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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF A SURGE CONTROL ON A TURBOJET ENGINE

By David Novik, Herbert Heppler, and Paul M. Stiglic

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The action of a surge control that reduced fuel flow after receiving an indication of surge initiation was investigated. From a survey of engine parameters, the derivative of compressor-discharge pressure was best suited as a surge-control signal. The control system could successfully limit surge to only 1 cycle but could not completely prevent surge. The inability of the control to interrupt a surge cycle and thereby prevent completion of 1 cycle of surge leads to the conclusion that a surge cycle is fundamentally irreversible.

At speeds below idle, a prolonged flat region of compressor-discharge pressure existed prior to surge, and the control had sufficient time to reduce fuel flow before surge could occur.

INTRODUCTION

The occurrence of stall or surge during rapid accelerations imposes a significant limitation on the acceleration potential of current turbojet engines. Stall and surge result in loss of acceleration, overtemperature operation, high compressor blade stresses, severe vibrations, and sometimes cause combustor flame-out; hence, it is necessary to restrict engine acceleration in order to avoid the stall and surge regions.

Schedule-type control systems, based on experimentally determined surge lines, have thus far afforded the best practical protection against surge during acceleration. However, these schedule controls are far from being completely satisfactory, primarily because it has been found that the surge lines vary from engine to engine of the same model and also vary with altitude, flight Mach number, inlet-air distortion, and previous engine operating history (ref. 1). In order to make surge schedules safe for the worst condition of operation, it is necessary to sacrifice acceleration in operating regions where greater engine acceleration would otherwise be permissible. This limitation on turbojet-engine acceleration has resulted in a search for control methods other than schedules.

The action of a control system that would trigger a reduction in fuel flow upon receipt of a signal indicative of surge initiation has been investigated at the NACA Lewis laboratory. Surge prevention with such a control would be a function of measured engine conditions rather than a function of a predetermined schedule. The control system was essentially incomplete in that provision was not made for continuation of acceleration following the fuel cut-back. However, the primary objective of this project was to determine whether a fuel-flow cut-back, triggered by a surge-initiation signal from the engine, could successfully eliminate surge.

Data are shown relative to the effects of fuel cut-back timing, the amount of fuel reduction, and the method of surge initiation on the effectiveness of the control system. The control was modified to actuate an increase in exhaust-nozzle area as an attempt to eliminate surge. The test engine was a two-spool turbojet engine fitted with a variable-area exhaust nozzle.

APPARATUS

Fuel System and Control

The engine fuel system, up to the flow divider, was supplanted by a research-facility fuel valve (fig. 1). The research-facility fuel valve consisted of a reducing-valve regulator controlling the pressure drop across a throttle valve, the position of which (and thus the area) was varied by an electrohydraulic servomotor. In such a system the fuel flow through the throttle valve is proportional to the throttle-valve position. If the engine fuel system, downstream of the fuel valve, has no capacitance, the throttle-valve position would therefore be indicative of engine fuel flow. The fuel system of the test engine incorporated a flow divider that fed into a small-slot fuel manifold and a spring-loaded large-slot manifold. In order to eliminate the capacitance effect of filling the spring-loaded manifold, engine operation was restricted to operation below and above the opening point of the large-slot manifold. For the data shown, therefore, the throttle-valve position was proportional to the engine fuel flow. The response of the research-facility fuel valve was flat to approximately 100 cps for the size of the fuel changes required (ref. 2).

An electronic computer was used to provide the desired control-system transfer function. The voltage output of the computer was fed to the input of the electrohydraulic servomotor of the research-facility fuel valve. The fuel flow was therefore regulated in accordance with the computer output (fig. 2).

The computer circuitry permitted an input voltage, indicative of a desired acceleration, to pass through to the fuel valve as long as the engine accelerated normally. Immediately upon the occurrence of surge, a signal from the engine, indicative of surge initiation, was used to cut back the acceleration input and thereby reduce the fuel flow. As shown in figure 2, the surge signal was biased with a variable voltage. For a given surge signal, this control bias had the effect of changing the voltage and therefore the timing of the control cut-back. An additional voltage bias was used in conjunction with the input function in order to permit adjustment of the cut-back level; this corresponded to adjustment of the amount of fuel reduction. The basic computer circuitry corresponded to a bistable multivibrator circuit (ref. 3).

Engine

A two-spool engine with a variable-area exhaust nozzle (fig. 3) was used in the investigation. The area was varied by means of a butterfly valve actuated by a high-speed electrohydraulic servomotor (fig. 3(a)). A time history of the butterfly response is shown in figure 3(b).

The engine was equipped with intercompressor bleeds that were maintained closed at the low engine speeds and open at the high engine speeds in order to facilitate surge occurrence. Inasmuch as the exhaust-nozzle area utilized differed from the manufacturer's exhaust nozzle and the intercompressor bleeds were maintained open and closed in an opposite sequence with normal engine operation, the engine data are not considered representative of any specific two-spool engine.

Instrumentation

Engine speed. - Engine speed was measured by recording the direct-current voltage output of an electronic counter that counted the pulses supplied from a 180-tooth tachometer generator. Before recording, the speed signal was filtered with two cascaded lags that had approximate time constants of 0.01 second each. Only the inner-spool speed was recorded.

Acceleration. - Acceleration was obtained from the derivative of the speed signal (taken electronically) after further filtering of the speed signal. The additional filter had characteristics as shown in figure 4. The derivative circuit itself had a stabilizing lag of 0.01 second.

Fuel flow. - As previously discussed, the fuel-valve position was recorded as an indication of fuel flow.

Engine pressures. - Engine pressures were measured by means of strain-gage pressure pickups. Pressure responses had apparent time constants less than 0.01 second.

Derivative of engine pressure. - The derivative of pressure was taken electronically with circuitry that incorporated a 0.01-second lag.

Recorder. - Data were recorded on a 6-channel oscillograph that had a flat response to approximately 100 cycles.

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RESULTS

Preliminary Investigation

Three types of preliminary tests were run on the engine prior to any surge-control investigation. First, a series of pulse-type fuel-input accelerations were made for the purpose of establishing basic engine surge characteristics and evaluating surge-control requirements. Second, a survey of compressor-discharge-pressure frequencies was made in order to determine whether a characteristic presurge frequency might appear that could be used for control purposes. Finally, engine surge data were examined with the object of selecting a parameter that would be indicative of engine surge.

