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RESEARCH MEMORANDUM

INVESTIGATION OF ACCELERATION CHARACTERISTICS OF A SINGLE-SPOOL TURBOJET ENGINE

By Frank L. Oppenheimer and George J. Pack

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
October 26, 1953

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

INVESTIGATION OF ACCELERATION CHARACTERISTICS OF A SINGLE-SPOOL TURBOJET ENGINE

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SUMMARY

Operation of a single-spool turbojet engine with constant exhaust-nozzle area was investigated at one flight condition. Data were obtained by subjecting the engine to approximate-step changes in fuel flow, and the information necessary to show the relations of acceleration to the sensed engine variables was obtained.

These data show that maximum acceleration occurred prior to stall and surge. In the low end of the engine-speed range the margin was appreciable; in the high-speed end the margin was smaller but had not been completely defined by these data.

Data involving acceleration as a function of speed, fuel flow, turbine-discharge temperature, compressor-discharge pressure, and thrust have been presented and an effort has been made to show how a basic control system could be improved by addition of an override in which the acceleration characteristic is used not only to prevent the engine from entering the surge region but also to obtain acceleration along the maximum acceleration line during throttle bursts.

INTRODUCTION

The transient behavior of a turbojet engine resulting from small disturbances has been explored at the NACA Lewis laboratory (ref. 1). This information is useful for stability analysis of controls. The normal acceleration from low thrust to high thrust, however, occurs in the presence of disturbances so large that the type of data presented in reference 1 is not applicable. A knowledge of the acceleration near the compressor stall or surge limit, and in the zone of maximum acceleration, together with the instantaneous values of the appropriate control parameters, engine speed, fuel flow, turbine-discharge temperature and pressure, compressor-discharge pressure, and thrust, are needed.

Large accelerations were reported in reference 2; however, no information regarding pressures and temperatures was reported. The data showed a maximum acceleration, which in some regions of engine operation occurred in the presence of surge. A subsequent investigation (ref. 3) showed in another turbojet engine a sharp loss in acceleration when stall or surge occurred. Although the relation of acceleration characteristics to surge characteristics differed greatly between these two engines (refs. 2 and 3), it has been found from experience with a number of engines that the most common effect of surge is to greatly reduce acceleration. For the present investigation, therefore, an engine which experienced large losses in acceleration during surge was used.

This report presents acceleration characteristics of a turbojet engine and shows how this acceleration information can be used to improve control design. A few possible control systems will be discussed in a general manner.

The data presented herein were obtained from an altitude-wind-tunnel investigation of a turbojet engine operated with a constant ratio of exhaust-nozzle area to turbine-exit annulus area of 1.1 and at fixed flight conditions (altitude of 15,000 ft and ram-pressure ratio of 1.02). The data are plotted to show the relations of acceleration $\dot{N}$ with engine speed N, fuel flow W_f, turbine-discharge temperature T_6 and pressure P_6, compressor-discharge pressure P_4, and thrust F. The relations of acceleration to the sensed outputs are examined with a view to the application of these relations in acceleration control. Stability derivatives of the engine at equilibrium are compared with previously published results of responses to small step changes in fuel flow (ref. 1). Finally, the thrust transient generated during acceleration is shown.

APPARATUS AND INSTRUMENTATION

A schematic diagram of the engine-inlet ducting and the instrumentation stations is shown in figure 1. The stations are compressor inlet (2), compressor discharge (4), and turbine discharge (6).

Engine. - This investigation was conducted on a turbojet engine having a single-spool, 11-stage, axial-flow compressor; a two-stage turbine; and a variable-area, clam-shell-type exhaust nozzle. The nozzle, however, was held at a fixed position for all data reported herein. At static sea-level rated conditions, the compressor pressure ratio was approximately 5 and the rotational speed was 7260 rpm.

Instrumentation. - Appendix A presents a detailed description of transient instrumentation located at stations 2, 4, and 6. The nature and characteristics of both the transient and the steady-state instrumentation are summarized in table I.

Installation. - The engine was mounted on a wing in the 20-foot-diameter test section of the Lewis altitude wind tunnel. A streamlined subsonic inlet and cowl were fitted to the engine in order to minimize inlet pressure losses. The capability of the tunnel to maintain constant atmospheric pressure during acceleration is established by figure 2, which shows the variation of ram pressure at the inlet to the engine, together with the variation of other engine parameters during a large acceleration. Other quantities shown are fuel flow, engine speed, acceleration, turbine-discharge temperature, compressor-discharge pressure, turbine-discharge pressure, and thrust. Figures 2(a) and (c) show ram pressure during acceleration with stall or surge, and figure 2(b) shows ram pressure during acceleration without stall or surge. In each case, the mean value of the ram pressure in the tunnel did not change, although the acoustic waves produced by compressor stall were shown as high-frequency fluctuations.

PROCEDURE

All data were obtained with a ratio of exhaust-nozzle area to turbine-exit annulus area of 1.1 and at the fixed flight condition of 15,000-foot altitude and 1.02 ram-pressure ratio. Transient data were obtained over the range of 30 to 100 percent of rated speed by introducing approximate-step as well as ramp changes in fuel flow.

Engine parameters recorded with both types of input were engine speed, acceleration, fuel flow, turbine-discharge temperature, turbine-discharge pressure, compressor-discharge pressure, and thrust.

Transient traces were calibrated by taking a steady-state reading before each run and when possible at the end of each run. In all cases data were available in the region encompassed by the transient to permit adequate calibration. Calibration of acceleration traces was obtained by calculations which depend on the slope of the speed trace.

In using the step input, several progressively larger steps were made from each starting point until the engine went into stall and surge. These data were obtained to characterize the stall and surge limit of the engine and to furnish acceleration data in the normal operating regions. Figures 2(a) and (b) present typical step-change data.

Ramp inputs were used, particularly from the lower-speed starting points, to determine stall and surge limits more accurately than was possible with the step technique and also to supply additional data regarding acceleration in the region approaching stall and surge. Typical ramp-change data are shown on figure 2(c).

RESULTS AND DISCUSSION

The stall and surge limit discussed herein is defined as the engine operating condition immediately preceding the characteristic drop in compressor-discharge pressure when surge is encountered. Values of all parameters at the stall and surge limit were obtained from transient traces by noting the time at which the compressor-discharge pressure reached a peak and then recording the values of the remaining parameters at the same time.

It can be seen from the approximate-step-change data shown in figure 2(a) that considerable difficulty was encountered in specifying accurately the values of all parameters. This is in large measure due to the overshoot which occurred in fuel flow. Ramp-change data, however, as shown on figure 2(c), indicate that values of pertinent parameters can be read with acceptable accuracy at the point of stall and surge. The transient effects of combustion efficiency were also not as pronounced when ramp changes were used in place of the step change.

Additional data used to define the engine characteristics in the region between the steady-state operation and the surge limit were also obtained from a large number of similar transient studies. All data have been corrected to the test conditions of 15,000-foot altitude and 1.02 ram-pressure ratio and then expressed as a percentage of rated value at those conditions.

It is noted that at the specified exhaust-nozzle area and the corrected rated speed, the turbine-discharge temperature is 1225° R. Although the fixed exhaust-nozzle area of the engine for this investigation is satisfactory for purposes of acceleration, it is larger than that required for maximum thrust at corrected rated speed. The variations in the engine characteristics with engine acceleration are presented in the following order: fuel flow, turbine-discharge temperature, compressor-discharge pressure, turbine-discharge pressure, thrust, and engine dynamics.

Fuel Flow - Acceleration Characteristic

The variation of fuel flow with engine speed for lines of constant acceleration is shown in figure 3. Also, the steady-state operating line and the stall and surge limit are indicated.

These data show that along a line of constant speed, maximum acceleration occurs at a value of fuel flow below that required for stall and surge. This effect is very pronounced at speeds below 70 percent of rated. Above the 70-percent speed point the lines of constant acceleration are dotted in near the limit line because relatively few data points were obtained in the high-speed region. Even though the data substantiate the conclusion that maximum acceleration occurs before stall and surge, the magnitude of the fuel flow margin between these two points has not been accurately determined.

Acceleration control with fuel flow - speed schedule. The existence of a maximum acceleration limit at fuel flows less than that required for stall and surge suggests the possibility of designing an overriding acceleration control schedule of fuel flow against speed such that the engine will not only avoid surge but will accelerate along a path which limits fuel flow to a value that gives either maximum acceleration or maximum allowable temperature.

The time required to accelerate through the low-speed region is approximately 80 percent of the total time for acceleration from low to high speed; therefore, maximum acceleration at low speed is essential.

While a cursory examination of the plotted data does not reveal any serious faults in a plan of scheduling fuel flow with engine speed to control acceleration, there are certain objections to such a schedule: (1) The schedule is a function of many flight variables such as altitude and flight speed; (2) the function usually cannot be generated from "corrected" parameters (parameters to which pressure and temperature factors have been applied to account for altitude conditions) because combustion efficiency does not generalize and is involved in any fuel schedule.

Optimalizing control. - Figure 4 is a cross plot of the data shown in figure 3. The constant-speed lines plotted as a function of acceleration and fuel flow also show that maximum acceleration occurs before stall and surge. The particular advantage of this form of data presentation is it indicates that techniques of optimalization as outlined in reference 4 can be applied. In this case acceleration could be optimalized during a throttle burst by sensing a signal which was related to the slope of the constant-speed lines shown on figure 4 and then by using this signal in the control proper to vary fuel flow so as to reduce the signal to zero. Such a control system would in theory automatically maintain maximum acceleration during the major part of the transient induced by a throttle burst and at the same time prevent the engine from entering the region of stall and surge. Practical consideration, however, must be given to maximum temperatures attained and the margin of safety between maximum acceleration and stall.

Unfortunately, insufficient data are available over the complete range of flight conditions and engine operation to permit a statement as to the margin of safety that would exist between the maximum acceleration line and the stall and surge line for all conditions. A very small margin would place severe demands of high gain and fast response on the fuel system.

Turbine-Discharge Temperature - Acceleration Characteristic

The variation of turbine-discharge temperature with engine speed for lines of constant acceleration and lines of constant fuel flow is shown in figure 5. The steady-state operating line and the stall and surge limit are included in this figure. From the data in figure 5 a schedule of temperature against speed can be devised which will give maximum acceleration at a given engine speed. This schedule together with the surge limit is shown in figure 6.

Another consideration besides surge enters into the acceleration potential in the low-speed region. At low speeds the temperature for maximum acceleration is well above present temperature limits imposed by turbine materials. Thus at very low speeds, below 45 percent of rated speed, the temperature cannot be set up to the value required for maximum acceleration.

