion Engine. Aero. Eng. Dept., M.I.T., pub. by A.S.M.E., Sept. 1951.

3. Delio, Gene J., and Stiglic, Paul M.: Experimental Investigation of Control Signals and the Nature of Stall and Surge Behavior in a Turbojet Engine. NACA RM E54I15, 1955.

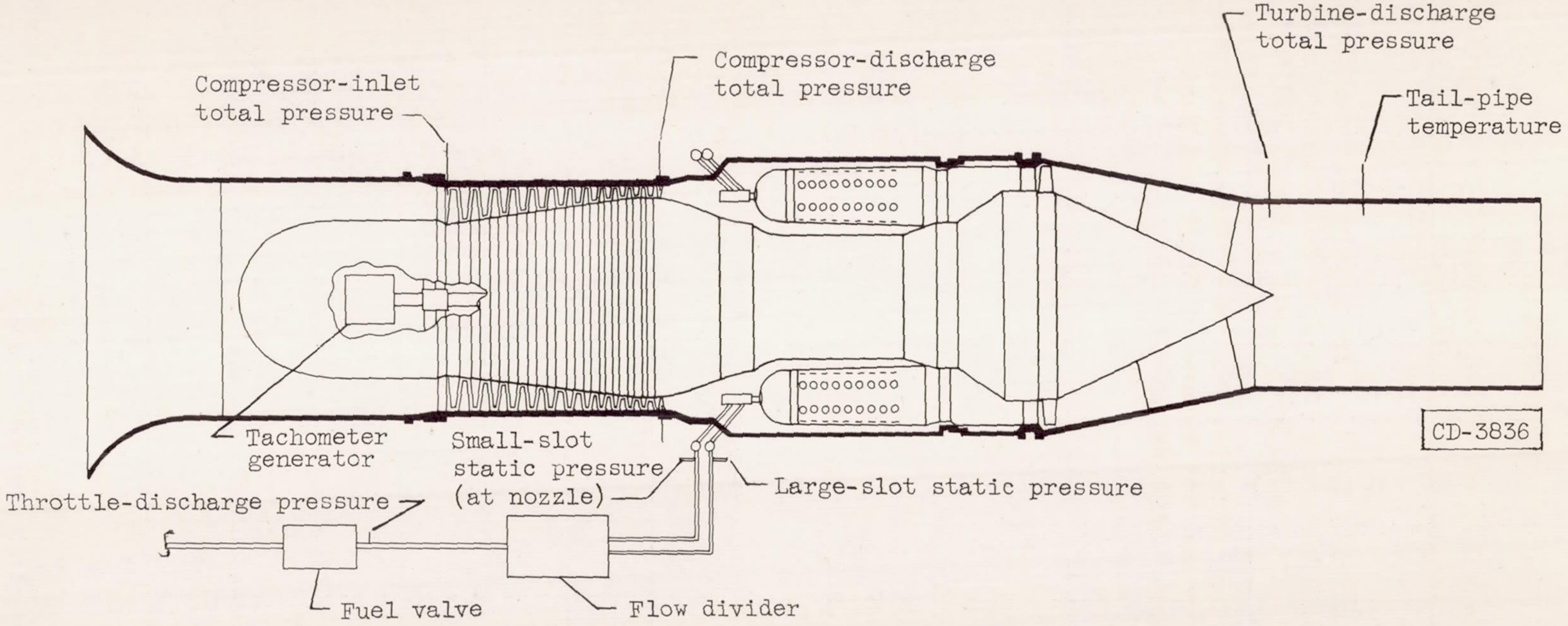
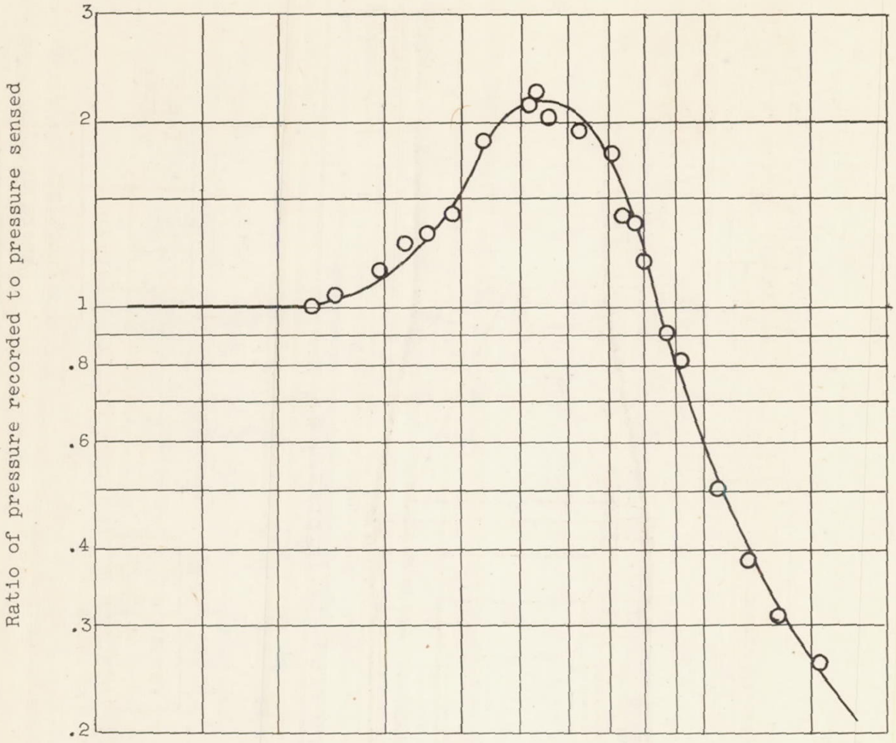
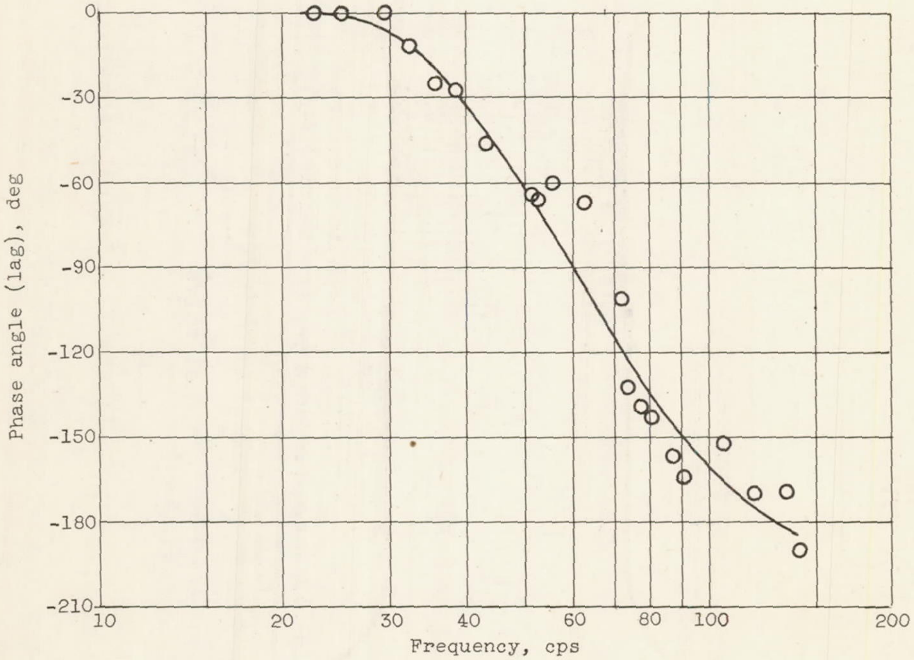


Figure 1. - Engine schematic showing location of instrumentation stations.



(a) Attenuation.



(b) Phase plot.

Figure 2. - Frequency response of typical pressure transducer with its associated probe and tubing.

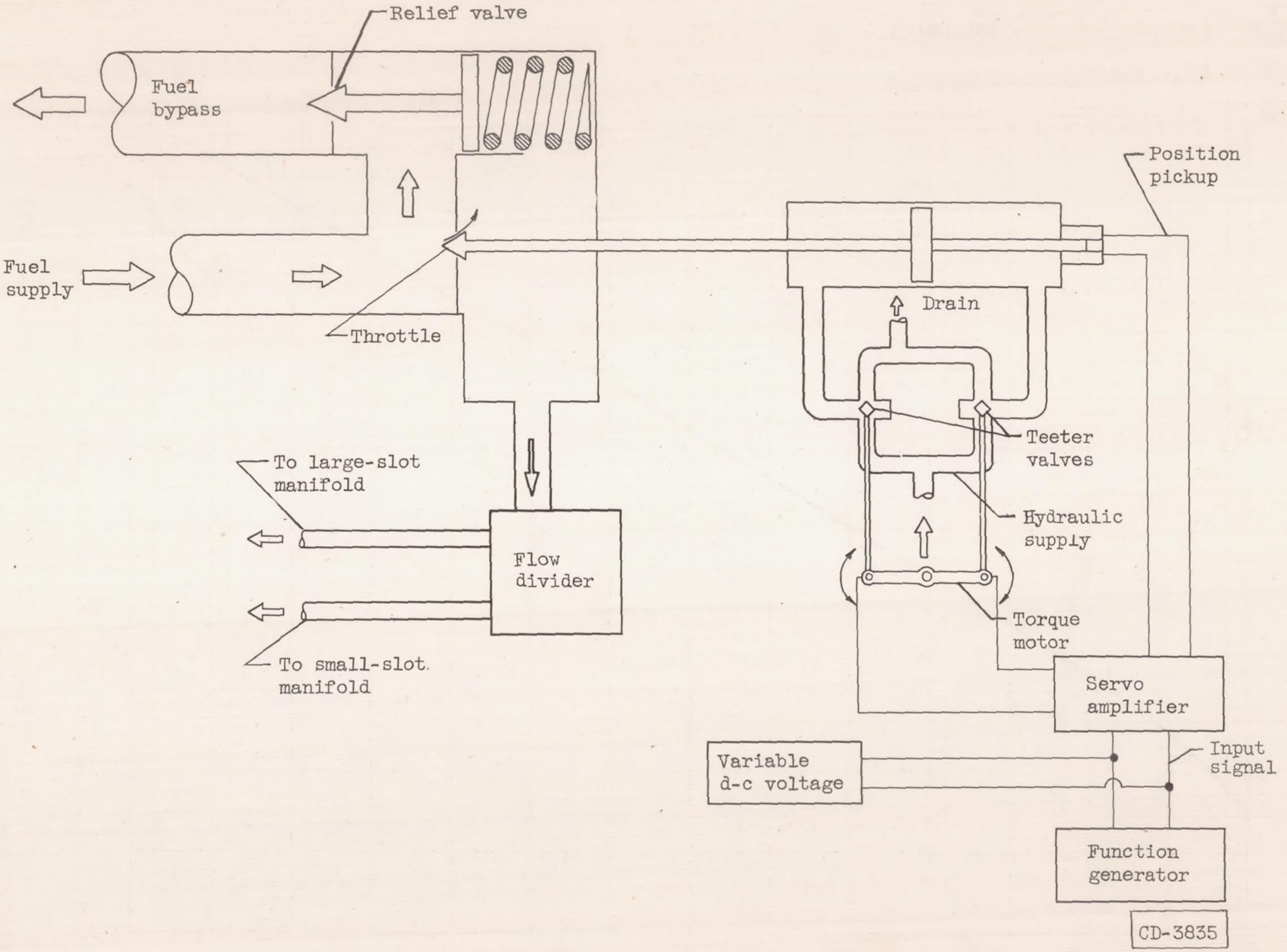


Figure 3. - Fuel system.