Pulse-type fuel inputs. - A single-pulse fuel input, resulting in engine surge, is shown in figure 5. The sharp drop in compressor-discharge pressure (pressure at discharge of inner compressor) and acceleration and the reversal in sign of the derivatives of these variables are typical of surge initiation. The data indicate that a complete cycle of surge occurred, despite the fact that the fuel flow was being reduced before the surge cycle had begun.

A series of repeated fuel input pulses is shown in figure 6. The pulse frequency was approximately 10 cps, whereas the surge frequency obtained for the prolonged period of fuel pulses was about 4 cps. The surge frequency was therefore independent of the fuel-pulse frequency, from which it may be inferred that a fuel cut-back cannot interrupt the completion of a surge cycle. Figure 6 also shows that the compressor-discharge pressure and its derivative respond to the fuel pulses during normal operation but do not respond during surge. In contrast, the acceleration and its derivative appear to respond to the fuel pulses during surge as well as during normal operation. Apparently, the changing energy inputs (fuel pulses) are sufficiently large to affect the acceleration during surge, but the forces involved in the surge cycle are too large to be affected by the fuel flow.

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Survey of compressor-discharge-pressure frequencies. - A survey of compressor-discharge-pressure frequencies was made in order to determine whether a characteristic frequency might appear as the engine approached surge. Such a characteristic frequency, if it existed, would be useful as a presurge warning and as a surge-control parameter. Figure 7 shows two accelerations in which the compressor-discharge-pressure traces were passed through a rejection filter that rejected all frequencies below 10 cps. An acceleration with approximately 100-percent exhaust-nozzle area is shown in figure 7(a), and a similar acceleration from the same initial speed but with approximately 80-percent exhaust-nozzle area is shown in figure 7(b). Comparison of figures 7(a) and (b) indicates that the smaller exhaust-nozzle area (fig. 7(b)) resulted in engine operation closer to the surge line, as evidenced by the higher compressor-discharge pressure and by the fact that surge was obtained with the same fuel input that resulted in the normal acceleration of figure 7(a). However, no characteristic frequency was found in figure 7(b), either during the steady-state operation or during the small time period of the acceleration into surge. The frequency that shows up in the filtered compressor-discharge-pressure traces of figure 7 is attributed to 60-cycle instrumentation noise.

Selection of surge-control parameter. - Engine variables were examined during surge in order to determine which variable might provide the maximum utility as a surge-control parameter. Figure 8 shows the behavior of engine variables at the inception of, and during, surge. Compressor-discharge pressure and its derivative and outer-compressor-discharge pressure and its derivative are shown in figure 8(a). Acceleration and its derivative and compressor-discharge pressure are shown in figure 8(b). It was possible to obtain the traces of compressor-discharge pressure without resorting to filtering so that the point of reversal in this pressure trace was considered as a reference with respect to surge initiation. For control purposes, however, the derivative of the compressor-discharge pressure (fig. 8(a)) was selected as the best control parameter. The value of the derivative changes sign from plus to minus at surge initiation and was therefore convenient to use in the diode circuitry of the electronic computer.

Inspection of the outer-compressor-discharge pressure trace and its derivative (fig. 8(a)) corroborates the selection of compressor-discharge pressure as the parameter indicative of surge initiation. There is a sudden build-up of outer-compressor pressure and its derivative that occurs at the same time as the drop in compressor-discharge pressure. Apparently surge is initiated in the inner compressor and the resultant break-down of air flow through the inner compressor causes a build-up of pressure at the discharge of the outer compressor. When the pressure build-up becomes great enough, the outer compressor is then apparently forced into surge. Outer-compressor-discharge pressure therefore did not drop until approximately 0.03 second after the initial drop in compressor-discharge pressure, and consequently it was not considered as a suitable surge-control parameter. The possibility of combining the effect of the decrease in compressor-discharge pressure with the increase in outer-compressor-discharge pressure was considered feasible, because the difference between the two pressures would emphasize the beginning of surge. Consequently, several control tests were made with the derivative of the difference between inner- and outer-compressor-discharge pressure taken as the surge-initiation signal.

Acceleration and its derivative are shown during surge on figure 8(b). For the particular instrumentation utilized in this investigation, speed derivatives required high-order filtering in order to reduce the noise level. As a result, the signals from acceleration and its derivaative lagged the compressor-discharge pressure and were not used as control parameters.

Surge-Control Tests

Surge-control tests were run with a control system that triggered a reduction in fuel flow when a feedback signal from the engine gave an indication of surge initiation. Except as noted, surge was induced as a result of fuel-flow inputs, and the derivative of compressor-discharge pressure was used as the signal to indicate surge. Control action was investigated for (1) variations of fuel inputs, (2) control bias (related to timing of fuel cut-back), and (3) size of fuel cut-back.

Effect of fuel input rate. - In figure 9 is shown the action of the control system and the resultant response of the engine as the control cut back the fuel flow following acceleration into surge. In figure 9(a) the acceleration was initiated by an approximate step increase in fuel flow. It can be seen that the engine accelerated normally for a short while after the fuel step and then began to surge. Surge initiation resulted in a negative value of the derivative of compressor-discharge pressure, and this negative signal (in conjunction with control bias) was used to trigger a reduction in fuel flow.

In figure 9(b) is shown a similar acceleration into surge, starting from the same initial conditions but with a 1/2-second lag on the acceleration fuel input. In both cases (figs. 9(a) and (b)) the control action, in cutting back the fuel flow, restricted surge to only 1 cycle. However, the completion of at least 1 cycle of surge could not be prevented, and a slower rate of change of the fuel input did not help the control to eliminate surge.

Effect of fuel cut-back timing. - By adding a negative voltage bias to the surge-indication signal, it was possible to obtain a negative signal to the control before the derivative of compressor-discharge

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pressure actually became negative, that is, before the pressure drop associated with surge actually occurred. It was thus possible to adjust the timing of the fuel cut-back to a slight degree and thereby permit fuel cut-backs prior to receipt of the surge indication.