Acceleration control with turbine-discharge temperature - speed schedule. - An overriding acceleration control can be added to a primary engine control so that the turbine-discharge temperature is limited as a function of the engine speed. Based on the data presented in figure 6, the schedule can be specifically designed to match the maximum acceleration characteristic shown or the maximum allowable temperature limit of the engine. This type of schedule would be feasible because at a given engine speed a margin exists between the maximum safe acceleration temperature and the surge-limit temperature. Thus a schedule of temperature against speed could give the engine maximum safe acceleration and yet avoid stall or surge.

However, because the temperature and speed characteristics vary with Mach number, compressor-inlet temperature, and altitude, it follows that a schedule based on the temperature - speed parameter must be corrected to maintain the desired action. The effect of increasing flight Mach number is to alter the position of the acceleration path with respect to the compressor stall and surge limit. At higher Mach numbers, lower temperatures will produce adequate acceleration; so this effect may not be important. In a similar manner, compressor-inlet temperature can be accounted for by considering the schedule to be one of the ratio of turbine-discharge temperature to the temperature at the compressor inlet T_6/T_2 against speed. Altitude effect on the schedule is minor and can be neglected. Since this system does not depend on fuel flow measurement but on temperature, it follows that the combustion-efficiency variations do not affect the schedule in any appreciable manner.

Two outstanding advantages accrue from the use of this system: (1) In case of inadvertent stall, automatic recovery can be achieved because a sharp increase in temperature accompanies stall, as indicated by point A in figures 2(a) and (c). This temperature increase would cause the control to reduce fuel flow sufficiently to overcome the hysteresis effect of coming out of surge. Reference 3 gives more detail on the hysteresis effect. (2) Temperature normally is sensed for overall protection of engine components; therefore, simplification results from not having to sense another engine-output parameter.

There are certain disadvantages associated with the temperature - speed schedule. At present, the measurement of an adequate temperature is difficult. An acceptable sensor should indicate an average temperature under all conditions of engine operation and not be sensitive to changes in temperature profile which result from changes in engine operating point and with flight conditions. A thermodynamic method, such as the pressure-sensitive system of reference 5, may have merit.

Compressor-Discharge Pressure - Acceleration Characteristic

The variation of compressor-discharge pressure with engine speed for lines of constant acceleration is shown in figure 7. The maximum acceleration limit and the steady-state operating line are indicated in this figure. An analysis of the data shows that the surge limit coincides with the maximum acceleration limit within ±1 percent of the total compressor-discharge pressure range. This percentage of deviation is within the accuracy of the data; therefore the data do not show a measurable separation between the surge limit and the maximum acceleration limit. The most significant conclusion to be drawn from the data is that compressor-discharge pressure is very insensitive as an indicator of how close the engine is to maximum acceleration or surge, particularly at low speeds.

One reason for the insensitivity of compressor-discharge pressure in distinguishing between maximum acceleration and surge is the inherent small change in compressor-discharge pressure that accompanies engine operation from the steady state to maximum acceleration with the speed held constant. The change in compressor-discharge pressure at low speeds is approximately 2 percent of the steady-state range of compressor-discharge pressure from idle speed to sea-level rated speed, and at high speeds the change is approximately 20 percent. These percentages are small when compared with the fuel flow and temperature changes available at a constant speed.

Acceleration control with compressor-discharge pressure, fuel flow, and speed parameters. - In addition to the difficulties associated with the insensitivity of compressor-discharge pressure as an indicator of how close the engine is to maximum acceleration or surge, corrections are required to account for altitude pressure, Mach number, and atmospheric temperature if compressor-discharge pressure is to be used as a control parameter.

Systems of acceleration control have been devised whereby fuel flow is scheduled as a function of compressor pressure rise. These systems, at the present stage of development, do not provide all the available acceleration at sea level if they are set to operate safely over a range of altitudes.

Turbine-Discharge Pressure and Thrust - Acceleration Characteristic

Figure 8 shows the turbine-discharge pressure - acceleration characteristic. Analysis indicates that the turbine-discharge pressure - acceleration relation for constant speed is substantially linear up to the maximum acceleration limit; beyond this limit the acceleration drops off. At the low end of the engine speed range the sensitivity of acceleration to turbine-discharge pressure is very great, while at the high-speed end the sensitivity is reduced. The ratio of these sensitivities is about 5:1.

In figure 9 is shown thrust as a function of acceleration for lines of constant speed. This figure shows that turbine-discharge pressure and thrust are very closely related parameters in that the same general relations hold. However, these data are for a constant- or fixed-area exhaust nozzle. It is to be expected that a change in area will change the proportionality factor between these two parameters.

A signal related to thrust can, however, be derived by computation from sensed values of turbine-discharge pressure and exhaust-nozzle area.

Acceleration control with turbine-discharge pressure or thrust parameters. - Turbine-discharge pressure or thrust also can be used in a schedule which provides an overriding control to limit the engine response during a transient to the safe region of operation or to maximum acceleration.

Comparison Between Small-Step Data and Large-Step Data

Figure 10 shows the variation of the engine time constant with engine speed and also a comparison of data obtained from small-step changes in fuel flow (ref. 2) with data from large-step changes in fuel flow. Time constants obtained from small-step data fell within a band as shown in figure 10. Large-step data resulted in a more accurate determination of the engine time constant as shown by the correlation of the time constants from the large-step changes with the mean of the small-step changes in fuel flow. An additional advantage of large-step changes is that it is possible to obtain acceleration data over a very broad range of off-equilibrium operating conditions, and therefore basic nonlinearities of operation in this region become evident.

CONCLUDING REMARKS

Operation of a single-spool turbojet engine with constant exhaust-nozzle area was investigated at one flight condition. Data were obtained by subjecting the engine to approximate-step changes in fuel-flow, and the information necessary to show the relations of acceleration to the sensed engine variables was obtained.

Maximum acceleration occurred prior to stall and surge. In the low end of the engine speed range the margin was appreciable; in the high-speed end the margin was smaller but had not been completely defined by these data.

Data involving acceleration as a function of speed, fuel flow, turbine-discharge temperature, compressor-discharge pressure, and turbine-discharge pressure or thrust were presented; and it was shown that basic control systems may be improved by addition of an override in which the acceleration characteristic is used not only to prevent the engine from entering the surge region but also to obtain acceleration along the maximum acceleration line during throttle bursts.

A number of possible schedules which could be used to avoid compressor surge were discussed, including fuel flow scheduled as a function of speed, turbine-discharge temperature scheduled as a function of speed, compressor-discharge pressure scheduled as a function of speed, and fuel flow scheduled as a function of compressor-discharge pressure. The variation of compressor-discharge pressure with fuel flow was found to be insufficient to permit satisfactory operation of an acceleration control that sets fuel flow to produce a scheduled value of compressor-discharge pressure at each engine speed.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 26, 1953

APPENDIX A

DESCRIPTION OF TRANSIENT INSTRUMENTATION

Recording equipment. - Engine parameters were recorded during transients on six-channel, direct-inking, magnetic-penmotor oscillographs. Each channel of the recorders was driven by either a d.c. or strain-analyser type of amplifier, depending on the parameter being measured. Strain-analyzer amplifiers were used with the sensing devices for pressures, fuel flow, and thrust, while d.c. amplifiers were used with the sensing devices for speed, acceleration, temperature, and position. The frequency response of the penmotors in combination with either type of amplifier is essentially flat over the range from 0 to 100 cycles per second. The oscillograph-chart speed was 12.5 millimeters ($2\frac{1}{2}$ units) per second.

Timing marks were introduced on certain channels by removing the signals from these channels, before or after a transient, simultaneously by means of a switch. These marks serve as a means of alining the traces from different recorders and for detecting slight variations in the length of individual pens.

Position indication. - The position of the exhaust nozzle, power lever, and fuel valve was indicated by a potentiometer attached in such a manner that the movable arm of the potentiometer was an indication of the position of the device. A d.c. voltage was applied across the potentiometer so that a d.c. voltage indicative of position appeared between the movable arm and either end of the potentiometer. For the transient indication, the initial level of the signal was cancelled out by series addition of an adjustable voltage opposite in polarity to that of the signal. This was done since it was desired to record only the change during the transient. The signal was then applied to a d.c. amplifier feeding one channel of a recorder. The frequency response of this circuit was limited by that of the amplifier and recorder.

Turbine-discharge temperature. - Turbine-discharge temperature was measured by a number of 18-gage, chromel-alumel, butt-welded thermocouples placed at the turbine discharge (station 6) and electrically connected in parallel. The signal from the thermocouples was applied to a magnetic amplifier to increase the amplitude of the signal without the introduction of excessive noise or drift. The magnetic amplifier was followed by an adjustable voltage to cancel out the initial level, a thermocouple compensator, and a d.c. amplifier feeding one channel of a recorder.

The thermocouple compensator is an electric network which, when properly adjusted, compensates for the thermal lag of the thermocouple.

A detailed discussion of the basic principles and circuitry involved is given in reference 6. This device allows the use of heavier thermocouple wire while obtaining faster response than could be ordinarily obtained with smaller wire. Methods for determining the time constant of thermocouples are given in reference 7.

The compensator was set by placing only one thermocouple in the circuit and then suddenly plunging the thermocouple from a cooled shield into the hot gas stream, which effectively subjects the thermocouple to a step change in temperature. The compensator was then adjusted until the temperature trace recorded as nearly as possible a step response.

The frequency response of this circuit with the compensator properly adjusted is flat over the range from 0 to 5 cycles per second at sea-level mass-flow conditions.

Engine speed. - An alternator on the engine provides an a.c. voltage whose frequency is directly proportional to speed and varies from 300 to 800 cycles per second over the speed range normally encountered. This signal was used in connection with an electronic tachometer which was modified to give an accurate steady-state and suitable transient indication of engine speed.

The steady-state indication is provided by a counting circuit that counts the input frequency for a period of 1.2 seconds, which is accurately set by a crystal-controlled oscillator. This count is then presented on a neon-lamp display panel for a suitable length of time, after which the process is repeated. Although the count is very accurate, unless the frequency is high in relation to speed, the speed cannot be precisely defined. Consequently, the alternator signal was first applied to two stages of full-wave rectification which increased the frequency by a factor of four. With this modification, the steady-state speed indication was precise to within 1 rpm.