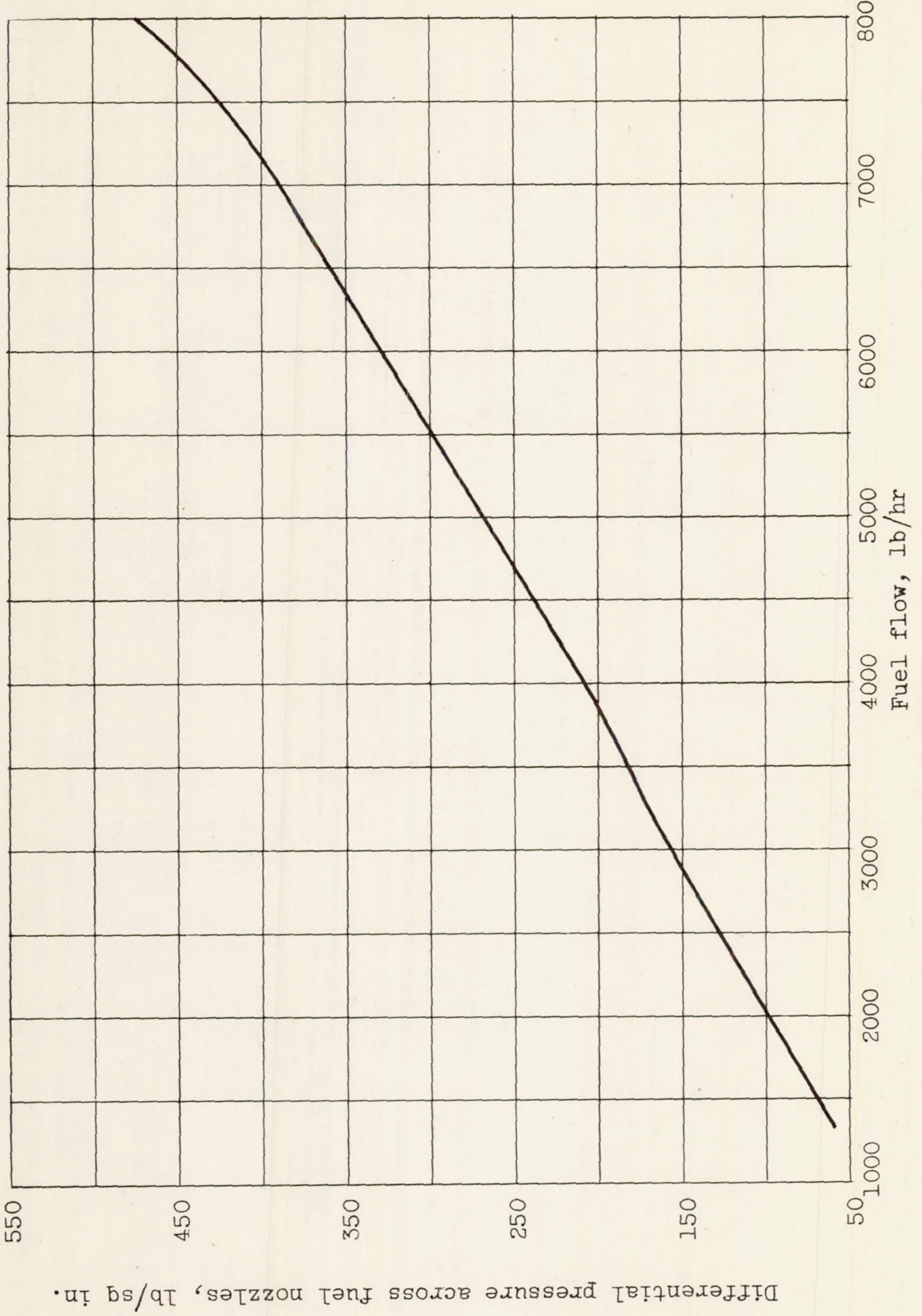
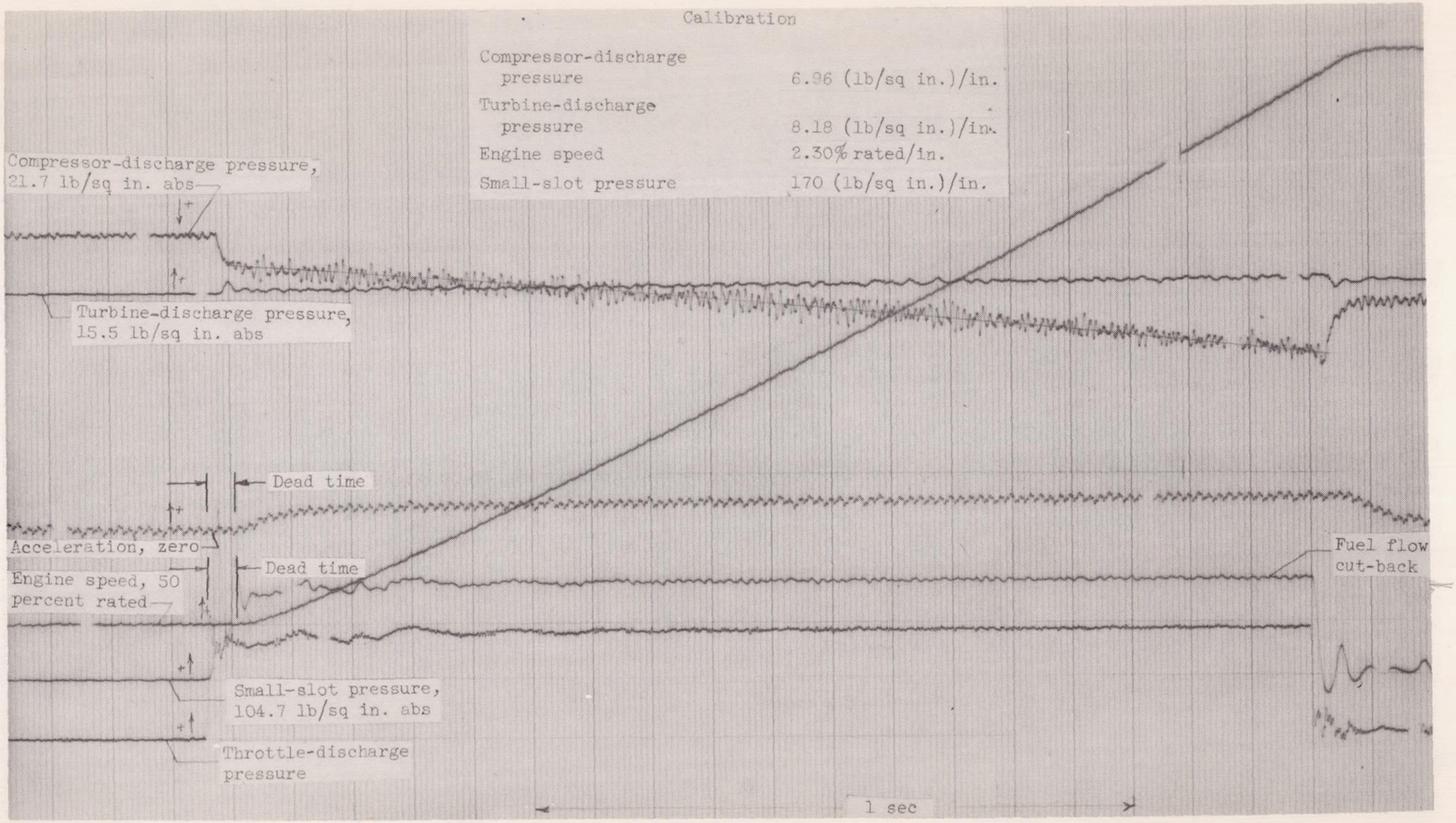
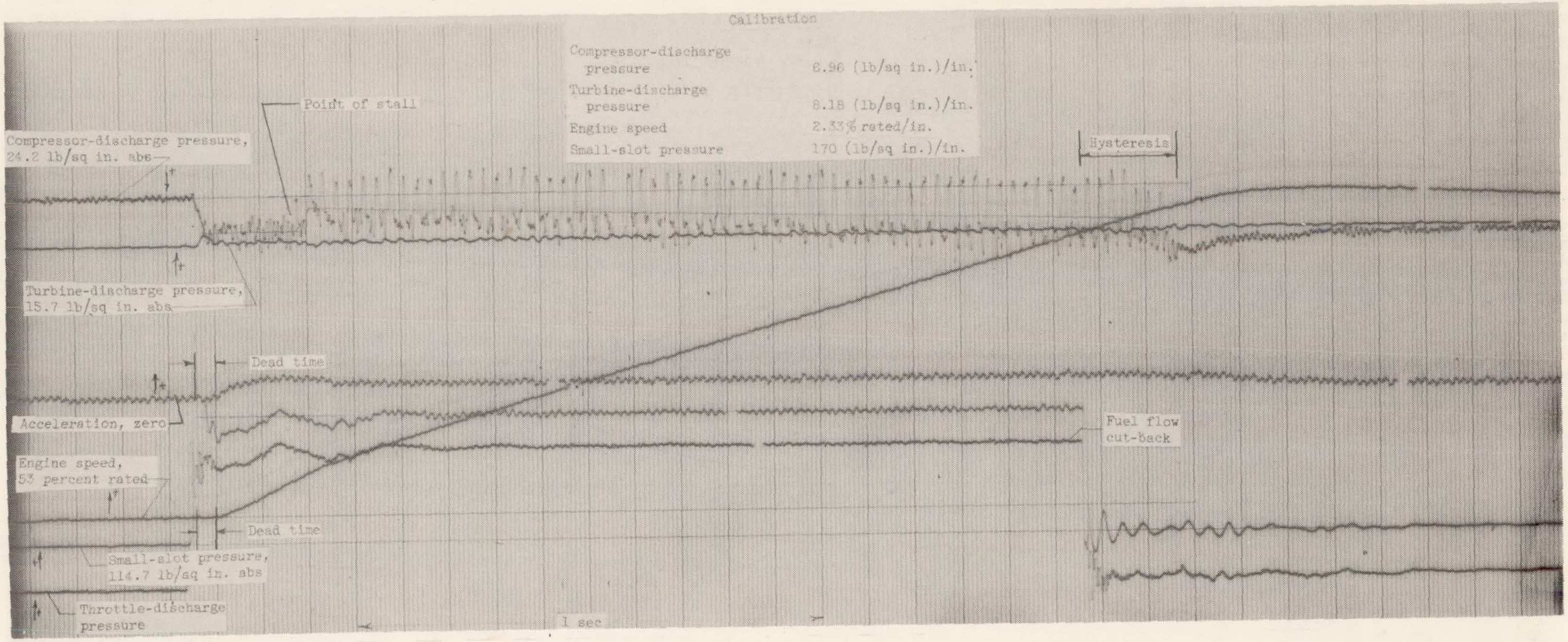