Figure 9 shows that fuel cut-backs were obtained before the compressor-discharge-pressure trace gave an indication of the occurrence of surge. In spite of the anticipatory reduction of fuel flow, the engine surged through 1 cycle. Figure 10 shows an attempt to further increase the anticipatory action of the control. In figure 10(a) an acceleration into surge is limited to 1 surge cycle by the fuel-reduction action of the control. The acceleration shown in figure 10(b) is a duplication of the previous acceleration with identical initial conditions. However, the anticipatory action of the control was increased slightly in an attempt to hasten the timing of the fuel-flow cut-back. The result of this attempt was a cut-back in fuel flow that interrupted normal acceleration without the requirement of a surge-indication signal. This type of cut-back does not represent desirable control action, in that application of such action to a surge-control system would require a schedule based on the determination of optimum control bias as a function of operating conditions. It is therefore indicated that maximum allowable anticipatory control action was used in the fuel cut-back of figure 10(a) and that further anticipation would result in fuel reductions whether or not surge was about to occur.

For purposes of comparison, the surge of figure 10(a) has been superimposed on figure 10(b), and the superposition indicates less than 0.01-second difference in timing between the two fuel-flow cut-backs. It is significant that a difference of only 0.01 second in the fuel cut-back could make the difference between either no surge or a surge cycle that required about 0.2 second for completion (20 times the difference in fuel cut-back time) and yet remained uninterrupted by the fuel cut-back.

Figure 10(b) indicates that a dead time of about 0.02 second exists before the effect of the fuel-flow cut-back is noticeable in either the compressor-discharge-pressure trace or in its derivative. The dead time means that, if the compressor is approaching surge, it will continue to do so for 0.02 second after the fuel cut-back. This probably accounts for the apparent paradox of surge initiation after the fuel has been cut back, as shown in the data presented herein, and may also account for much of the data spread obtained in many fuel-flow surge-line determinations on various engines.

Effect of size of fuel-flow cut-back. - The size of the fuel-flow cut-backs were varied over an extensive range in order to determine whether a sufficiently large cut-back might succeed in preventing the completion of a surge cycle. Figure 11(a) shows an acceleration into surge with the fuel flow cut back to a value slightly greater than the initial fuel flow. The cut-back flow is 16.2 percent of the acceleration fuel flow. Figure 11(b) shows an identical acceleration from essentially identical initial conditions but with the fuel flow cut back to a value less than the initial-condition value of fuel flow. The cut-back fuel flow is 6.3 percent of the acceleration fuel flow. No significant difference in the surge cycle resulted from the change in size of the fuel-flow cut-back.

Control action for surge entry resulting from closing of exhaust-nozzle area. - It was considered possible that the failure of the control to interrupt the surge cycle might be attributable to poor fuel combustion during transients. Combustion of previously unburned fuel might therefore occur after the fuel-flow cut-back. In order to eliminate combustion transient effects, the engine was brought into surge by gradually closing the exhaust-nozzle area. Upon surge initiation, the control triggered a reduction in fuel flow as in previous attempts to eliminate surge. This transient is shown in figure 12. The initial condition was 100 percent rated speed, and the exhaust-nozzle area (trace not shown) was gradually reduced until surge occurred. The control then triggered a fuel reduction down to idle fuel flow. The surge was again limited to only 1 cycle, but the combined effect of maximum feasible fuel cut-back and elimination of combustion dynamics did not succeed in interrupting the surge cycle.

Successful surge elimination. - Out of all the control data obtained, only one condition of operation, illustrated by the sequence of accelerations in figure 13, may be construed as a successful elimination of surge that resulted from reproducible control action. Figure 13(a) shows an engine acceleration into surge with the surge control disconnected. The prolonged flat region of increased compressor pressure just prior to surge is characteristic of surge approach only at speeds below idle speed. This characteristic flat region prior to surge gives the control sufficient time to reduce the fuel flow before surge can occur. Figure 13(b) shows an acceleration with surge control that started from the same initial conditions as the acceleration shown in figure 13(a). The surge control decreased the fuel flow in time to prevent surge despite the fact that the compressor-discharge-pressure attained the same maximum value as that obtained in the acceleration into surge of figure 13(a). A dead time of about 0.02 second is discernible between the end of the fuel cut-back and the response of compressor-discharge pressure.

Figure 13(c) shows a similar acceleration with surge control, but the initial speed was 1-percent higher (based on rated speed) than the initial speed of the uncontrolled acceleration of figure 13(a). Apparently, the flat region of pressure prior to surge was not long enough,

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at the slightly higher speed, to enable the control to prevent the surge cycle.

It should be emphasized that there is a basic difference between the control action shown in figure 13 and the control action previously discussed for figure 10, where surge was also prevented. In the low-speed region (fig. 13), the prolonged flat region prior to surge provided a true indication of impending surge so that the control action was triggered by a reproducible and predictable signal. In the higher-speed run of figure 10(b), the control action was the result of an arbitrary control bias that would differ with every operating condition rather than on a signal from the engine actually indicative of surge initiation.

Other surge-control attempts. - As noted in the discussion of the selection of a surge-control parameter, the use of the derivative of the difference between inner- and outer-compressor-discharge pressures appeared to have possible utility. Several runs were made with this variable as the surge-indication parameter, and once more the most successful runs were those in which surge was limited to 1 cycle.

A series of runs was made in which the engine was surged as a result of fuel addition, but the surge-control action was modified to open the exhaust-nozzle area rather than to cut back the fuel flow. Here again it was possible to limit surge to 1 cycle, but the surge cycle could not be successfully interrupted.

DISCUSSION OF RESULTS

Factors Involved in Surge Control

The primary objective of this investigation was to determine the feasibility of an acceleration surge control that would operate as a function of an engine surge indication rather than as a function of predetermined schedules. Inasmuch as no presurge indication was apparent from preliminary tests, the control was designed to trigger a reduction in fuel flow upon receipt of an engine signal that was indicative of surge initiation. Application of this type control requires the sensing of surge initiation and the cut-back in fuel flow to occur in at least less time than the period of a surge cycle. In addition, successful control operation is based on the major premise that a surge cycle, once begun, can be interrupted without completion of the cycle.

The data presented show that the control system designed and used in this investigation was successful in limiting surge to only 1 cycle but was unsuccessful in its attempts to interrupt and prevent completion of the first surge cycle. Failure of the control to completely prevent surge could be attributable to several factors:

(1) The control system may have been too slow.