The transient signal was obtained by modifying an existing meter circuit included in the instrument to provide a continuous indication of frequency and, hence, speed. A d.c. voltage, proportional to speed, is produced by the modified meter circuit. After cancellation of the initial level, this signal was applied to a d.c. amplifier feeding one channel of a recorder.

The frequency response of this circuit is limited by a filter circuit required in the modified meter circuit and is essentially flat over the range from 0 to 10 cycles per second.

Engine acceleration. - The transient acceleration signal was obtained by differentiating the speed signal with an R-C circuit. The signal from the differentiating circuit was applied to a d.c. amplifier feeding one channel of a recorder.

For the R-C differentiating circuit there is an inherent lag associated with the circuit which limits the frequency response to 2 cycles per second.

Air pressures. - Transient measurements of ram pressure, compressor-discharge pressure, and turbine-discharge pressure were made with the use of standard, four-element, strain-gage pressure pickups, and strain-analyzer-type amplifiers. A network in the analyzer provides a means of adjustable output of the amplifier so that only the change need be recorded.

The pressure pickups were mounted in the wing section in a centrally located box which reduced the effect of engine vibration on the pickups.

The dynamic response of these circuits is a function of the diameter and length of the tubing used to transmit the pressure from the engine to the pressure pickup and of the density of the air. Design of tubing size is outlined in reference 8. All tubing was experimentally tested and adjusted before installation to give a frequency response which is essentially flat from 0 to 10 cycles per second at sea-level conditions.

Fuel flow. - The transient indication of fuel flow was obtained by measuring the pressure drop across an orifice in the fuel line by means of a differential strain-gage pressure pickup. The operation of the pressure pickup is the same in this case as for those used to measure air pressures. In order to obtain a sufficiently large pressure drop regardless of the fuel flow, the size of the orifice was made variable by means of a remotely controlled positioning system.

It should be noted that, for the fuel flow trace, the deflection is not a linear function of the fuel flow change since the pressure drop across the orifice is proportional to the square of the fuel flow. When obtaining values from the fuel flow trace, it is necessary to adjust for this effect.

The major limitations on the fuel information obtained were the mass and capacitance effects of the fuel and piping system. These limited the useful frequency range to 0 to 2 cycles per second. The pressure measuring device, the fuel valve, and the pressure regulator across the valve produced negligible effects in this frequency band.

Thrust. - The transient thrust measurement, like the pressure measurements, was obtained with a strain-gage and a strain-analyzer type of amplifier. In this case, however, the strain gage is bonded to a thrust link attached from the engine to the mount. The engine is supported in such a manner that the total force of the engine is transmitted to the mount through this thrust link.

The frequency response of the circuit to a change in the thrust link is limited by the recorder and amplifier, but the response of the entire system is dependent on the dynamics of the entire mounting system, which has not been determined.

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TABLE I. - INSTRUMENTATION

Measured quantity	Steady-state instrumentation	Transient instrumentation	
		Sensor	Range over which frequency response is essentially flat, cps
Exhaust-nozzle area	Potentiometer attached to rack and gear assembly and connected in electric circuit to give indication on microammeter; microammeter reading converted to area	Control feedback potentiometer	0-100
Turbine-discharge total temperature	Twenty-four individual thermocouples connected to potentiometer-type strip-chart record	Six, paralleled, 18-gage, chromel-alumel, butt-welded thermocouples and electric network to compensate for thermocouple lag	0-5 at sea-level static when used with properly adjusted compensator
Engine speed	Modified electronic tachometer	Modified electronic tachometer	0-10
Engine acceleration	Calibration obtained from transient speed traces	Modified electronic tachometer and differentiating circuit	0-2
Ram pressure	Water manometers	Aneroid-type pressure sensor, with strain-gage element	0-10 at sea-level static
Compressor-discharge total pressure	Mercury manometers	Aneroid-type pressure sensor, with strain-gage element	0-10 at sea-level static
Turbine-discharge total pressure	Alkazene manometers	Aneroid-type pressure sensor, with strain-gage element	0-10 at sea-level static
Thrust	Scale	Strain gage mounted on strain link attached to forward engine suspension	0-100
Fuel flow	Rotameter	Aneroid-type pressure sensor, with strain-gage element, connected to measure pressure drop across a variable orifice in the fuel line	Undetermined

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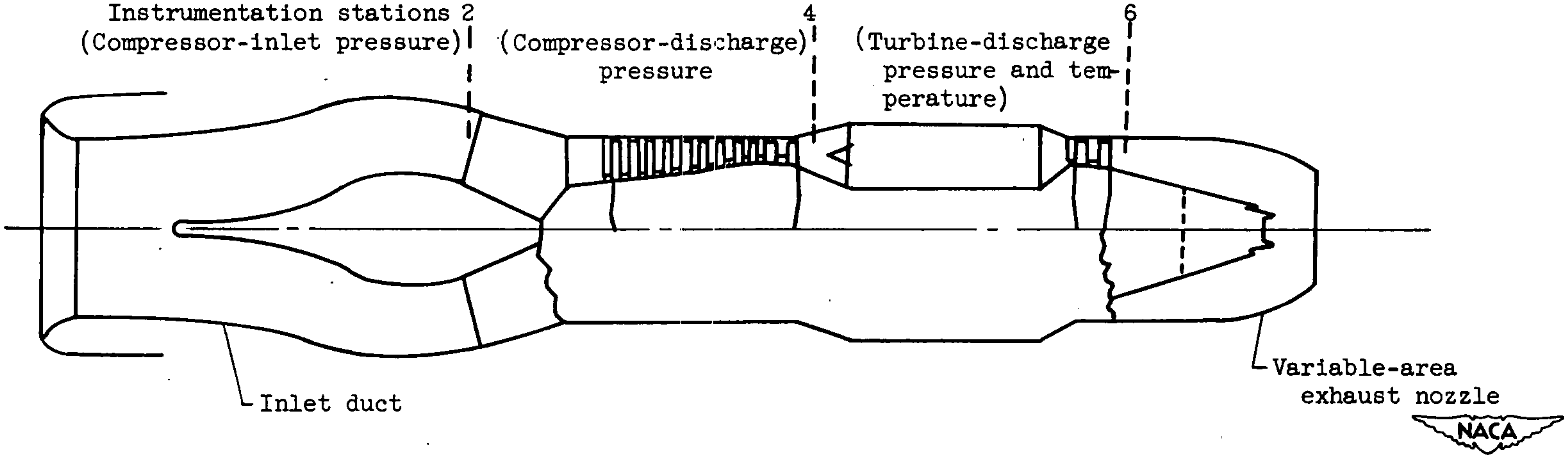

Figure 1. - Schematic diagram illustrating engine-inlet ducting and instrumentation stations.

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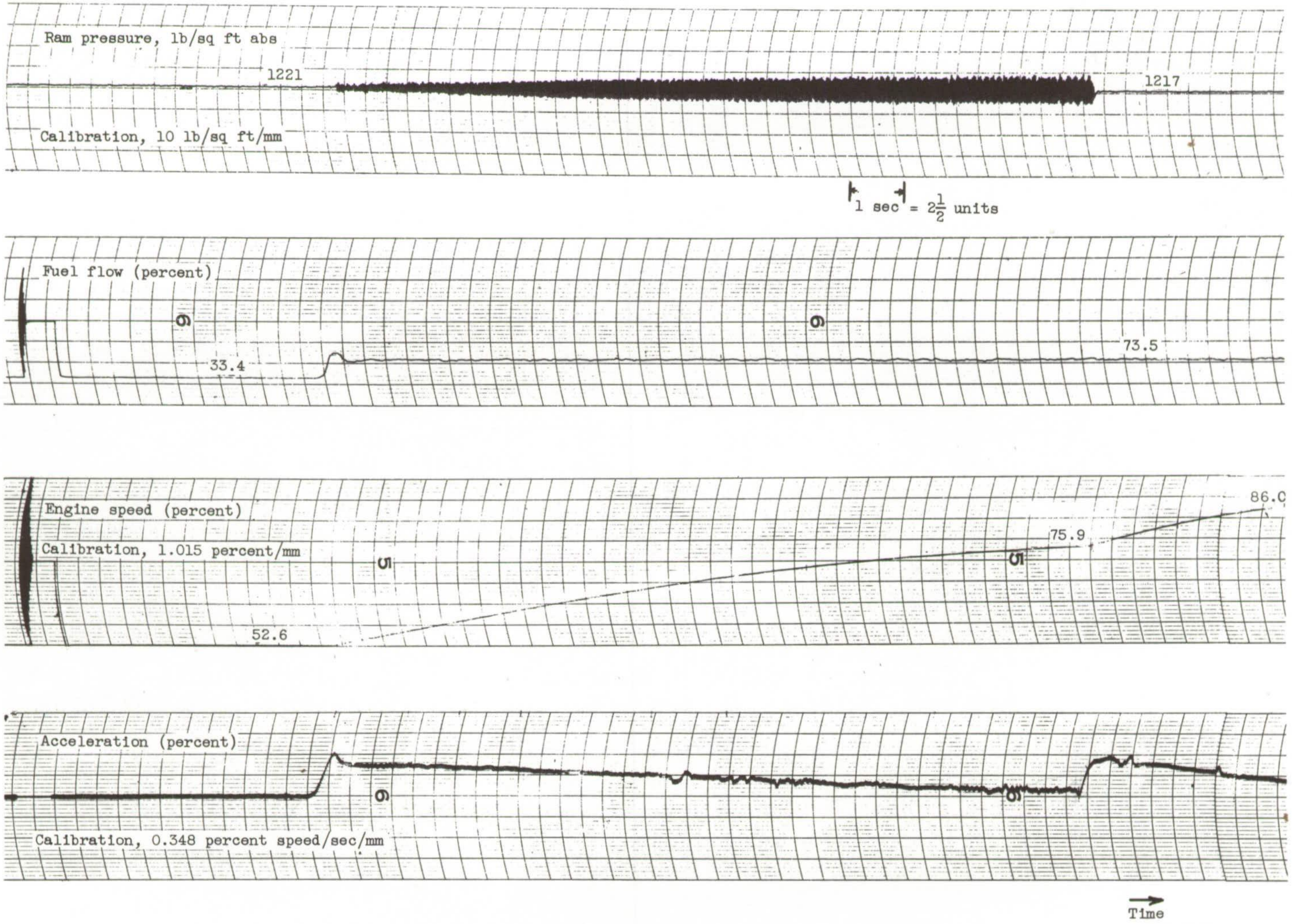
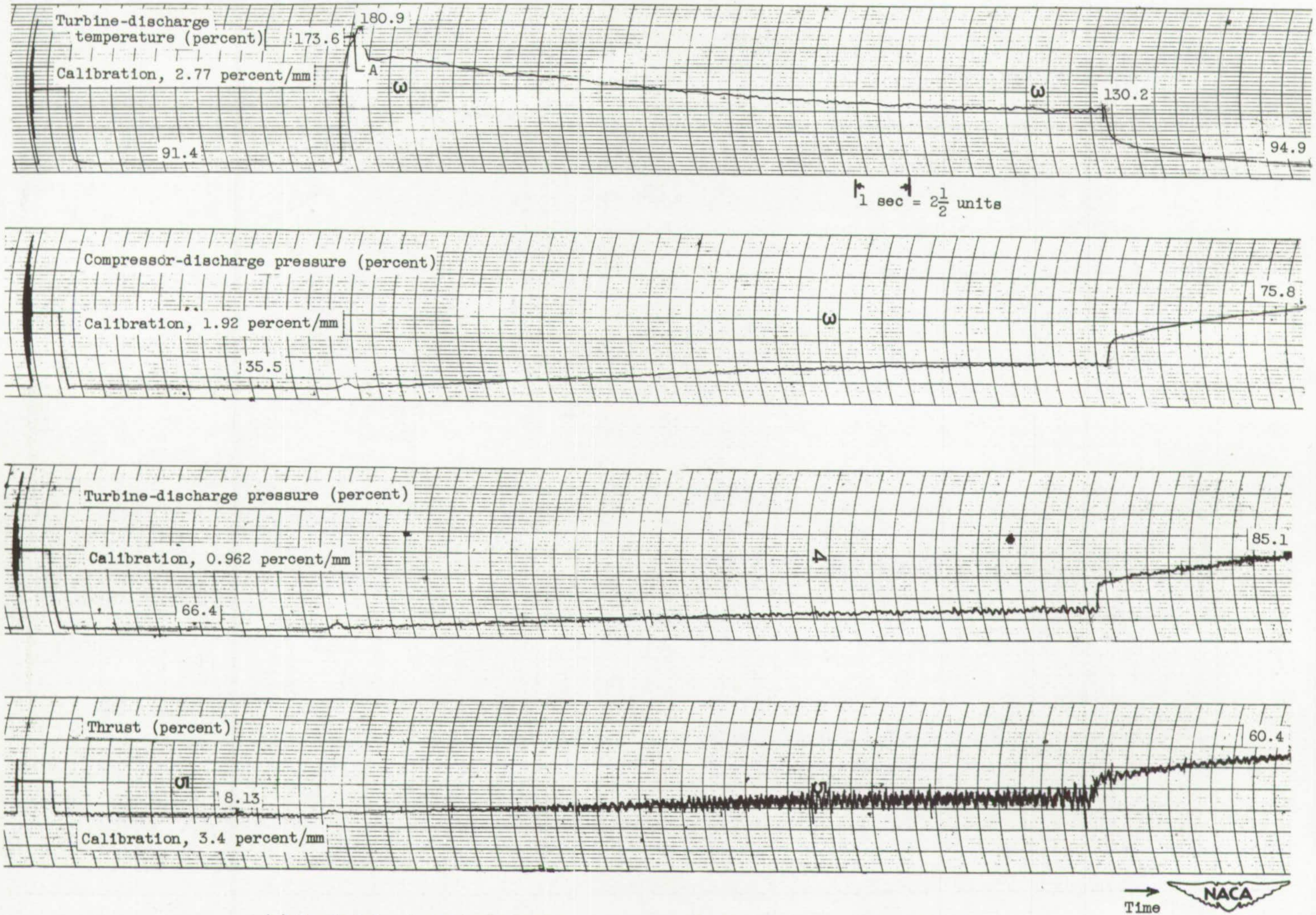