Figure 4. - Fuel-system calibration.



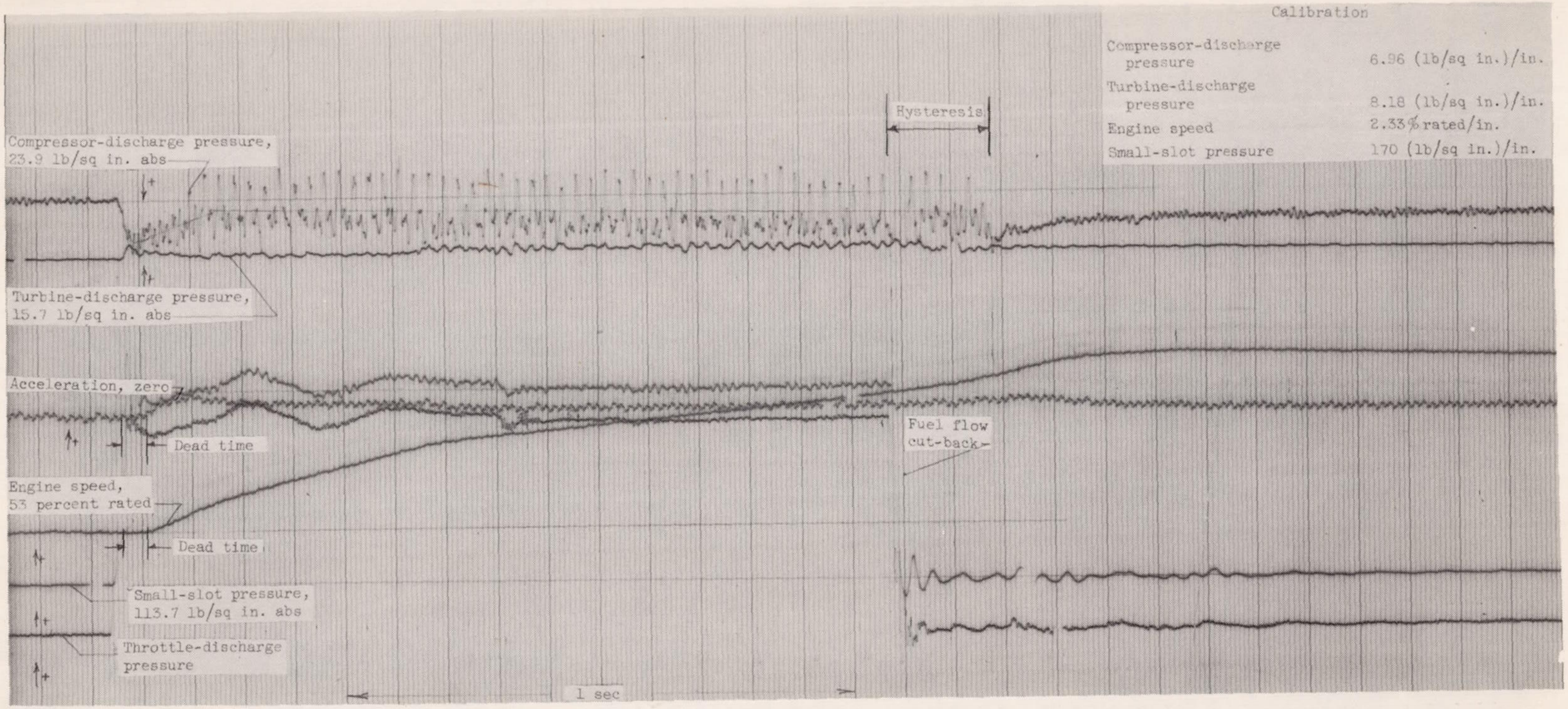
(a) Normal acceleration showing partial stall.

Figure 5. - Transient response of engine variables to fuel flow step. Altitude, sea level; ram-pressure ratio, 1.0.



(b) Acceleration into stall.

Figure 5. - Continued. Transient response of engine variables to fuel flow step. Altitude, sea level; ram-pressure ratio, 1.0.



(c) Continuation of acceleration after fuel flow cut-back.

Figure 5. - Concluded. Transient response of engine variables to fuel flow step. Altitude, sea level; ram-pressure ratio, 1.0.

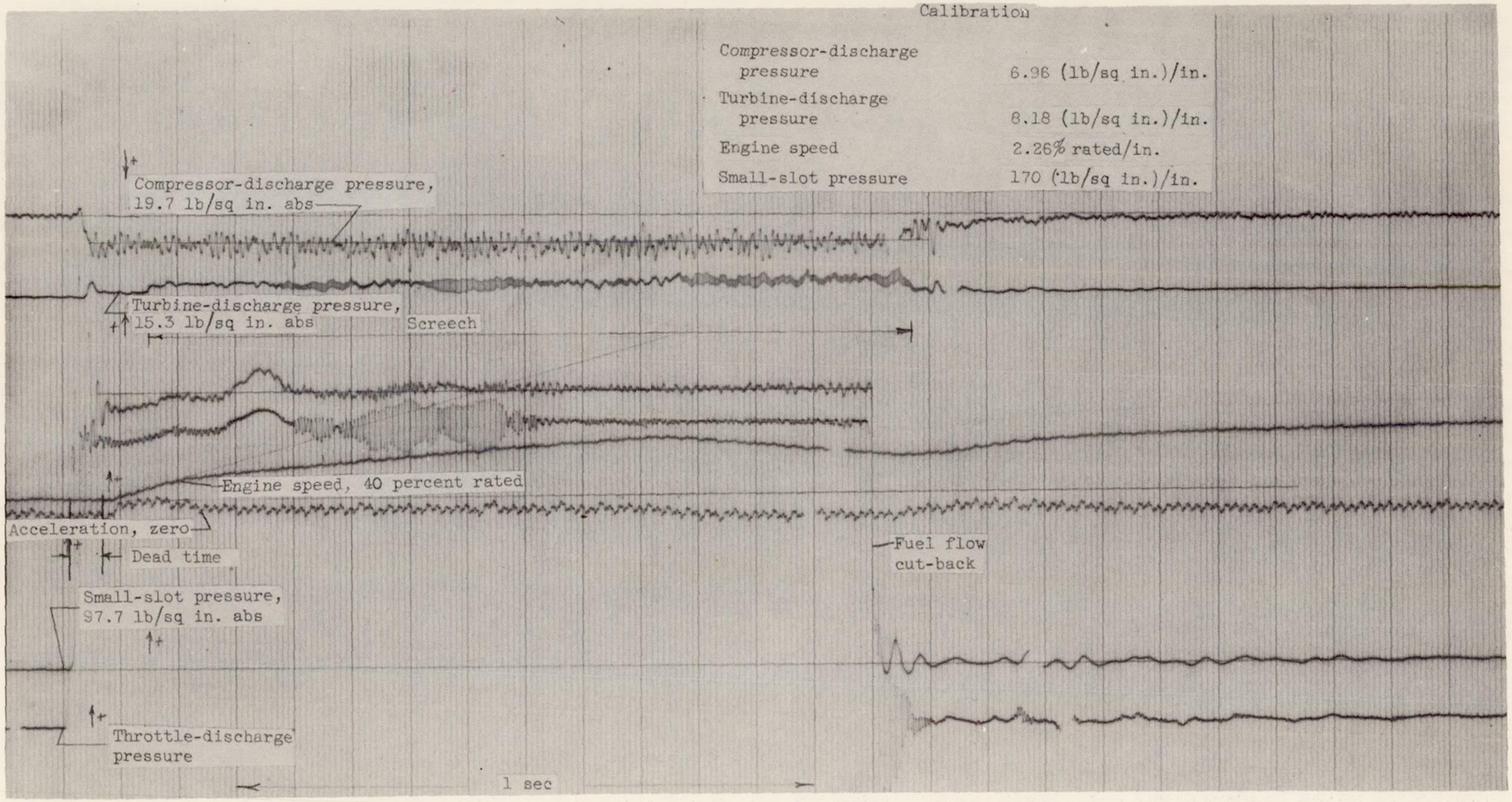


Figure 6. - Transient response of engine variables to fuel flow step into screech region. Altitude, sea level; ram-pressure ratio, 1.0.