(2) Combustion during acceleration transients may have been poor, so that unburned fuel may have extended combustion beyond the point of fuel-flow cut-back.

(3) It may be physically impossible to interrupt a surge cycle and prevent its completion.

Analysis of the data indicates that the action of the control system resulted in a fuel-flow cut-back that occurred as much as 0.03 second before the indicated surge-initiation point. Even if allowance is made for the lag in measuring compressor pressures (less than 0.01 second) and for a possible dead time of 0.02 second between fuel-valve position and compressor-discharge pressure, it is obvious that the fuel cut-backs must have occurred well at the beginning of the surge cycles. It is therefore very doubtful that slowness of the control was responsible for the unsuccessful attempts at surge elimination.

In figure 12 surge was caused by a gradual reduction of exhaust-nozzle area at constant fuel flow in order to minimize any possible combustion effects that might result from rapid addition of fuel. The control limited surge to 1 cycle in the same manner as if surge had been the result of a fuel addition. It is therefore indicated that unsuccessful attempts to completely prevent surge were not attributable to combustion dynamics.

Elimination of control response and combustion dynamics as factors that might have been responsible for unsuccessful elimination of surge leaves the premise that surge, at least in this engine, is fundamentally irreversible. Irreversibility, in this case, means that, after a surge cycle has begun, it cannot be interrupted until the cycle has been completed. In corroboration of the conclusion that a surge cycle is irreversible, it is pointed out that a complete surge cycle always resulted from a sufficiently large fuel pulse (fig. 5), that periodic fuel pulses did not affect either compressor-discharge pressure during surge or the surge frequency (fig. 6), and, finally, that surge recovery always came from the same direction and in the same manner.

Surge Elimination at Low Engine Speed

The control action of figure 13 was successful in preventing surge, but the engine operating condition represented a special case. At engine speeds below idle speed, the compressor-discharge pressure flattens out for a prolonged period (possibly 0.05 sec) before it reverses sharply in the characteristic manifestation of surge initiation. Because of the prolonged flat region, it was possible for the control to cut back fuel flow and prevent surge even after the compressor-discharge pressure had approximately reached its maximum value at the beginning of the flat region. Unfortunately, the flat region of compressor-discharge pressure is not characteristic of turbojet engines in their operating ranges, and successful control operation in the flat region is, therefore, a matter only of academic interest.

Appraisal of Control

If the premise is accepted that a surge cycle cannot be interrupted, then the optimum action of the control would be to limit surge to a single cycle. In this respect the control action was successful.

On many engines a single cycle of surge might be acceptable, particularly because acceleration surge control is usually required in the region below cruise speed where 1 surge cycle may not be very damaging (above cruise speed, engines are usually temperature limited before the surge point is reached). It would appear feasible to couple the surge control investigated with an adjustable schedule, so that occurrence of surge would be limited to 1 cycle and the schedule would simultaneously be reset to a new lower value.

SUMMARY OF RESULTS

An investigation was made of a surge-control system that triggered a reduction in fuel flow upon receipt of a signal from the engine that was indicative of surge initiation. The derivative of compressor-discharge pressure was selected as a surge-control signal from a survey of engine parameters. It was found that the control system could successfully limit surge to only 1 cycle; however, a minimum of 1 surge cycle could not be avoided. Variations in fuel cut-back timing, size of fuel cut-back, and method of surge entry (whether from a fuel step, fuel ramp, or exhaust-nozzle-area change) did not improve the control action beyond its ability to limit surge to a single cycle.

The inability of the control to successfully interrupt and thereby prevent completion of a surge cycle leads to the conclusion that, at least in the engine investigated, a surge cycle is fundamentally irreversible.

At speeds below idle speed, a prolonged flat region of compressor-discharge pressure existed, prior to the pressure reversal, that is characteristic of surge initiation only at these low speeds. This prolonged flat region permitted the control sufficient time to reduce the fuel flow before surge occurred. Completely successful prevention of surge was therefore obtained at speeds below idle, in contrast with the limitations of the control in the normal operating range.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 12, 1955

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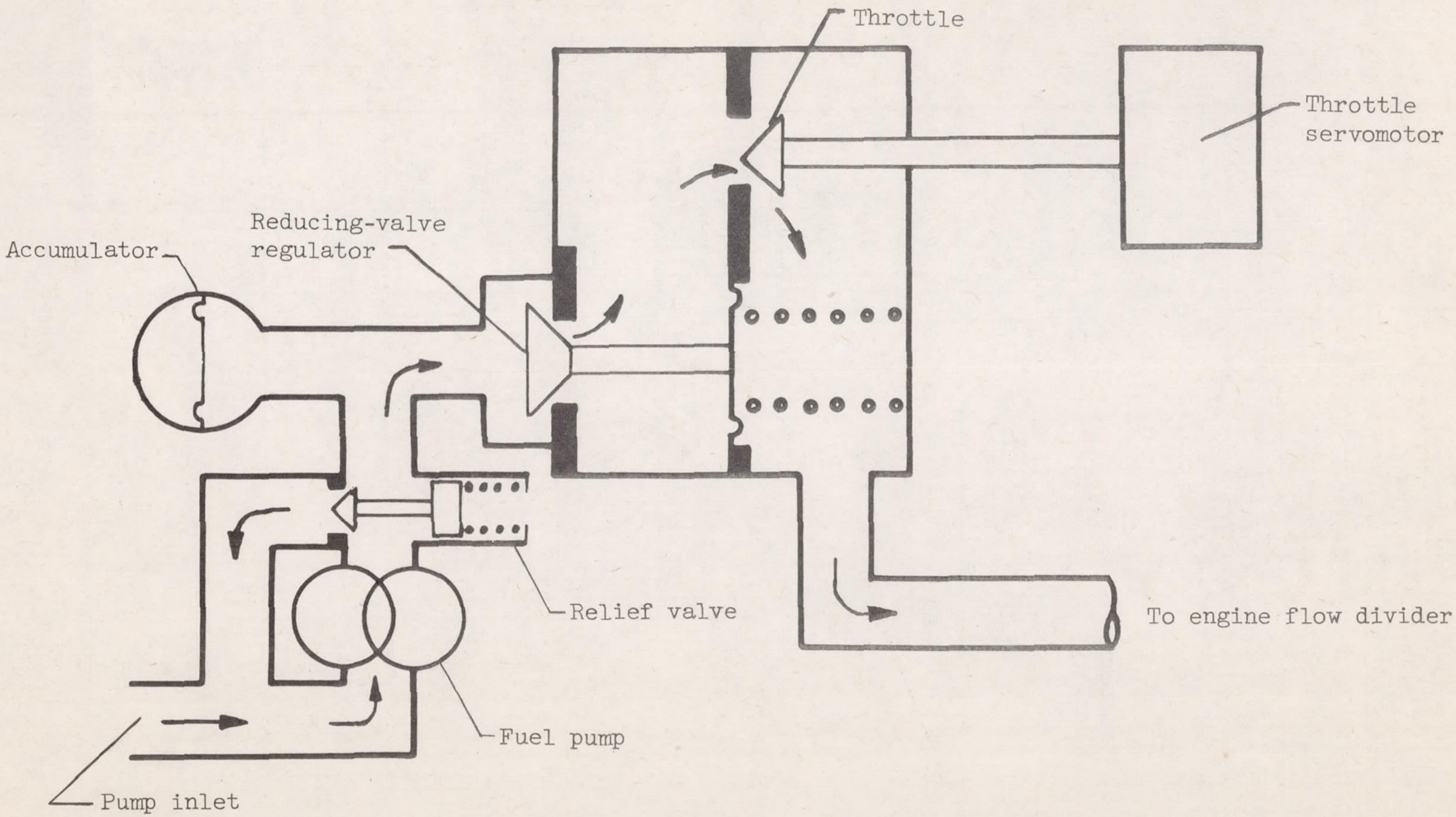