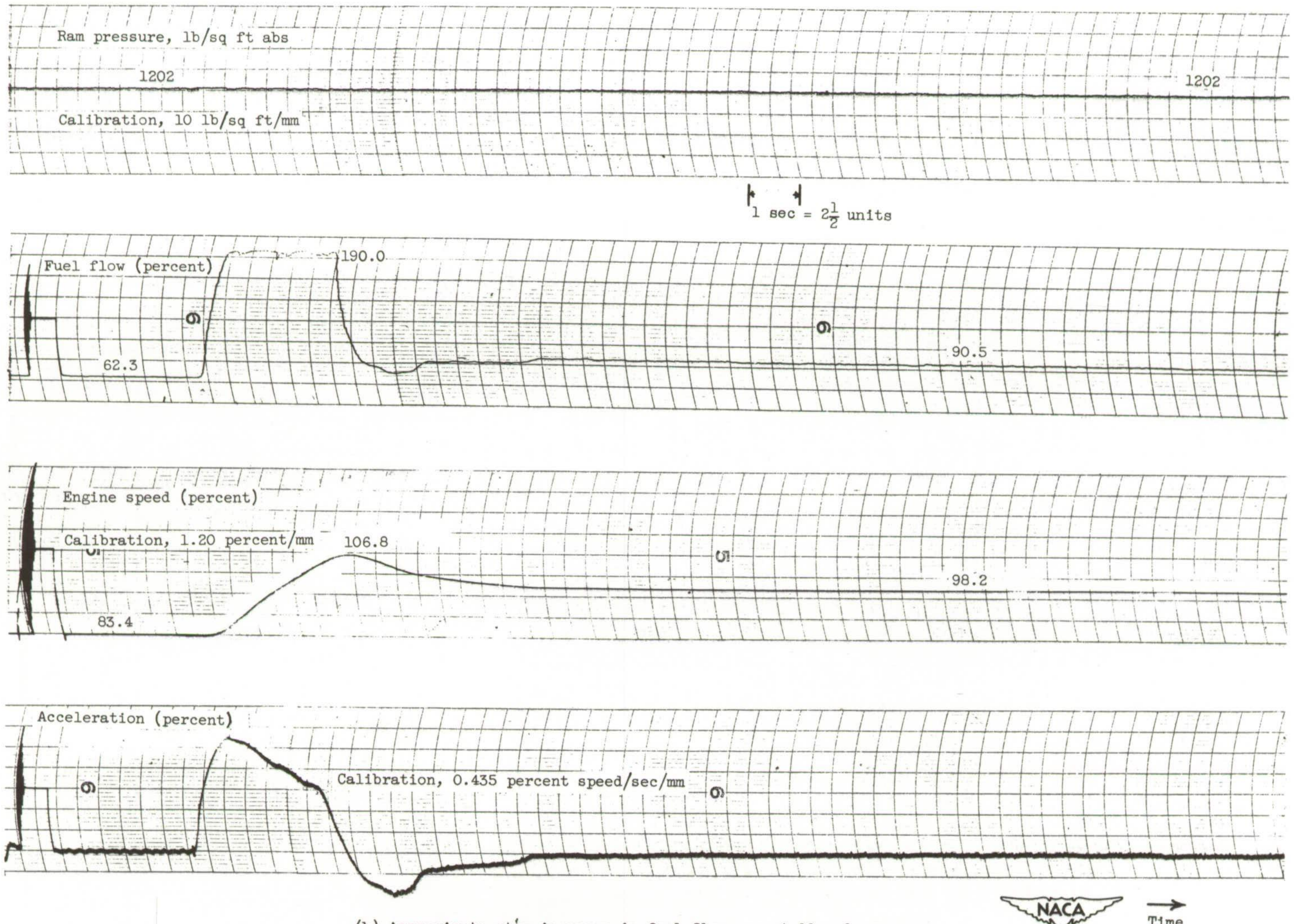
(a) Approximate-step increase in fuel flow; occurrence of stall and surge.

Figure 2. - Sample data taken during acceleration. Parameters shown given in percentage of value at rated rpm at 15,000-foot altitude and 1.02 ram-pressure ratio.



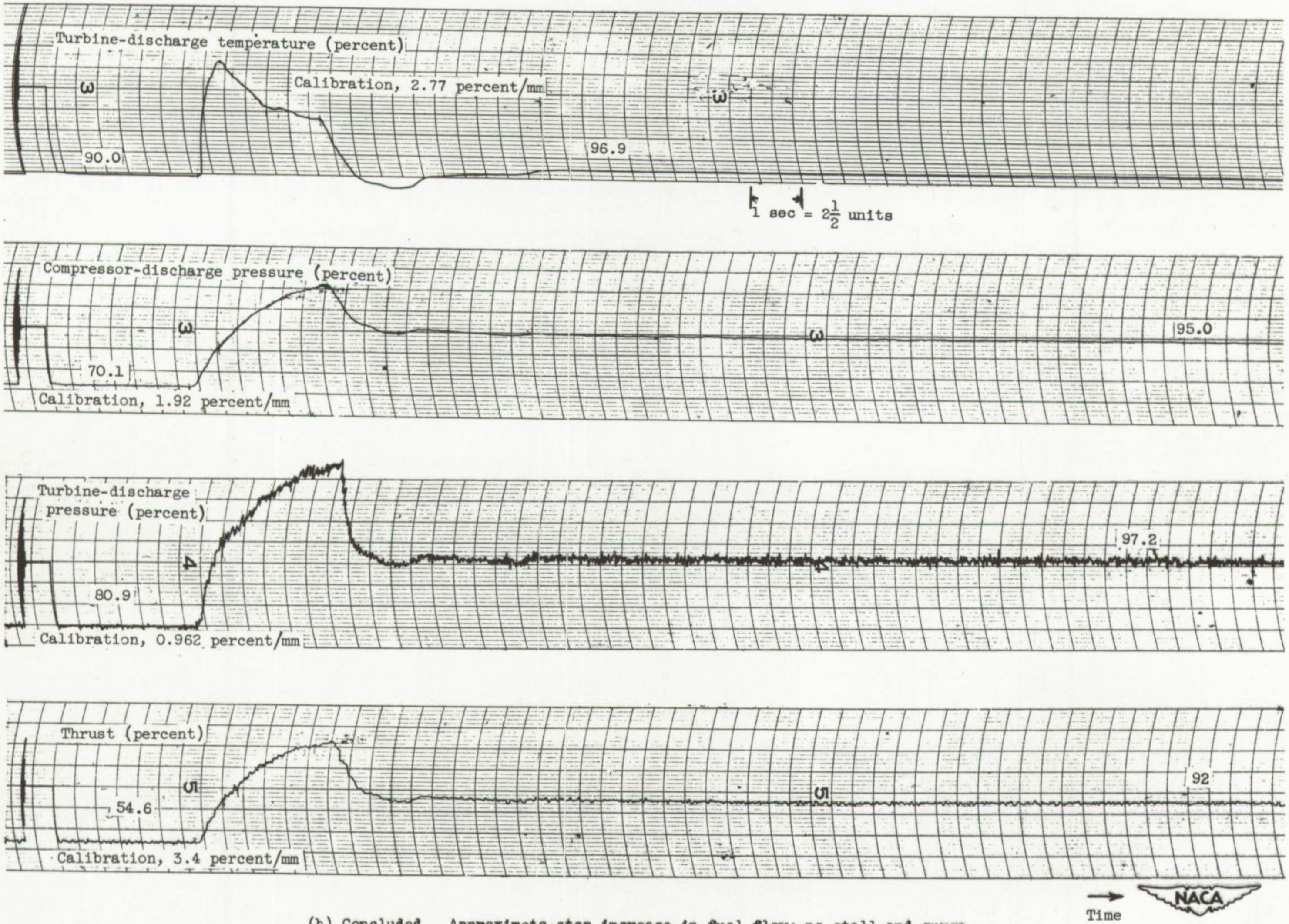
(a) Concluded. Approximate-step increase in fuel flow; occurrence of stall and surge.