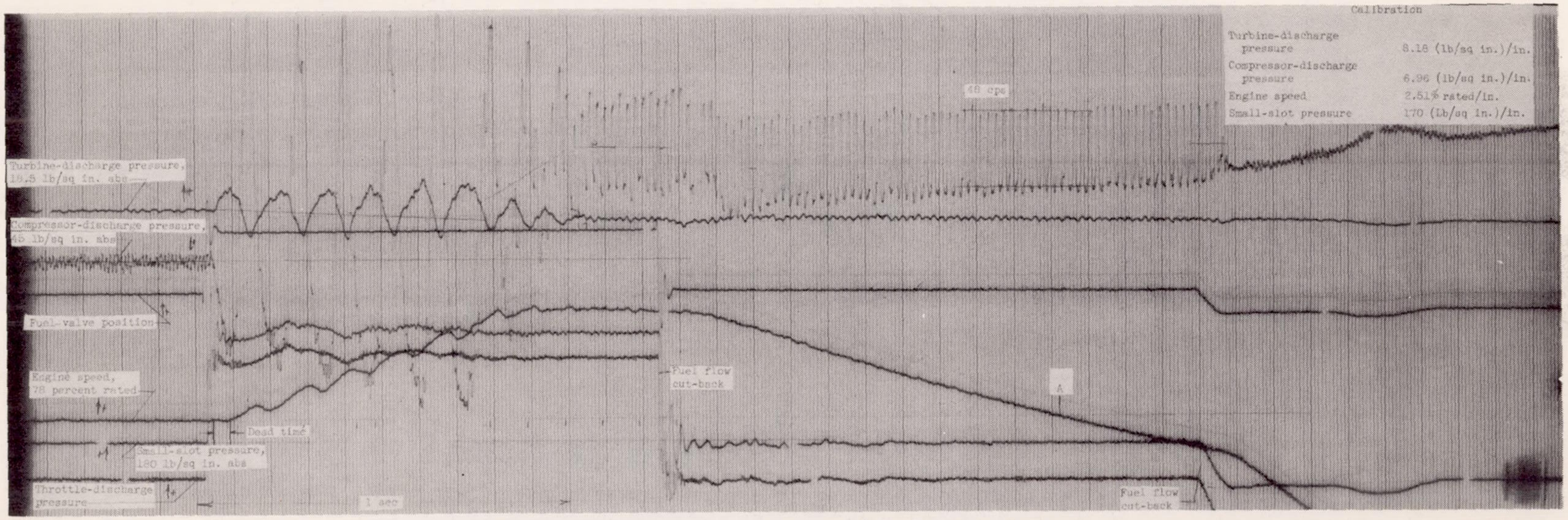


Figure 7. - Transient response of engine variables to fuel flow step into surge and stall regions. Altitude, sea level; ram-pressure ratio, 1.0.

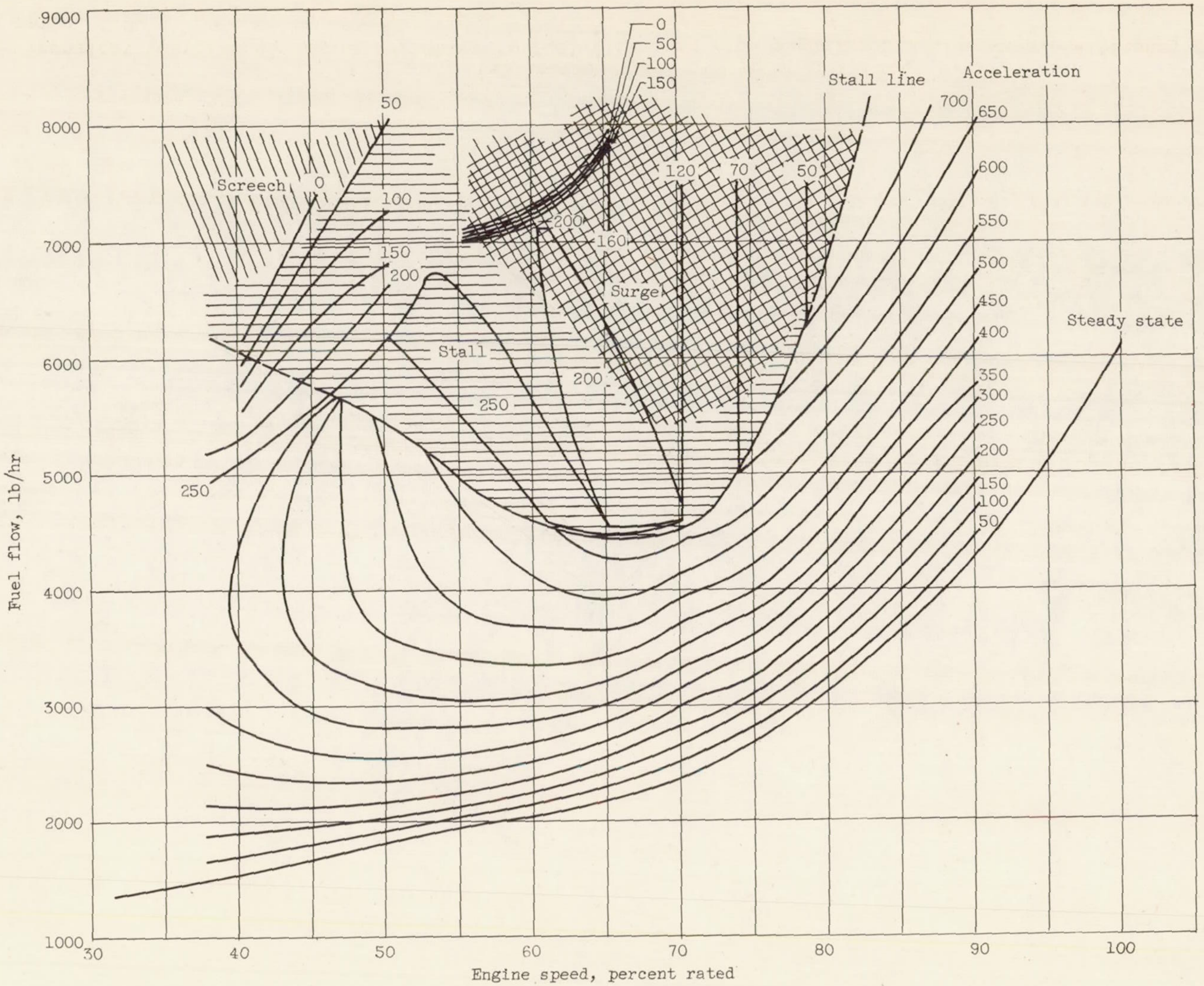
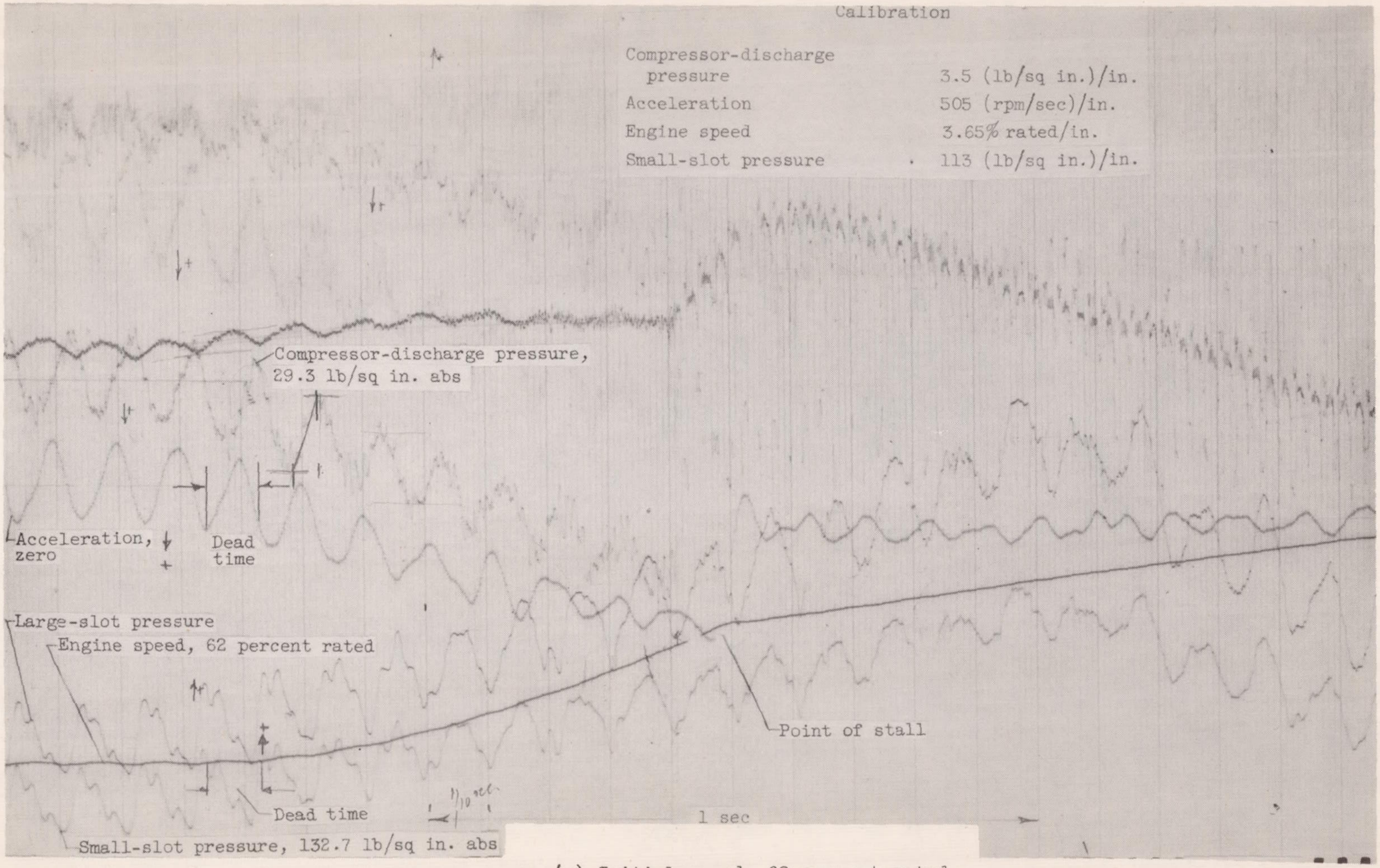
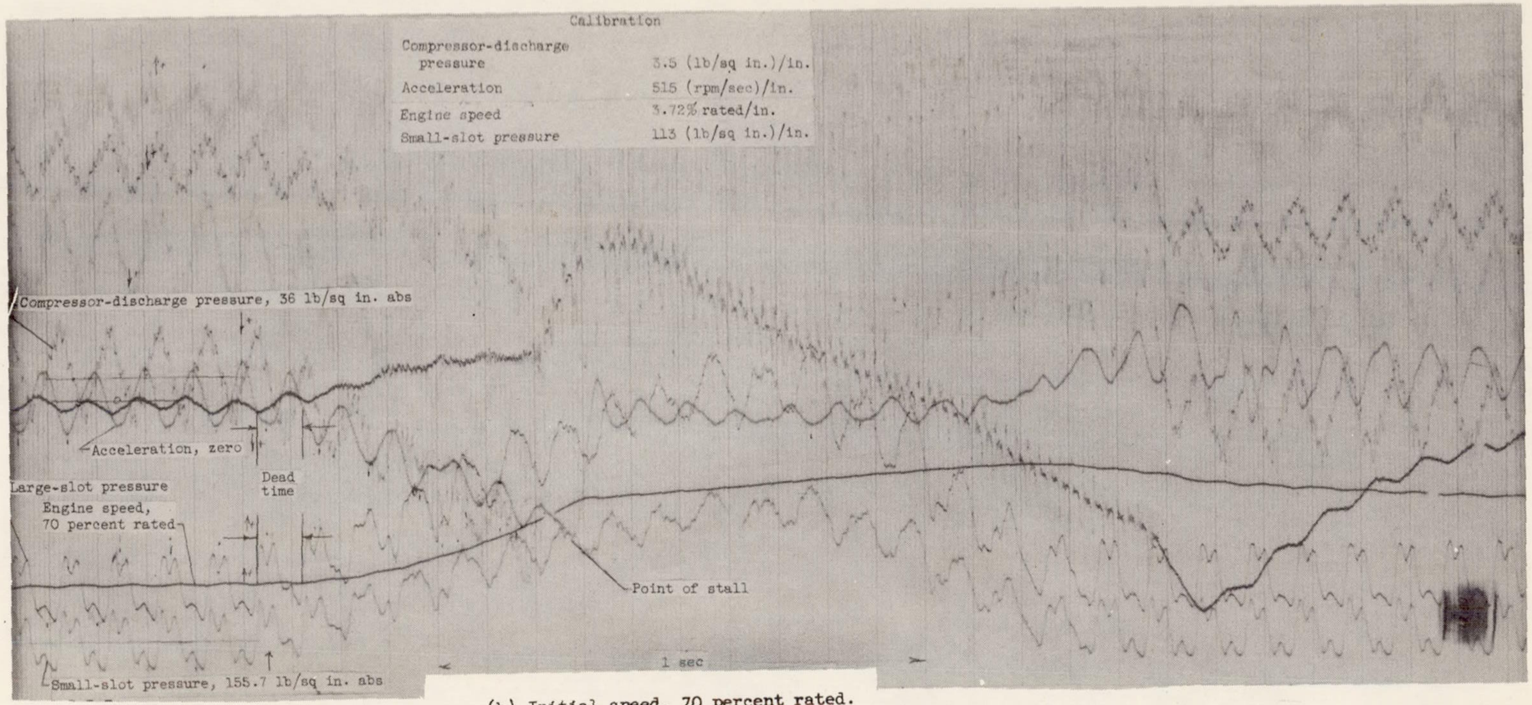