Figure 1. - Research-facility fuel valve.

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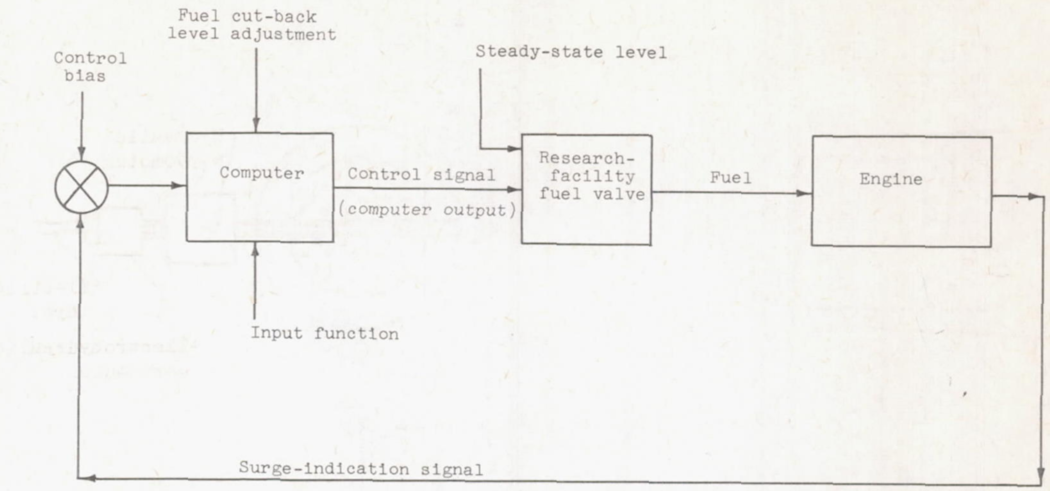
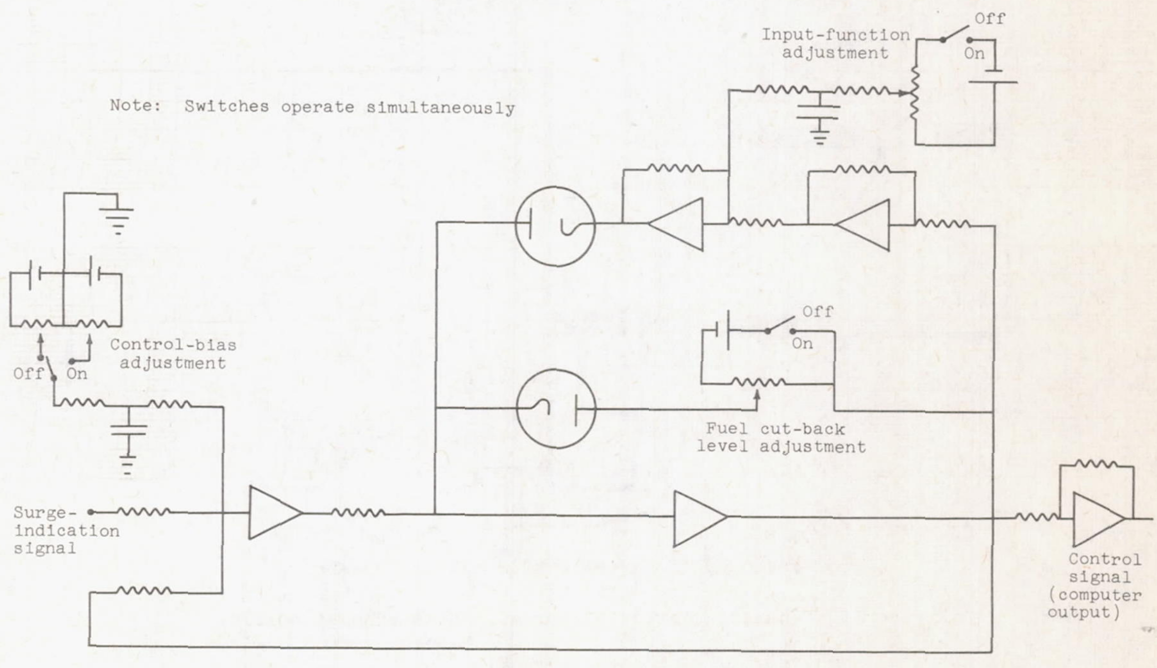


(a) Block diagram of surge control.



(b) Computer circuitry.

Figure 2. - Schematic diagram of surge control.