Figure 2. - Continued. Sample data taken during acceleration. Parameters shown given in percentage of value at rated rpm at 15,000-foot altitude and 1.02 ram-pressure ratio.



(b) Approximate-step increase in fuel flow; no stall and surge.

Figure 2. - Continued. Sample data taken during acceleration. Parameters shown given in percentage of value at rated rpm at 15,000-foot altitude and 1.02 ram-pressure ratio.



(b) Concluded. Approximate-step increase in fuel flow; no stall and surge.

Figure 2. - Continued. Sample data taken during acceleration. Parameters shown given in percentage of value at rated rpm at 15,000-foot altitude and 1.02 ram-pressure ratio.

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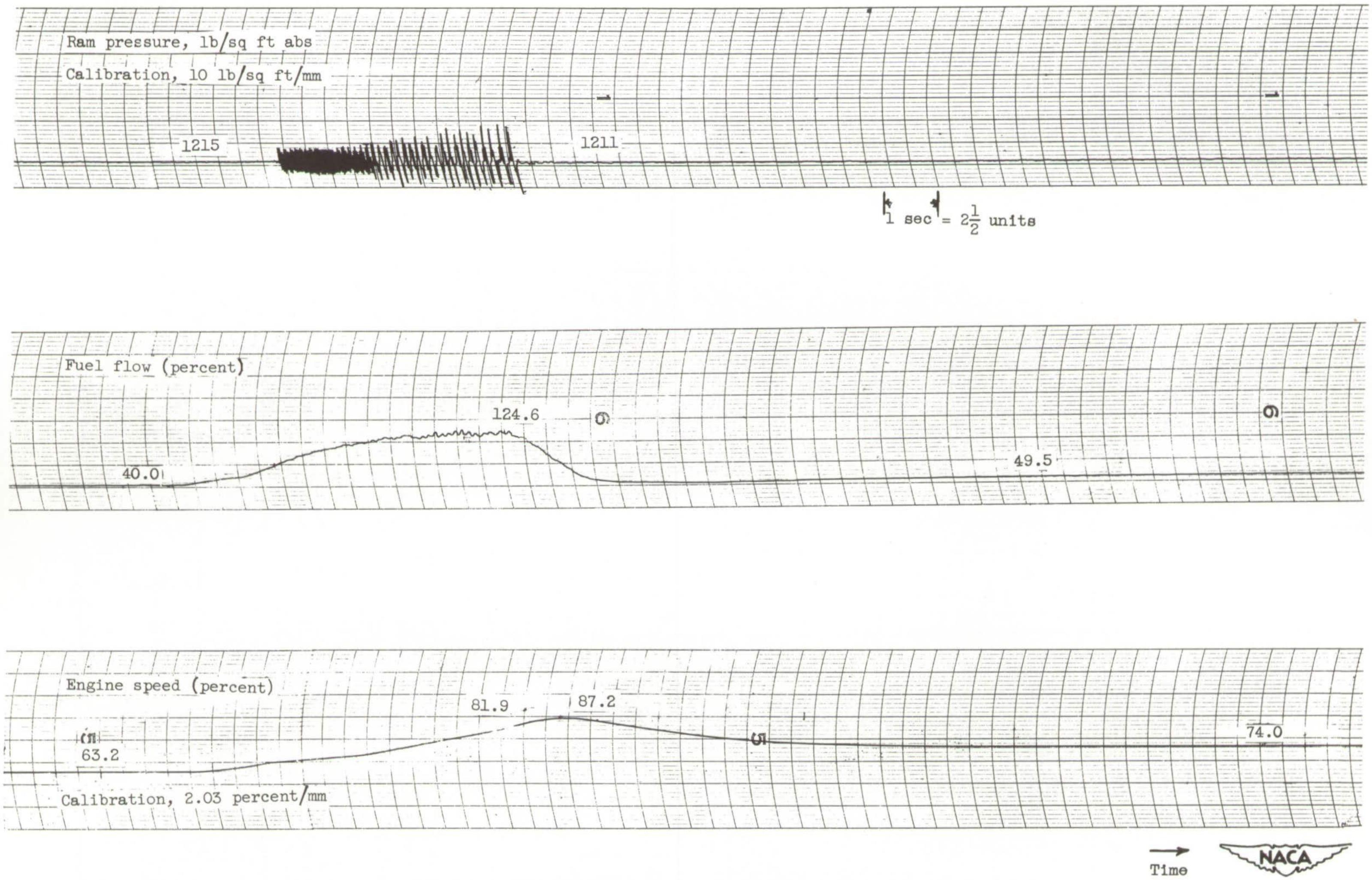

(c) Gradual increase in fuel flow; occurrence of stall and surge.

Figure 2. - Continued. Sample data taken during acceleration. Parameters shown given in percentage of value at rated rpm at 15,000-foot altitude and 1.02 ram-pressure ratio.

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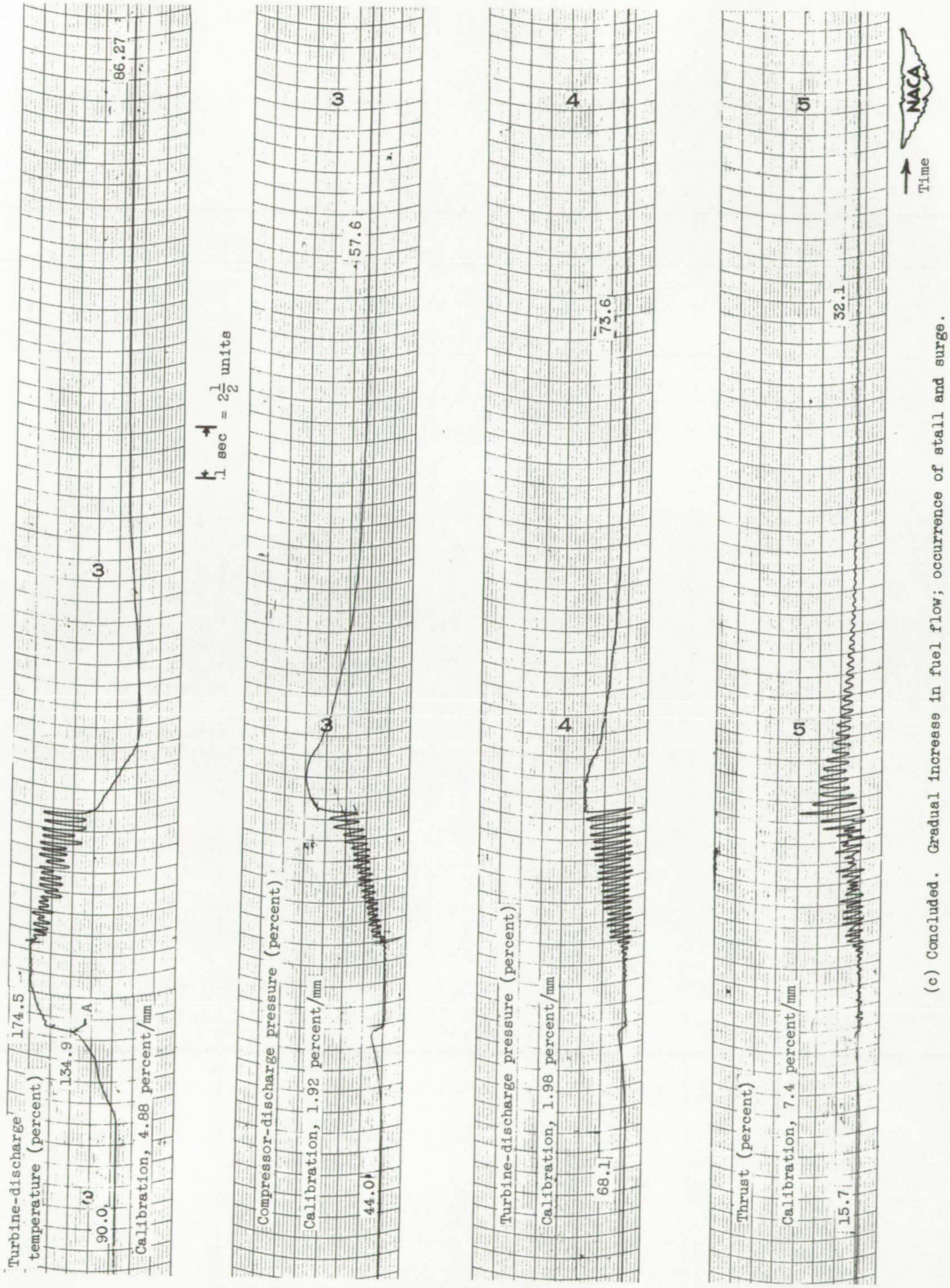

(c) Concluded. Gradual increase in fuel flow; occurrence of stall and surge.

Figure 2. - Concluded. Sample data taken during acceleration. Parameters shown given in percentage of value at rated rpm at 15,000-foot altitude and 1.02 ram-pressure ratio.