Figure 8. - Map of screech, stall, and surge regions as function of fuel flow and engine speed showing lines of constant acceleration. Altitude, sea level; ram-pressure ratio, 1.0.



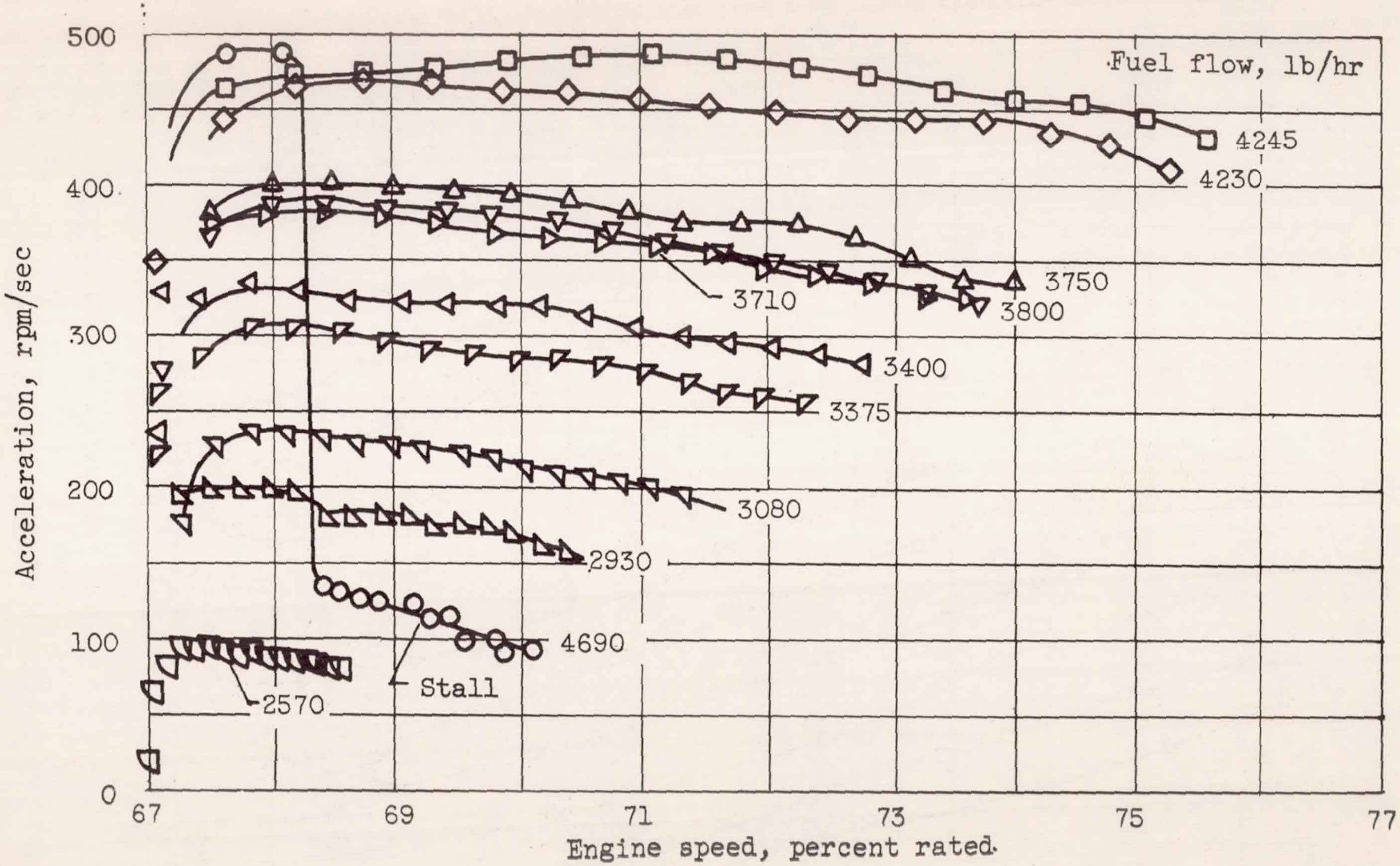
(a) Initial speed, 62 percent rated.

Figure 9. - Transient response of engine variables to fuel flow ramp with superimposed sine wave. Altitude, sea level; pressure ratio, 1.0.



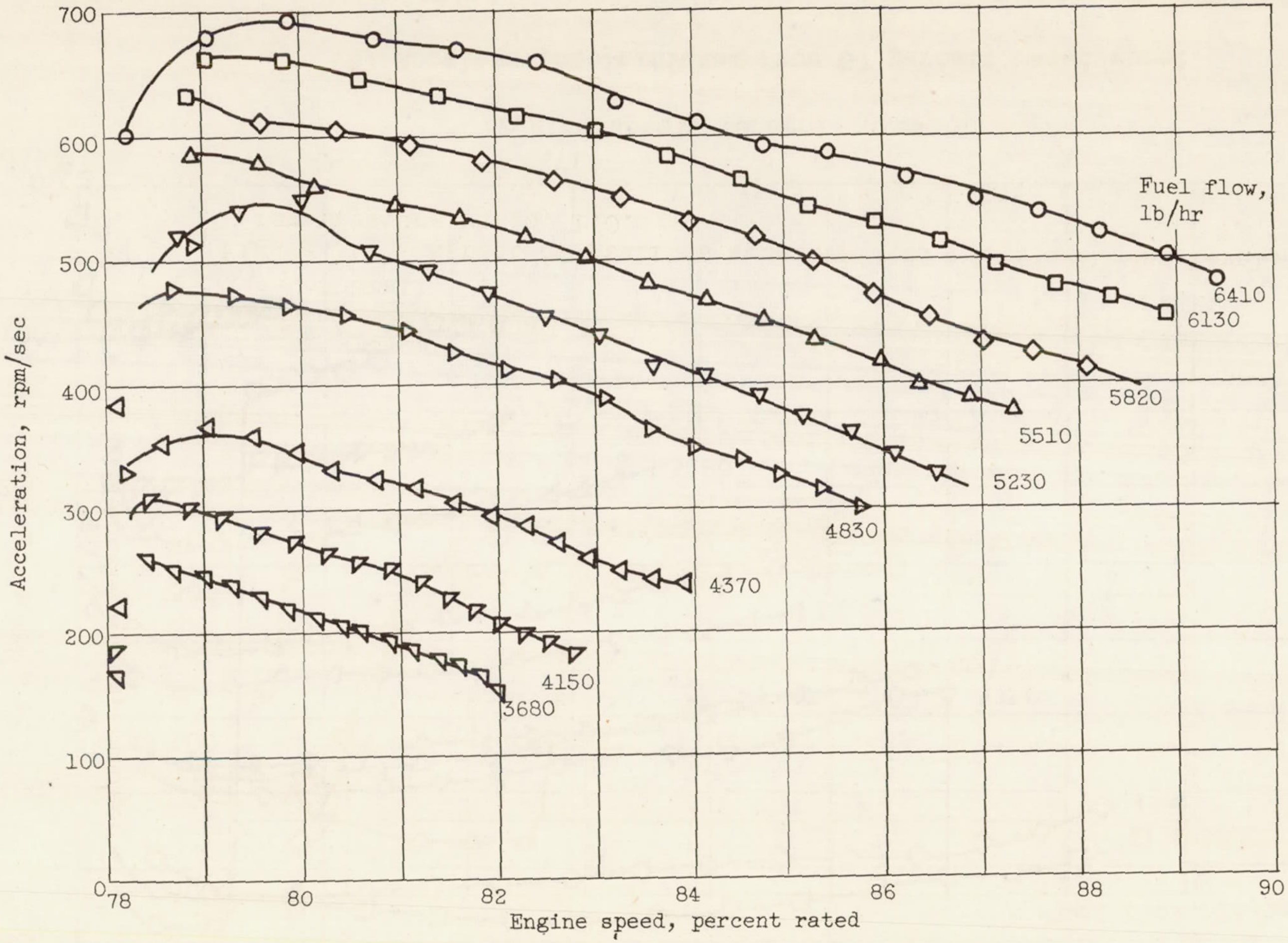
(b) Initial speed, 70 percent rated.