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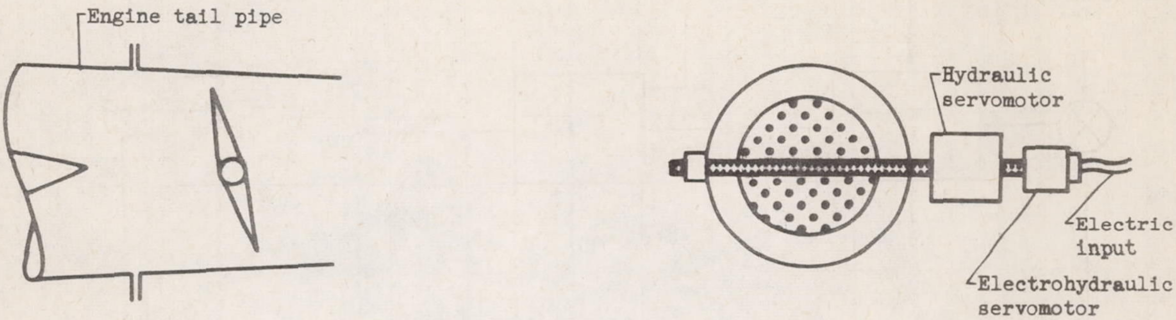
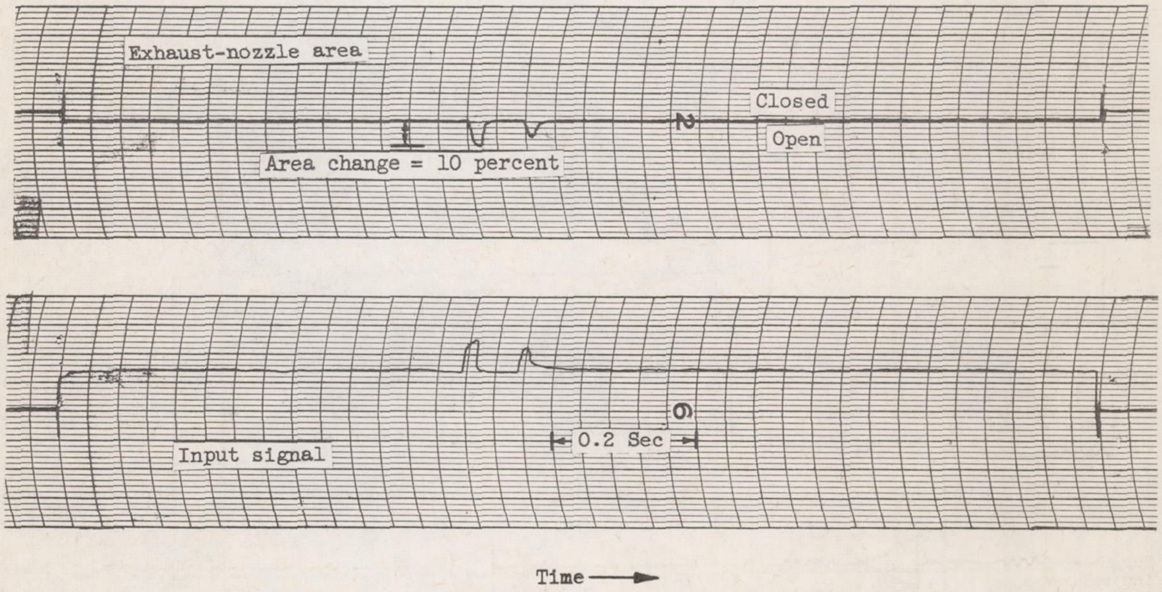


(a) Schematic of variable-area exhaust nozzle.



(b) Response of variable-area exhaust nozzle.

Figure 3. - Characteristics of variable-area exhaust nozzle.

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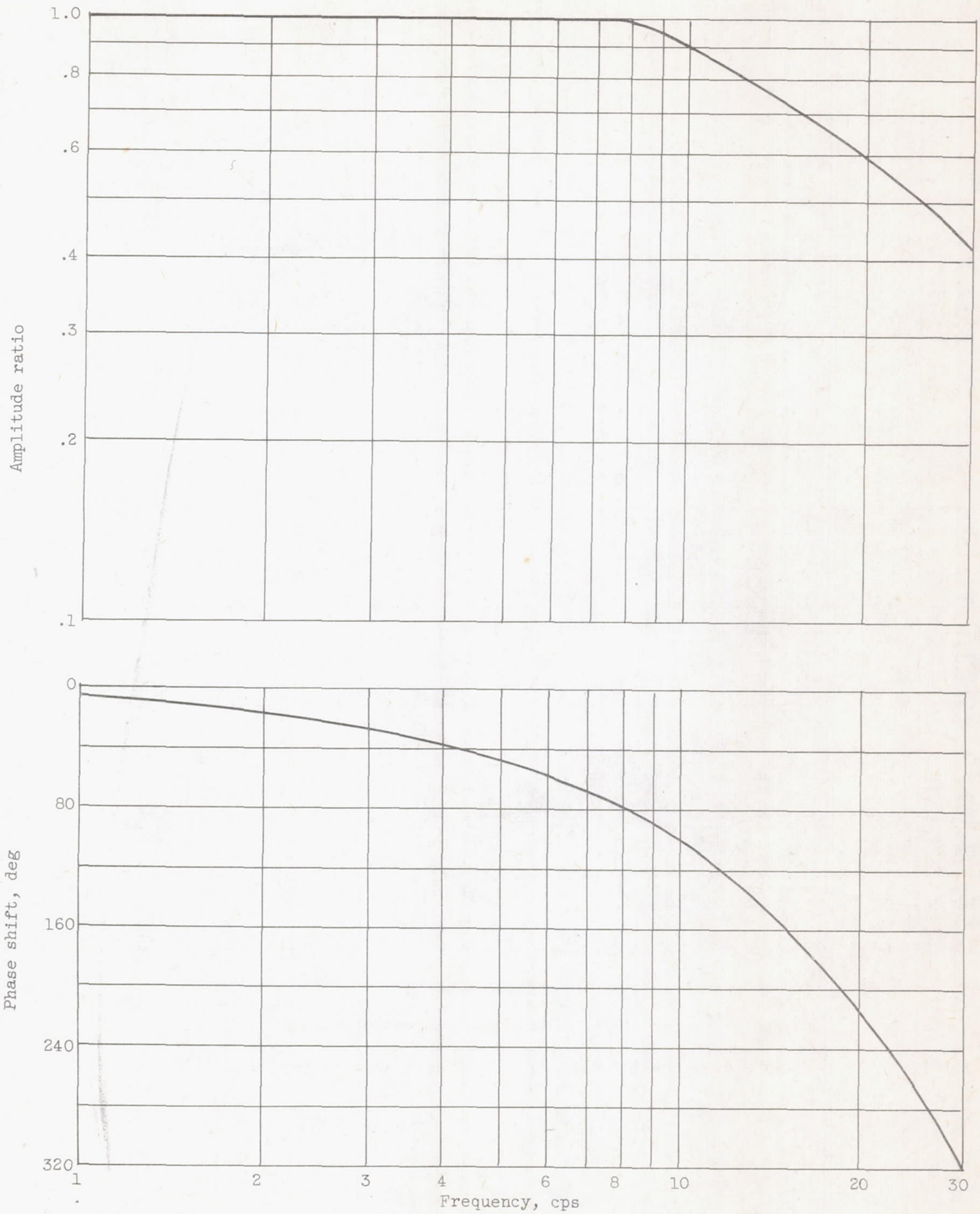