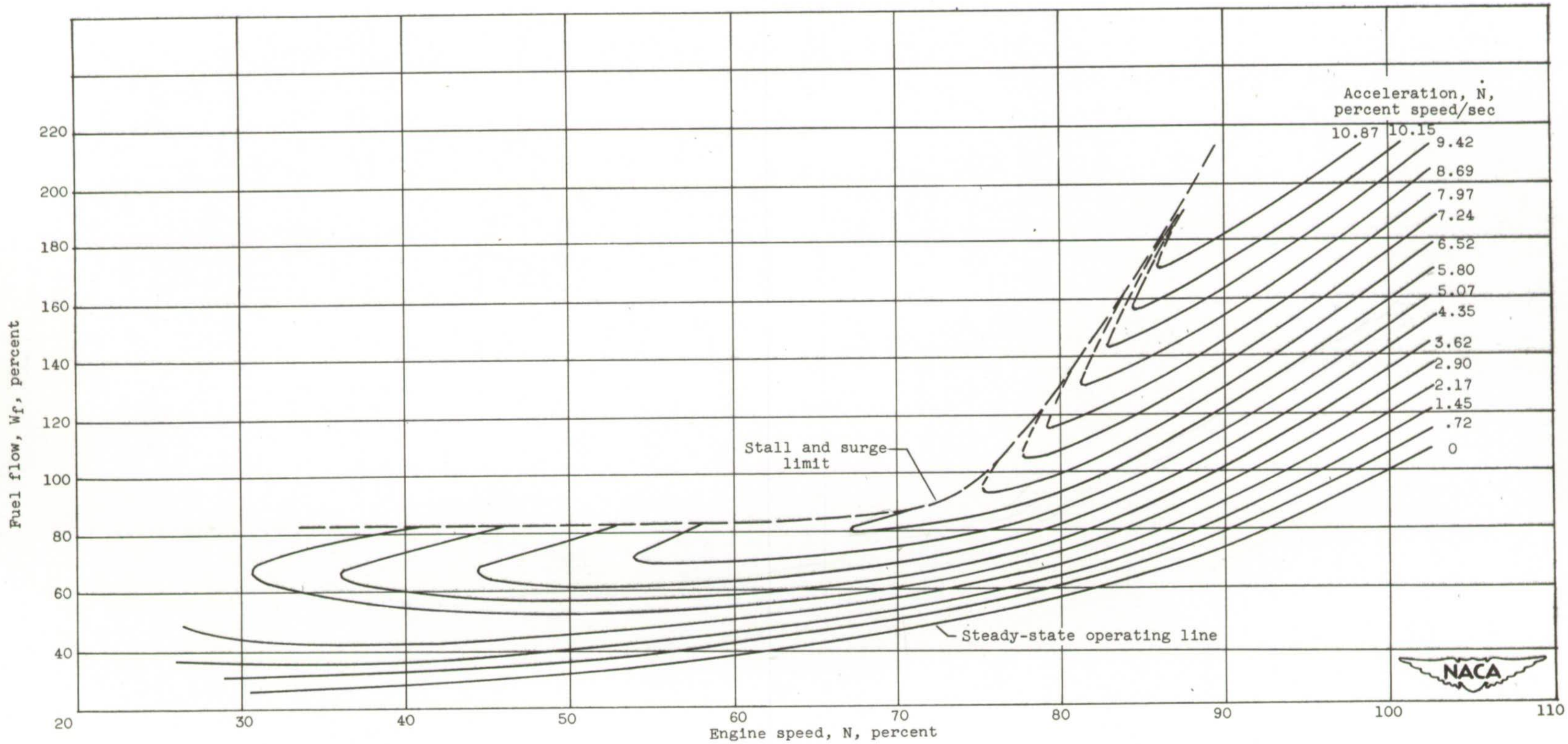

Figure 3. - Fuel flow - acceleration characteristic. Parameters shown given in percentage of value at rated rpm at 15,000-foot altitude and 1.02 ram-pressure ratio.

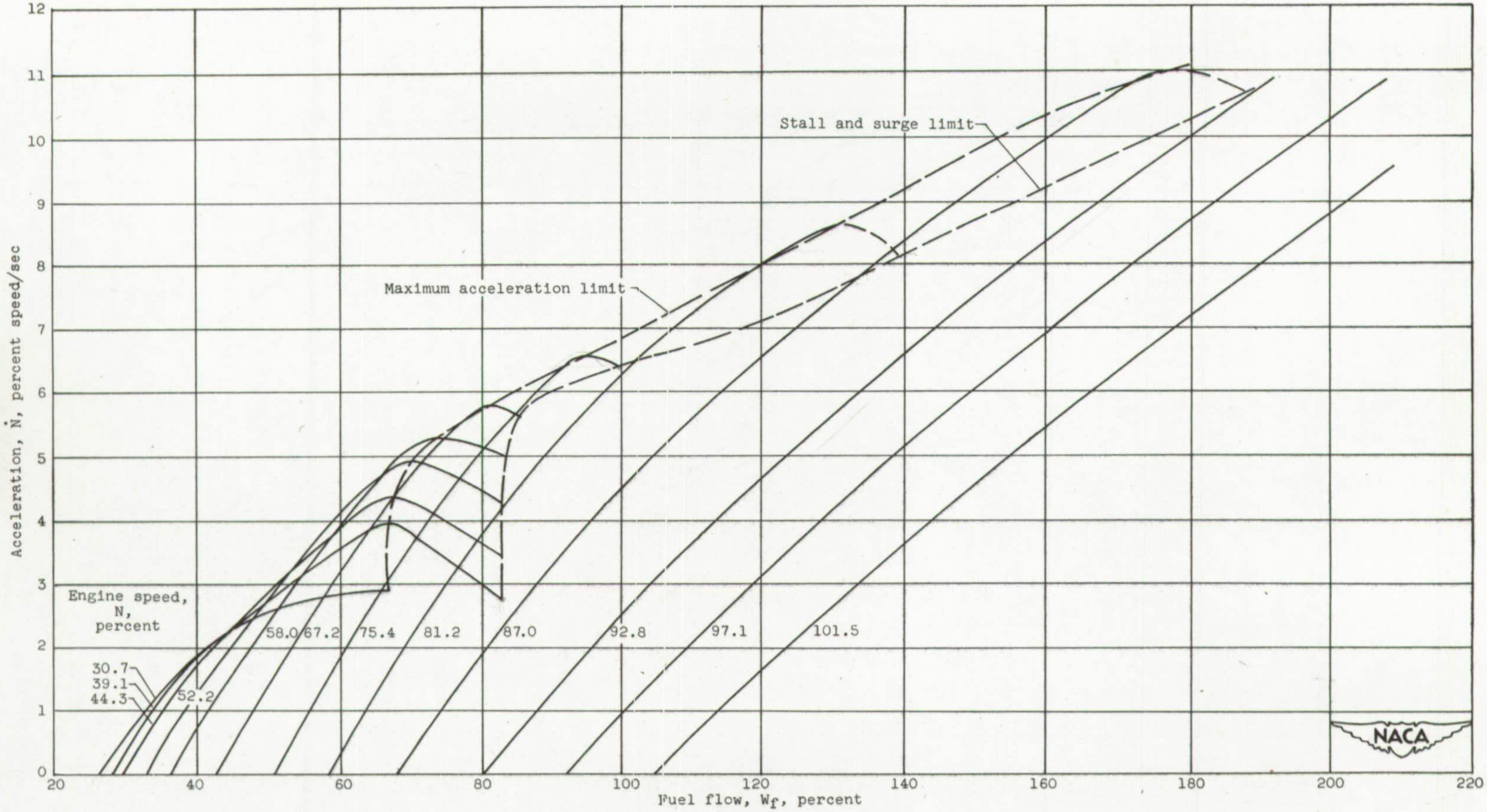

Figure 4. - Acceleration - fuel flow characteristic at constant engine speeds. Parameters shown given in percentage of value at rated rpm at 15,000-foot altitude and 1.02 ram-pressure ratio.

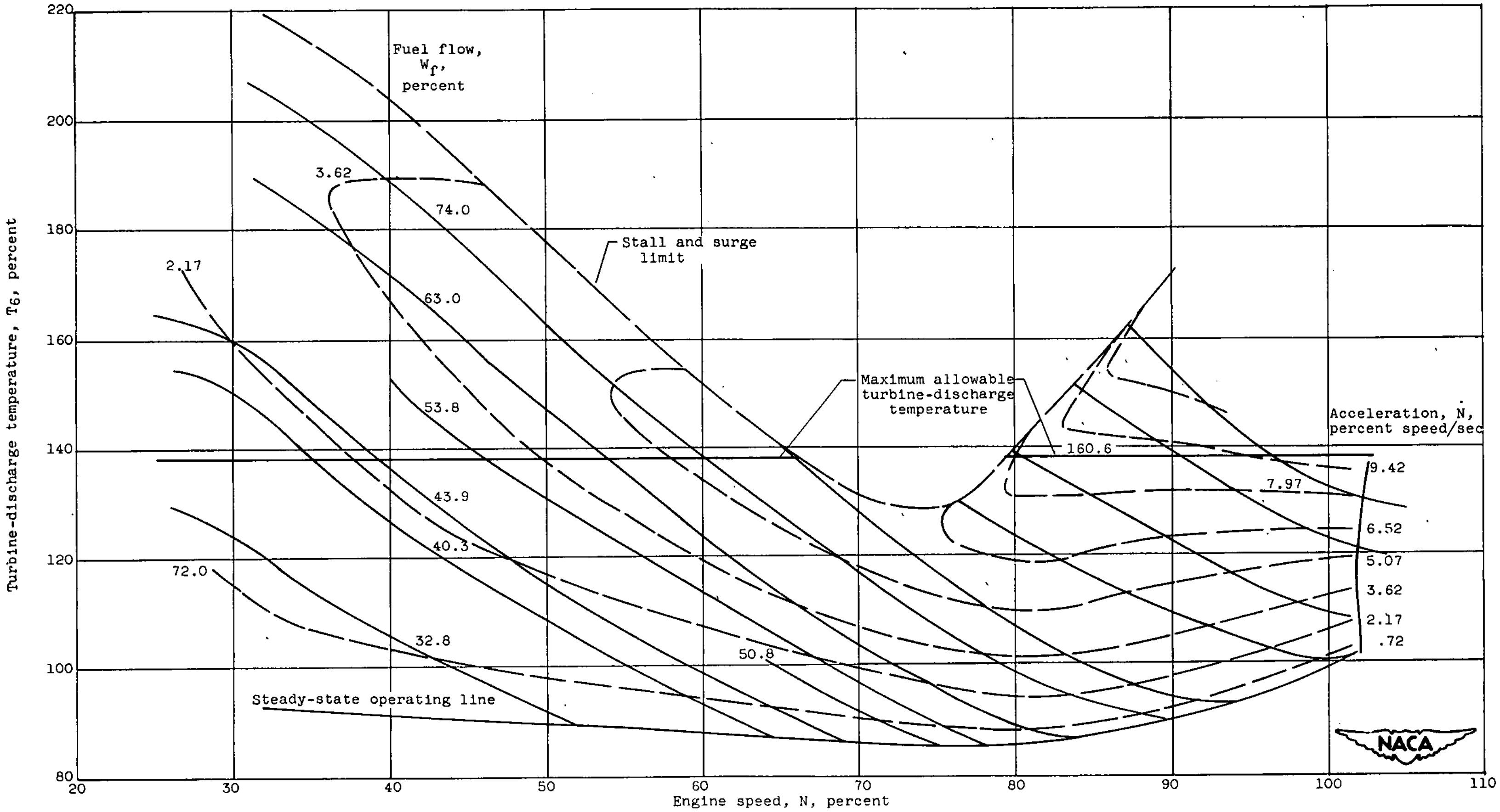

Figure 5. - Sample data taken during acceleration. Parameters shown given in percentage of value at rated rpm at 15,000-foot altitude and 1.02 ram-pressure ratio.