Figure 9. - Concluded. Transient response of engine variables to fuel flow ramp with superimposed sine wave. Altitude, sea level; ram-pressure ratio,



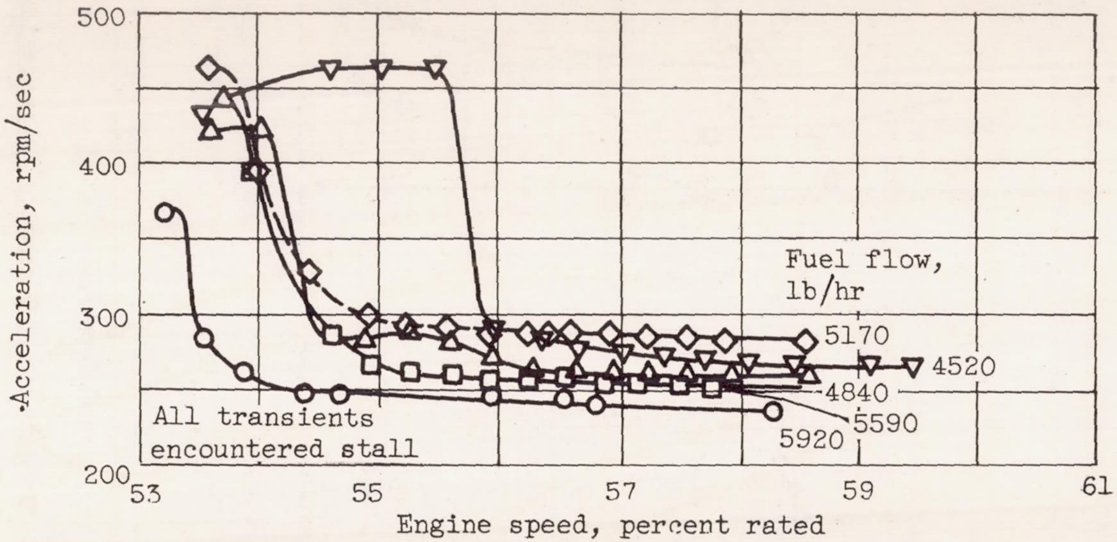
(a) Acceleration initiated from 67 percent rated speed.

Figure 10. - Variation of acceleration with engine speed for lines of constant fuel flow. Altitude, sea level; ram-pressure ratio, 1.0.



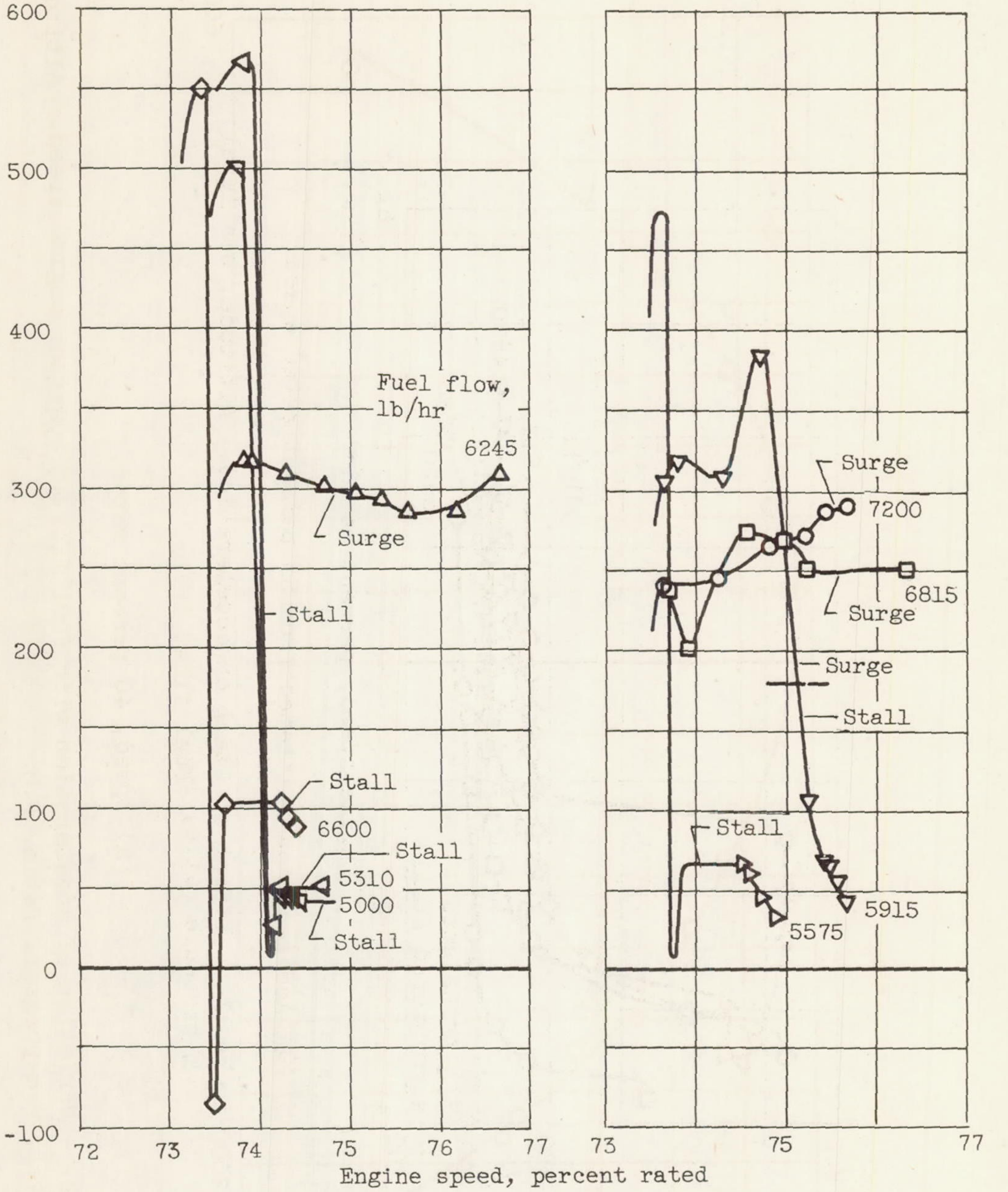
(b) Acceleration initiated from 78 percent rated speed.

Figure 10. - Concluded. Variation of acceleration with engine speed for lines of constant fuel flow. Altitude, sea level; ram-pressure ratio, 1.0.



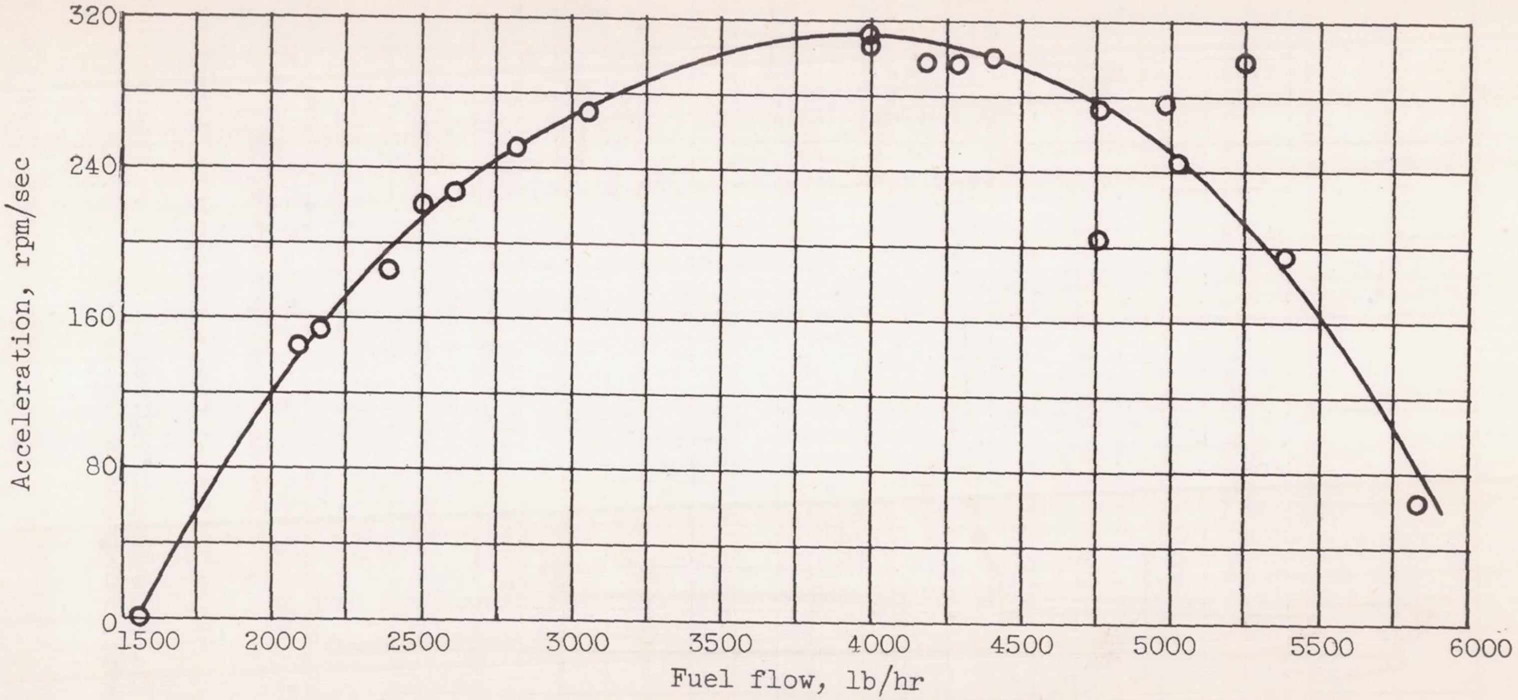
(a) Acceleration initiated from 53 percent rated speed.