Figure 4. - Characteristics of filter used for acceleration signal.

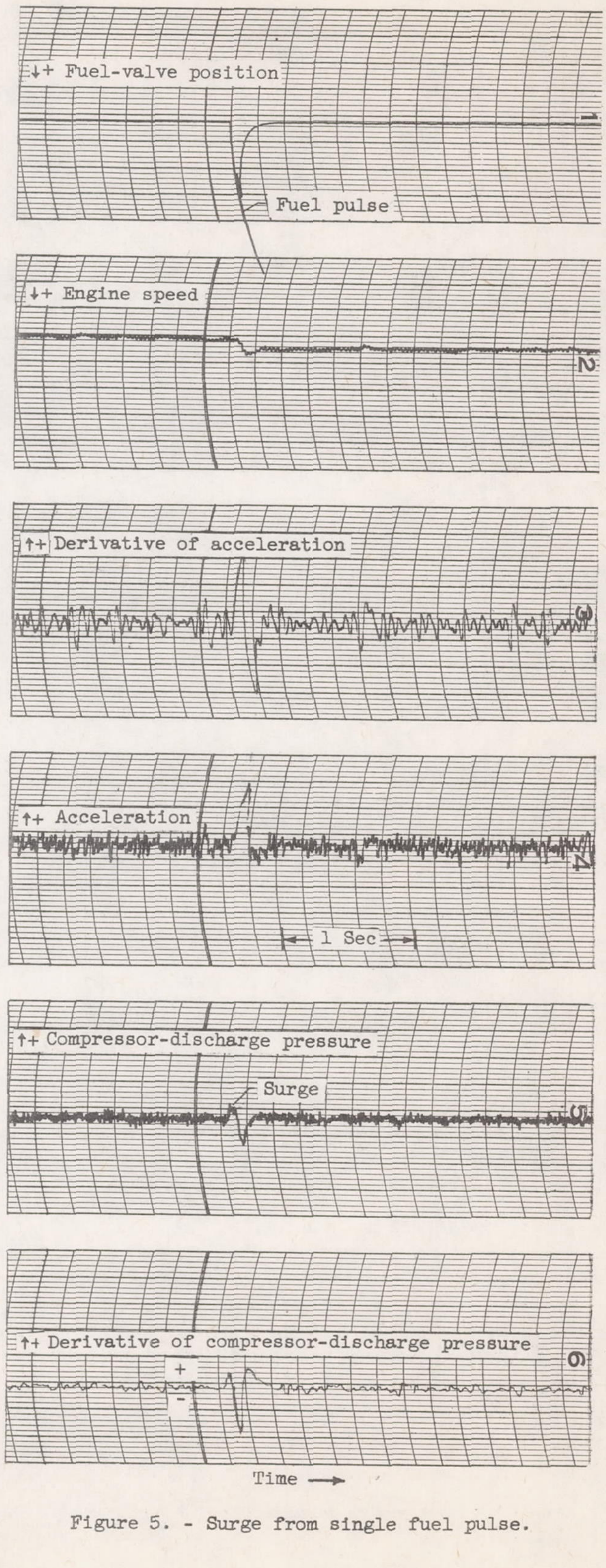

Figure 5. - Surge from single fuel pulse.