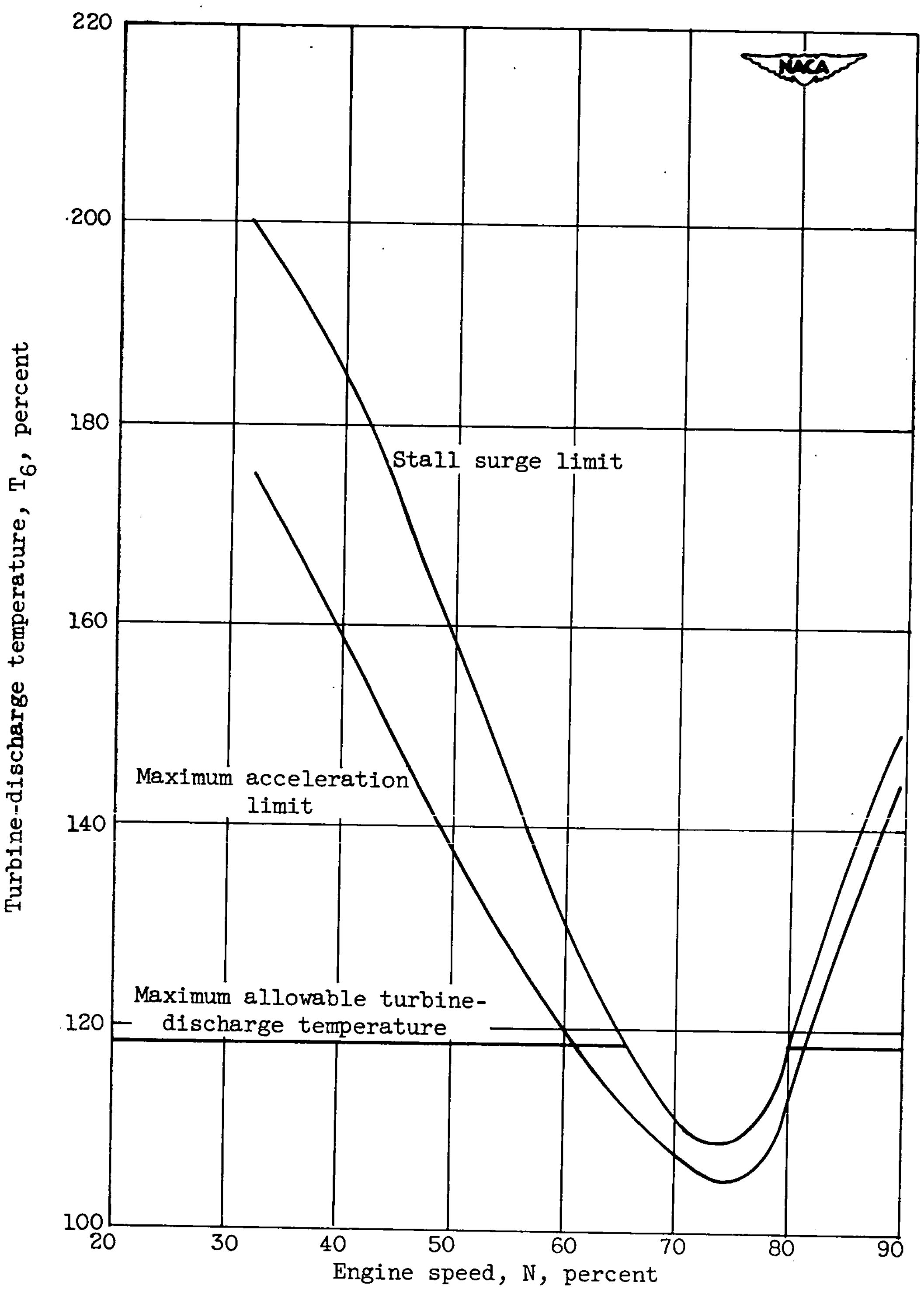

Figure 6. - Acceleration temperatures at stall and surge limit, and at maximum acceleration. Parameters shown given in percentage of value at rated rpm at 15,000-foot altitude and 1.02 ram-pressure ratio.

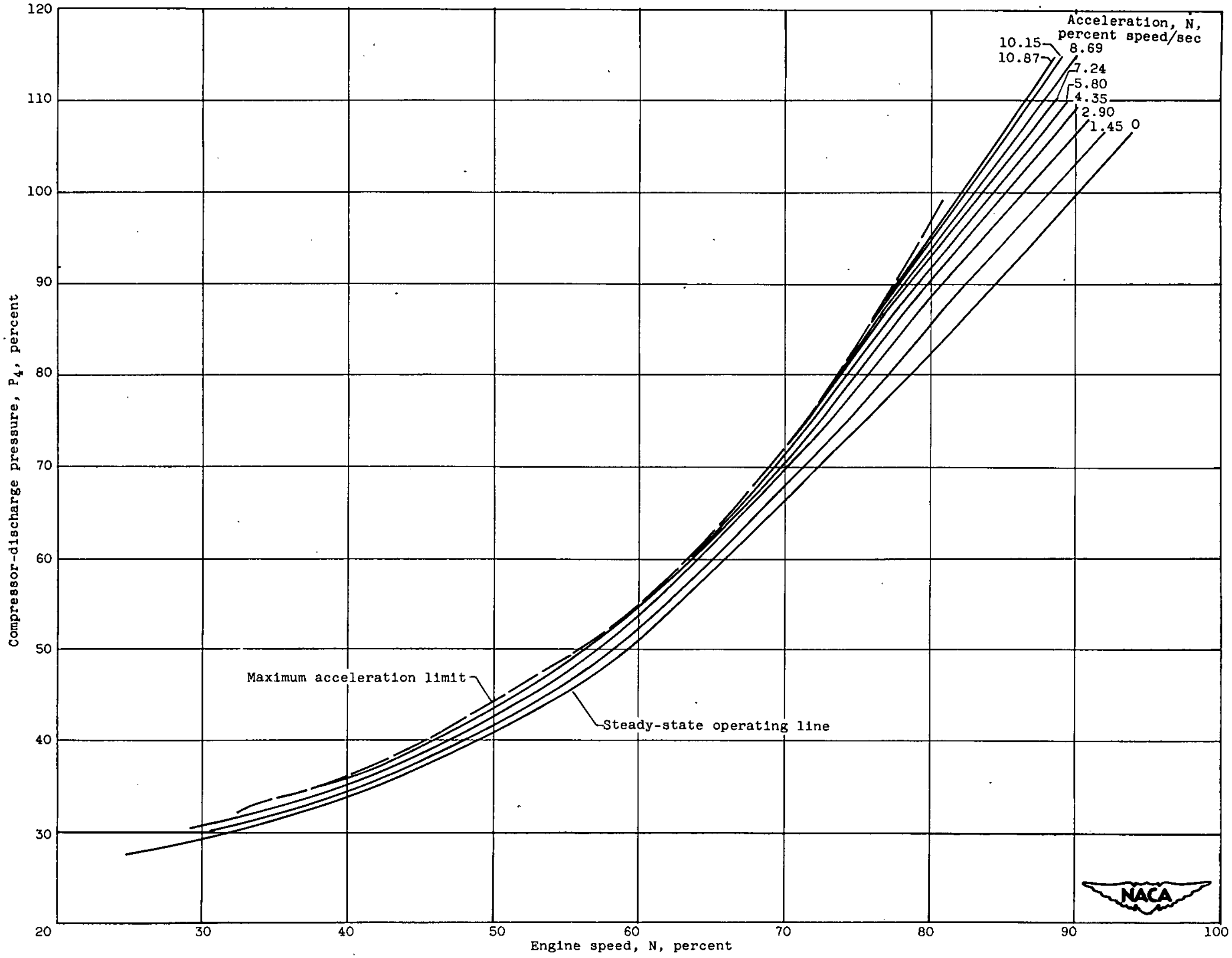

Figure 7. - Compressor-discharge pressure during acceleration. Parameters shown given in percentage of value at rated rpm at 15,000-foot altitude and 1.02 ram-pressure ratio.