Figure 11. - Effect of stall on acceleration. Altitude, sea level; ram-pressure ratio, 1.0.



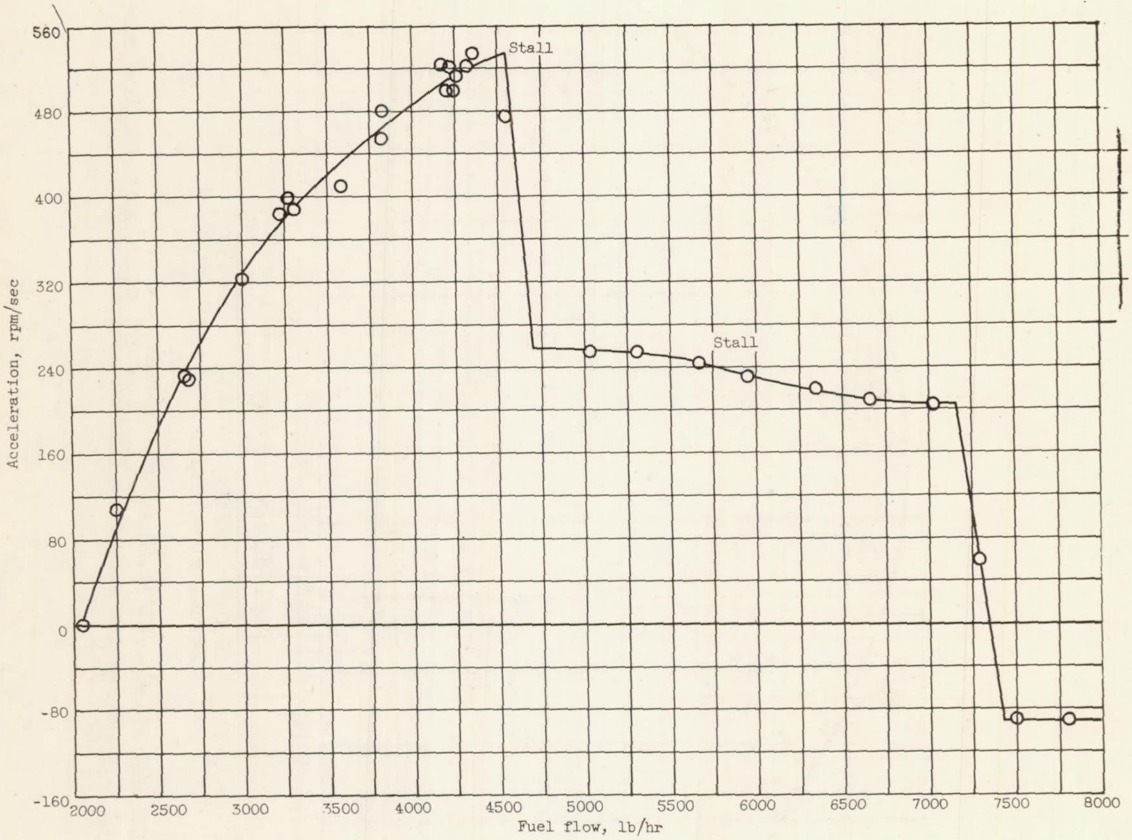
(b) Acceleration initiated from approximately 74 percent rated speed.

Figure 11. - Concluded. Effect of stall on acceleration. Altitude, sea level; ram-pressure ratio, 1.0.



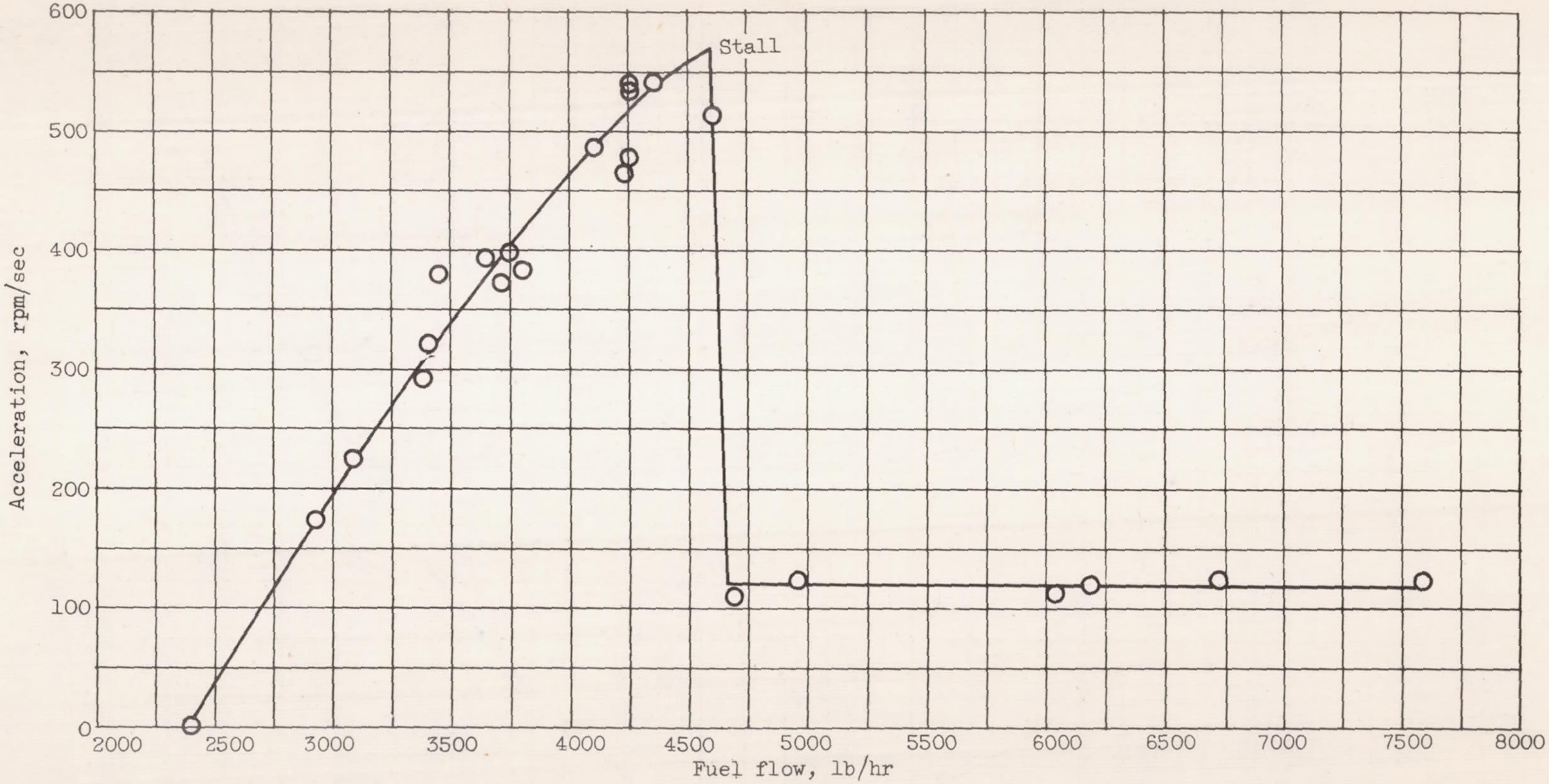
(a) Speed, 40 percent rated.

Figure 12. - Variation of acceleration with fuel flow at constant engine speed. Altitude, sea level; ram-pressure ratio, 1.0.



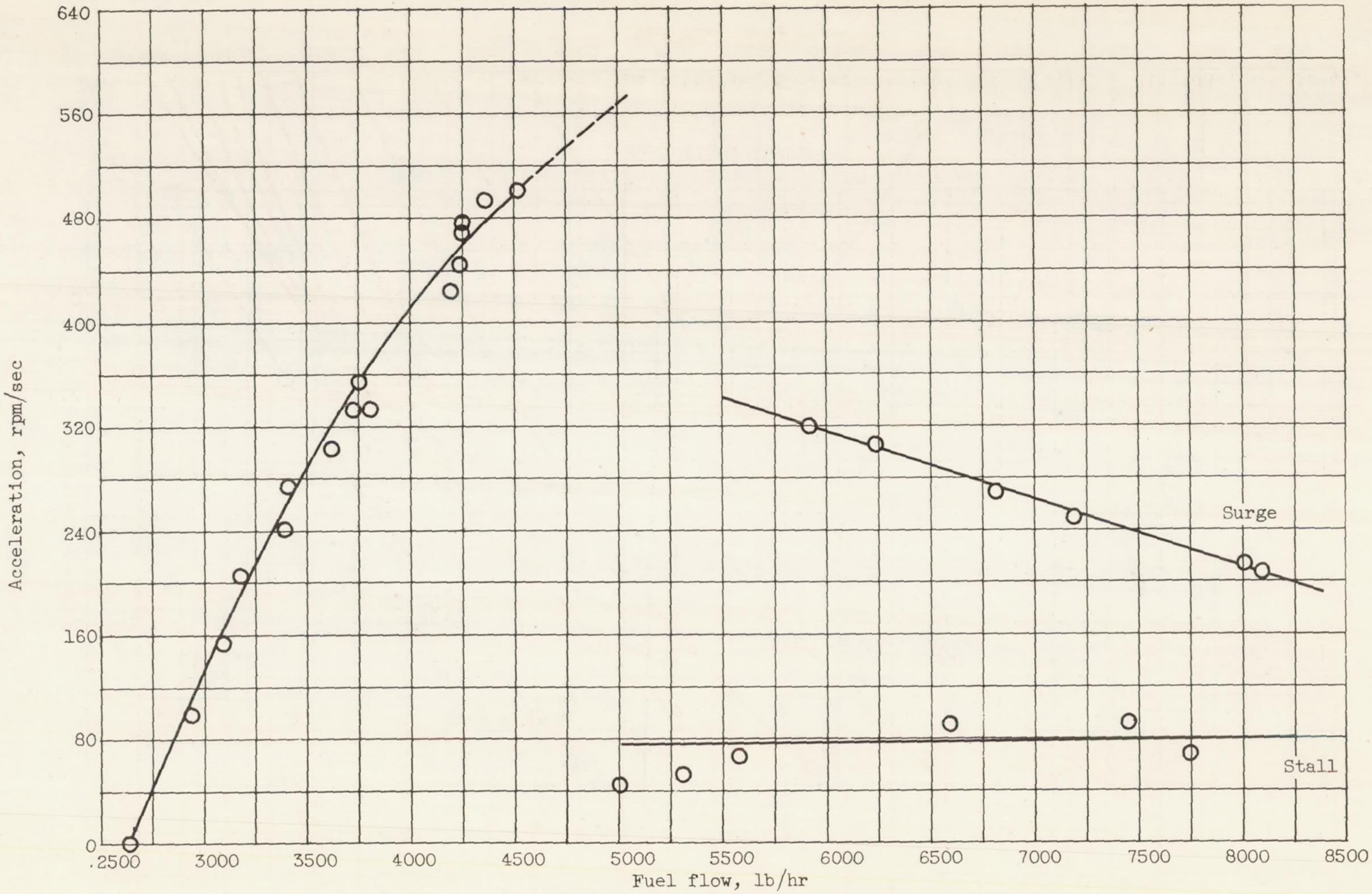
(b) Speed, 60 percent rated.