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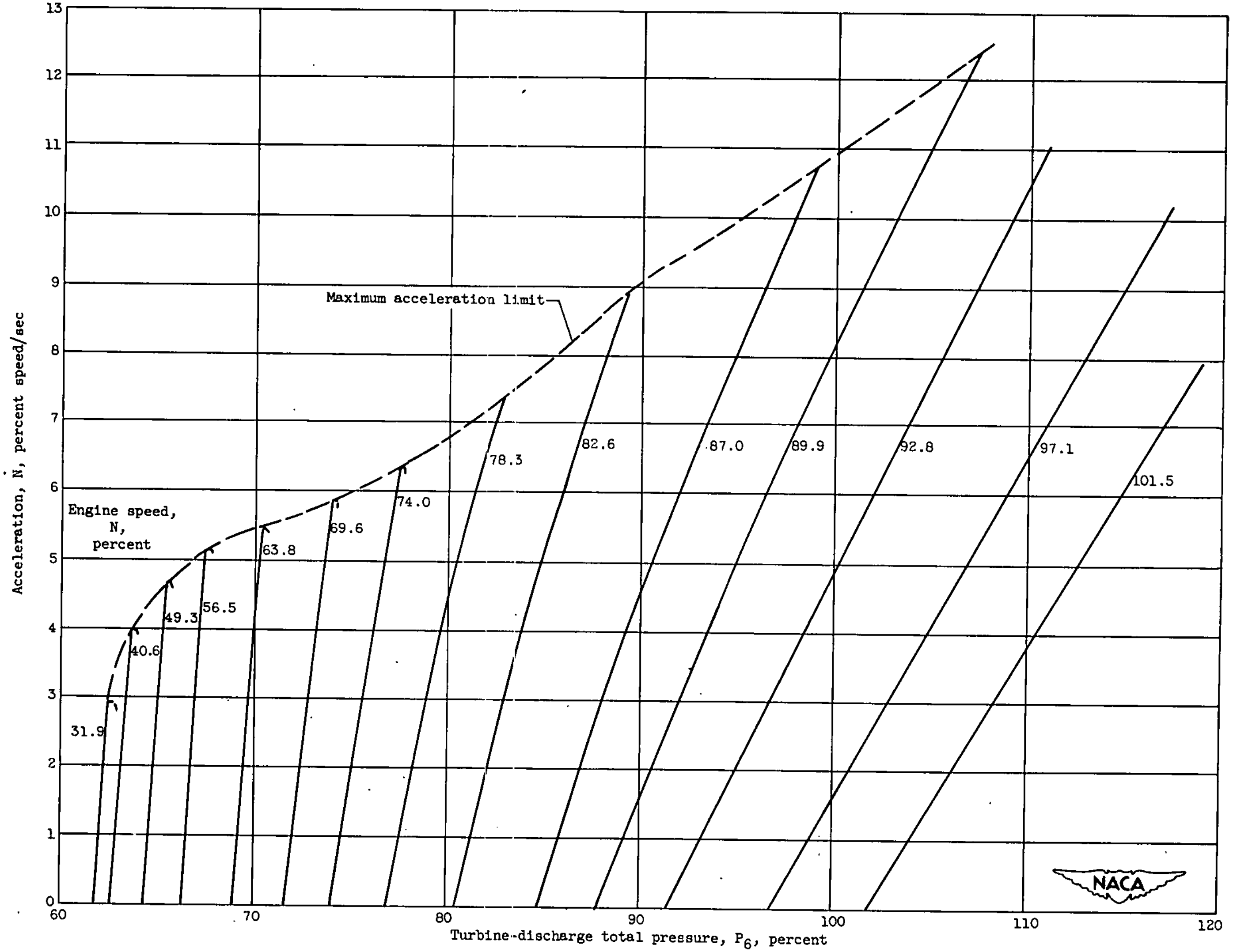

Figure 8. - Turbine-discharge total pressure during acceleration at constant engine speeds. Parameters shown given in percentage of value at rated rpm at 15,000-foot altitude and 1.02 ram-pressure ratio.

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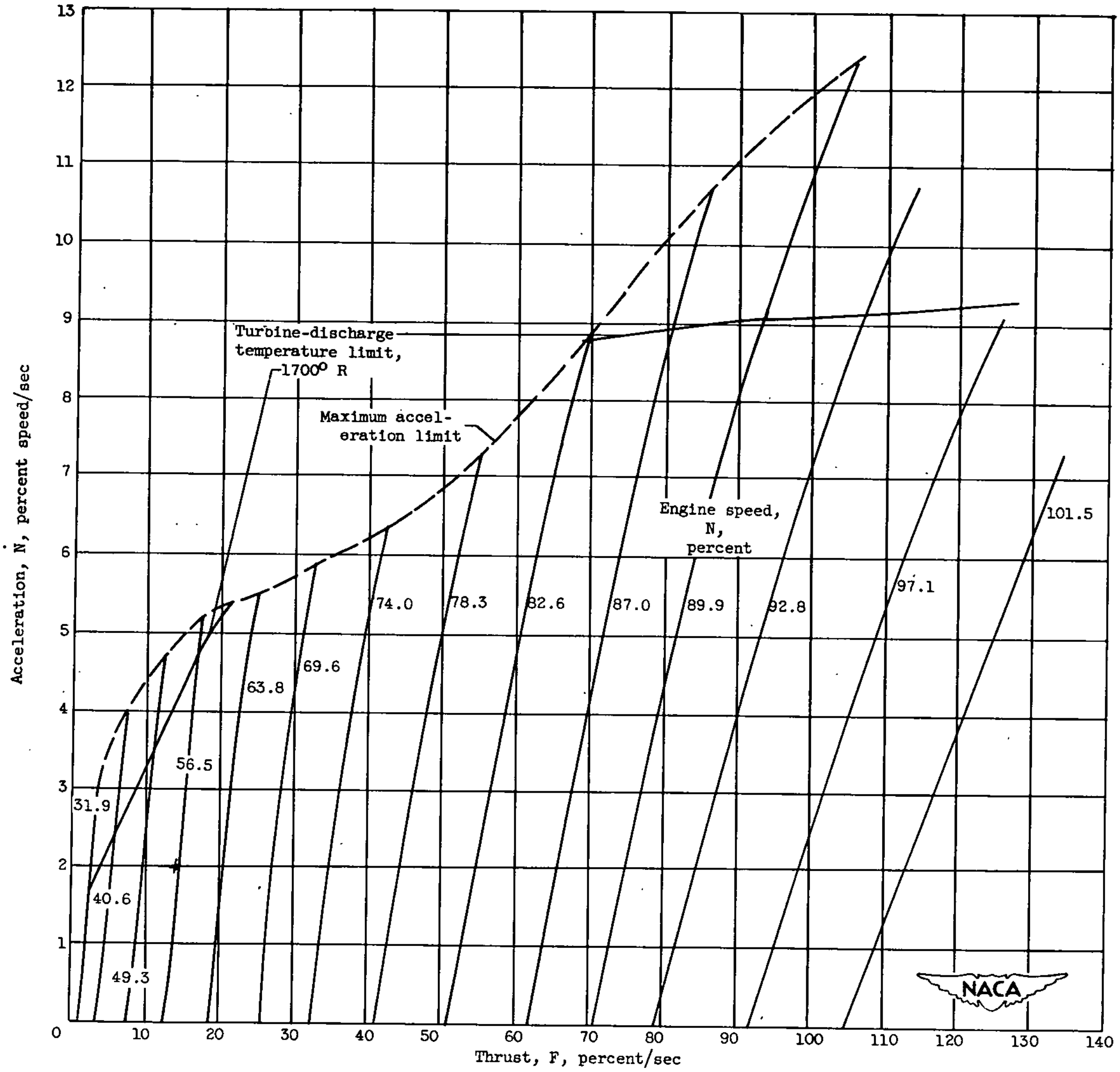

Figure 9. - Thrust during acceleration at constant engine speeds. Parameters shown given in percentage of value at rated rpm at 15,000-foot altitude and 1.02 ram-pressure ratio.

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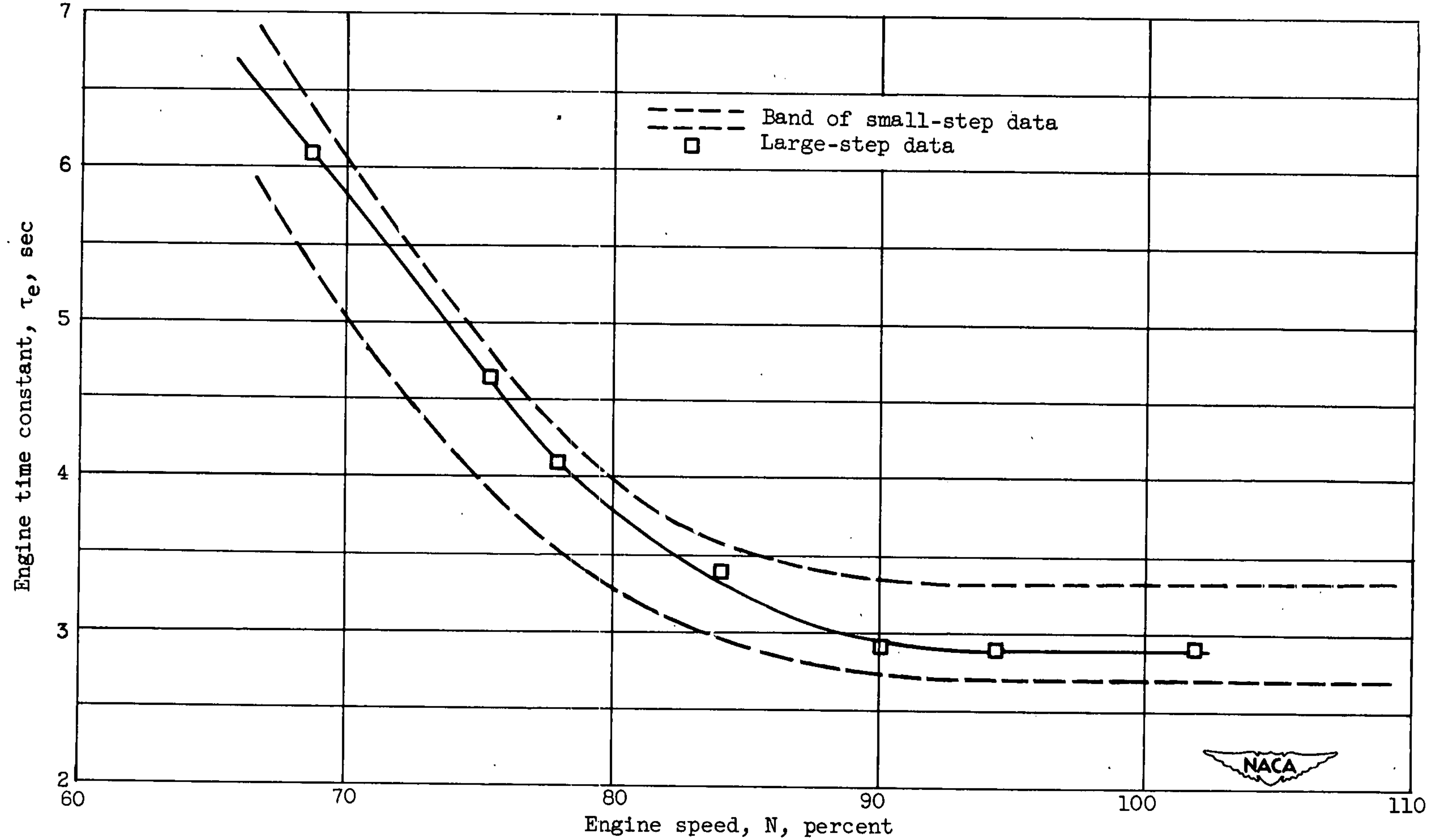

Figure 10. - Comparison of engine time constant determined from large- and small-step changes. Parameters shown given in percentage of value at rated rpm at 15,000-foot altitude and 1.02 ram-pressure ratio.

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