Figure 12. - Continued. Variation of acceleration with fuel flow at constant engine speed. Altitude, sea level; ram-pressure ratio, 1.0.



(c) Speed, 70 percent rated.

Figure 12. - Continued. Variation of acceleration with fuel flow at constant engine speed. Altitude, sea level; ram-pressure ratio, 1.0.



(d) Speed, 74 percent rated.

Figure 12. - Concluded. Variation of acceleration with fuel flow at constant engine speed. Altitude, sea level; ram-pressure ratio, 1.0.

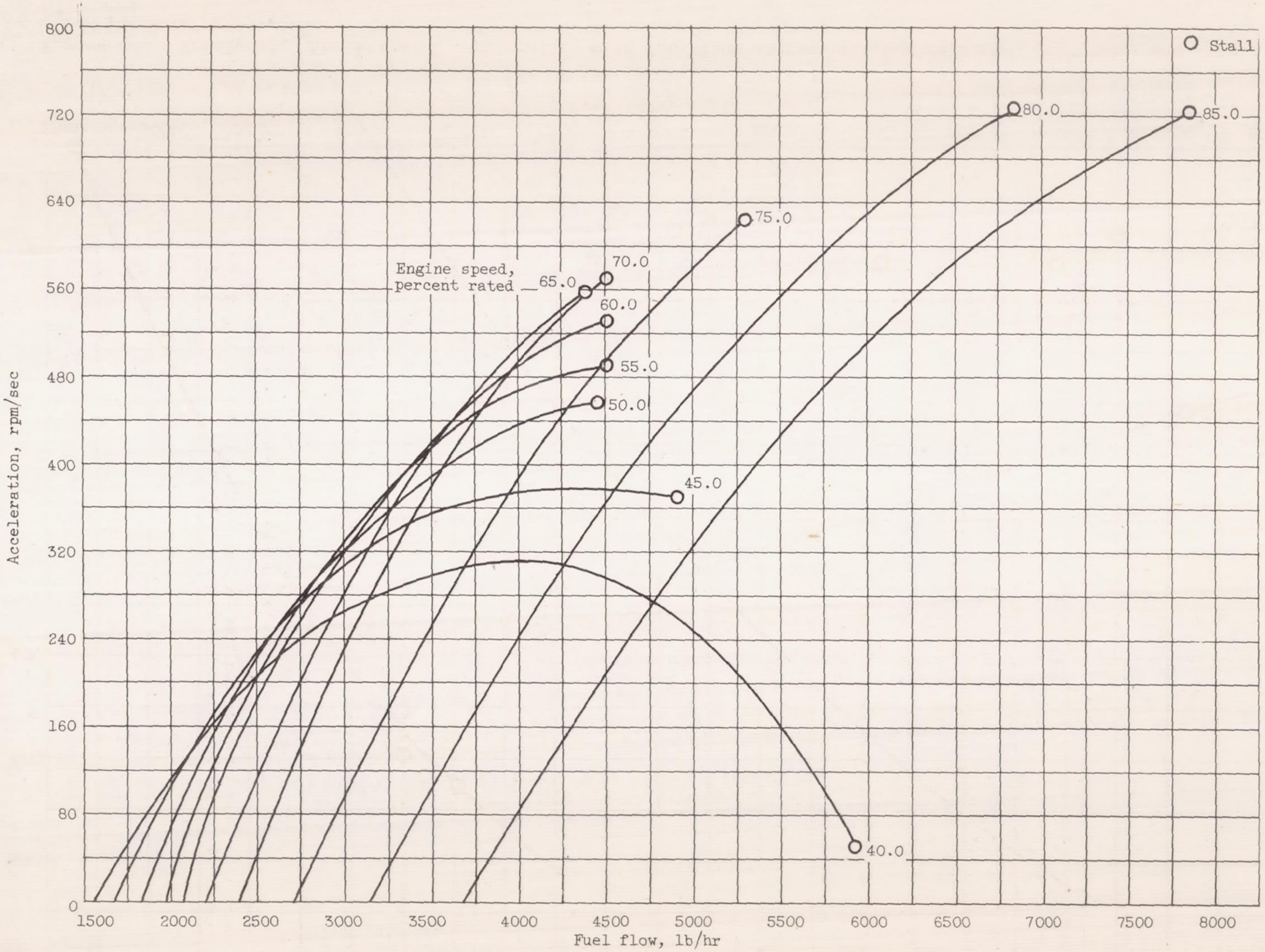


Figure 13. - Acceleration - fuel flow map for lines of constant engine speed. Altitude, sea level; ram-pressure ratio, 1.0.

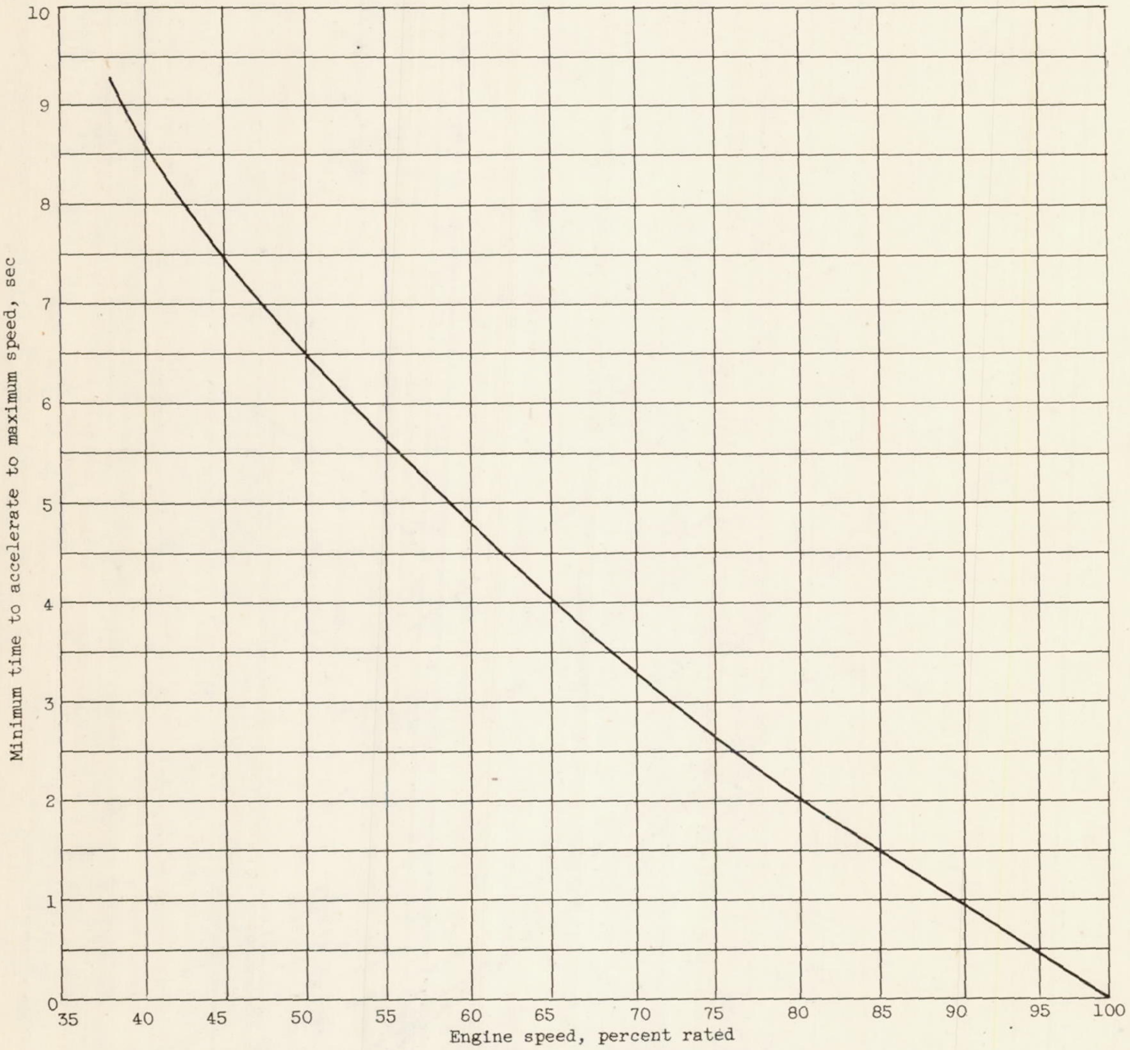


Figure 14. - Calculated minimum time for acceleration to maximum engine speed as a function of engine speed. Altitude, sea level; ram-pressure ratio, 1.0.

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