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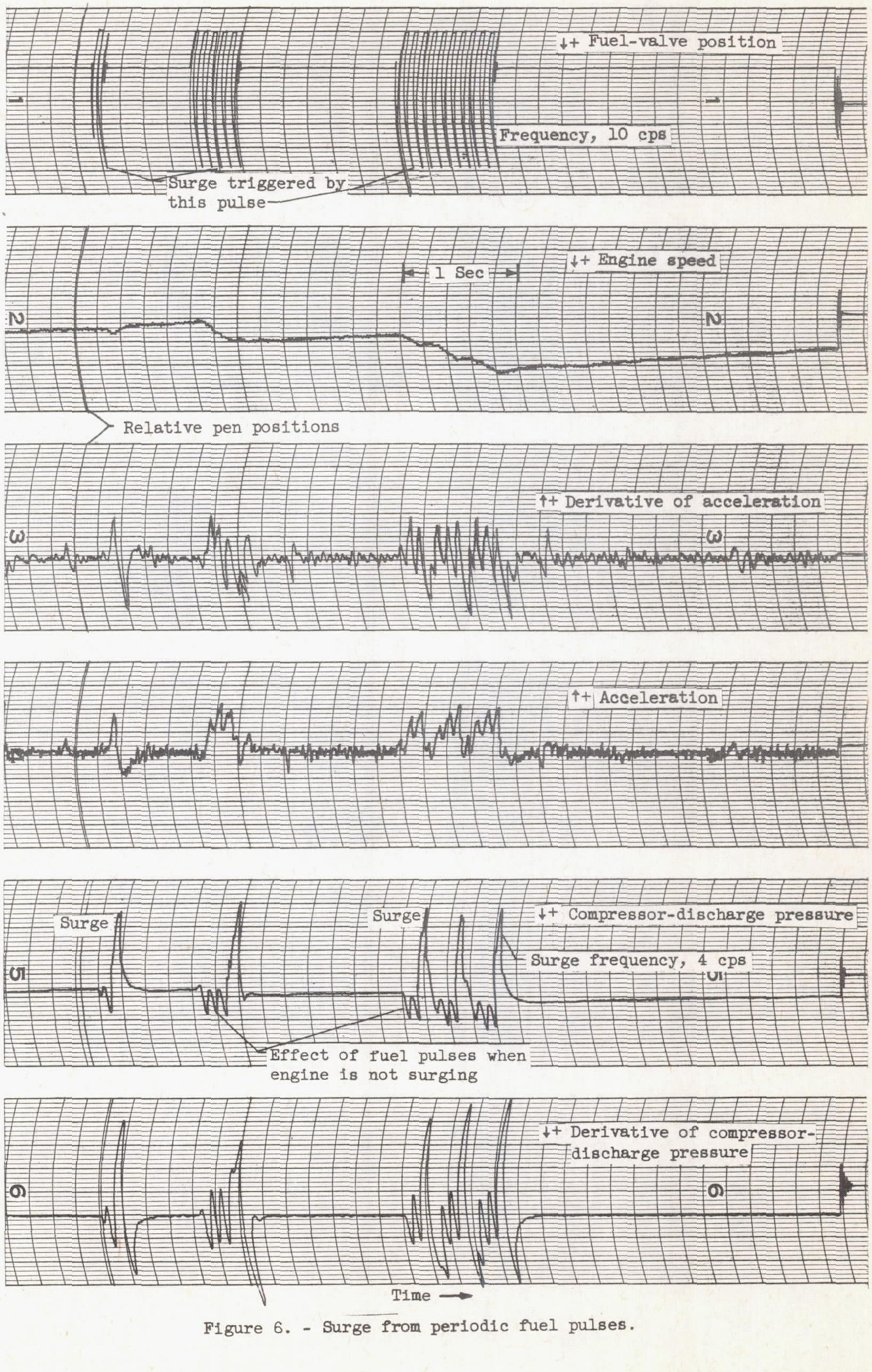

Figure 6. - Surge from periodic fuel pulses.

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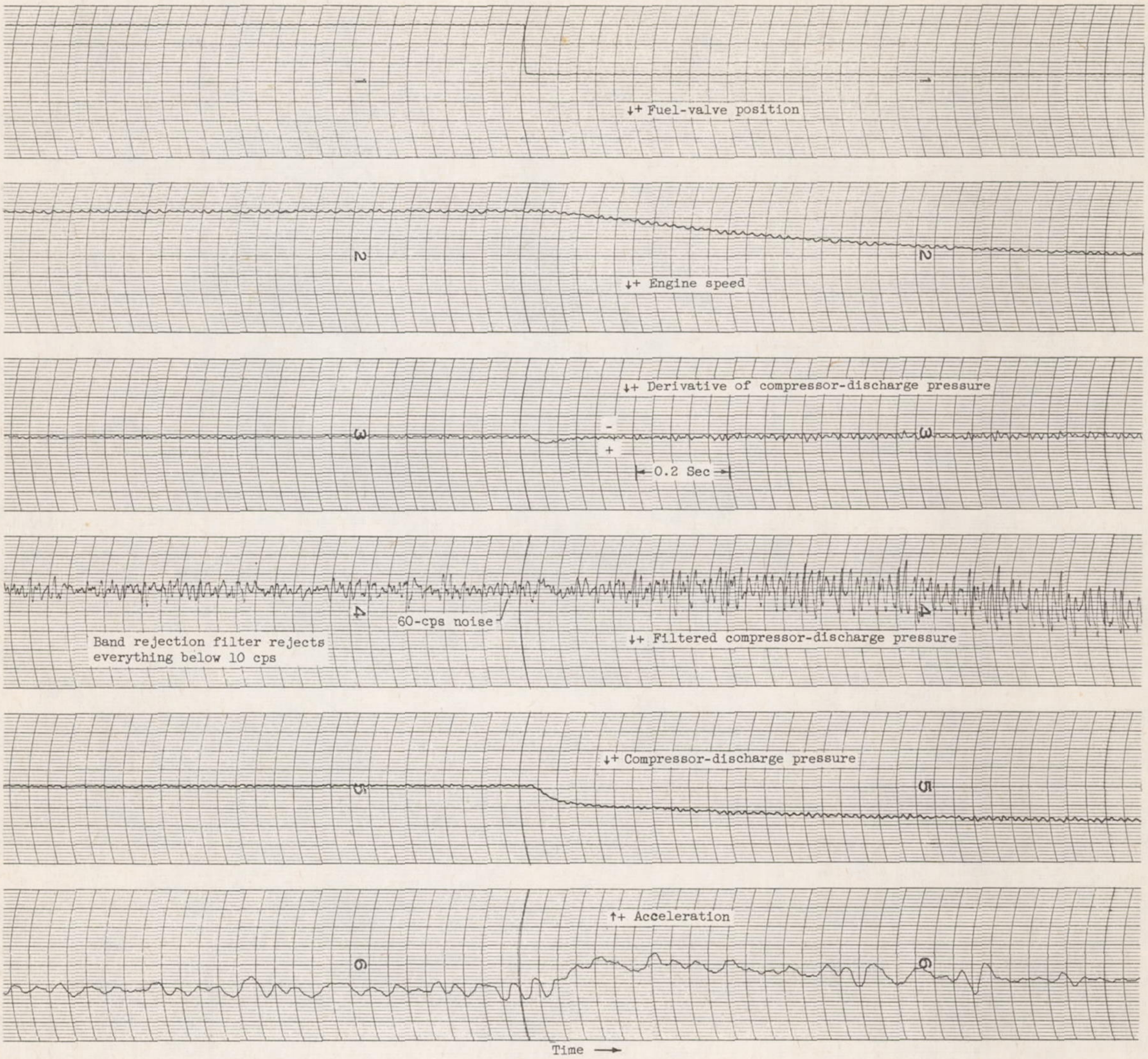

(a) Acceleration with 100-percent exhaust-nozzle area.

Figure 7. - Survey of compressor-discharge-pressure frequencies.

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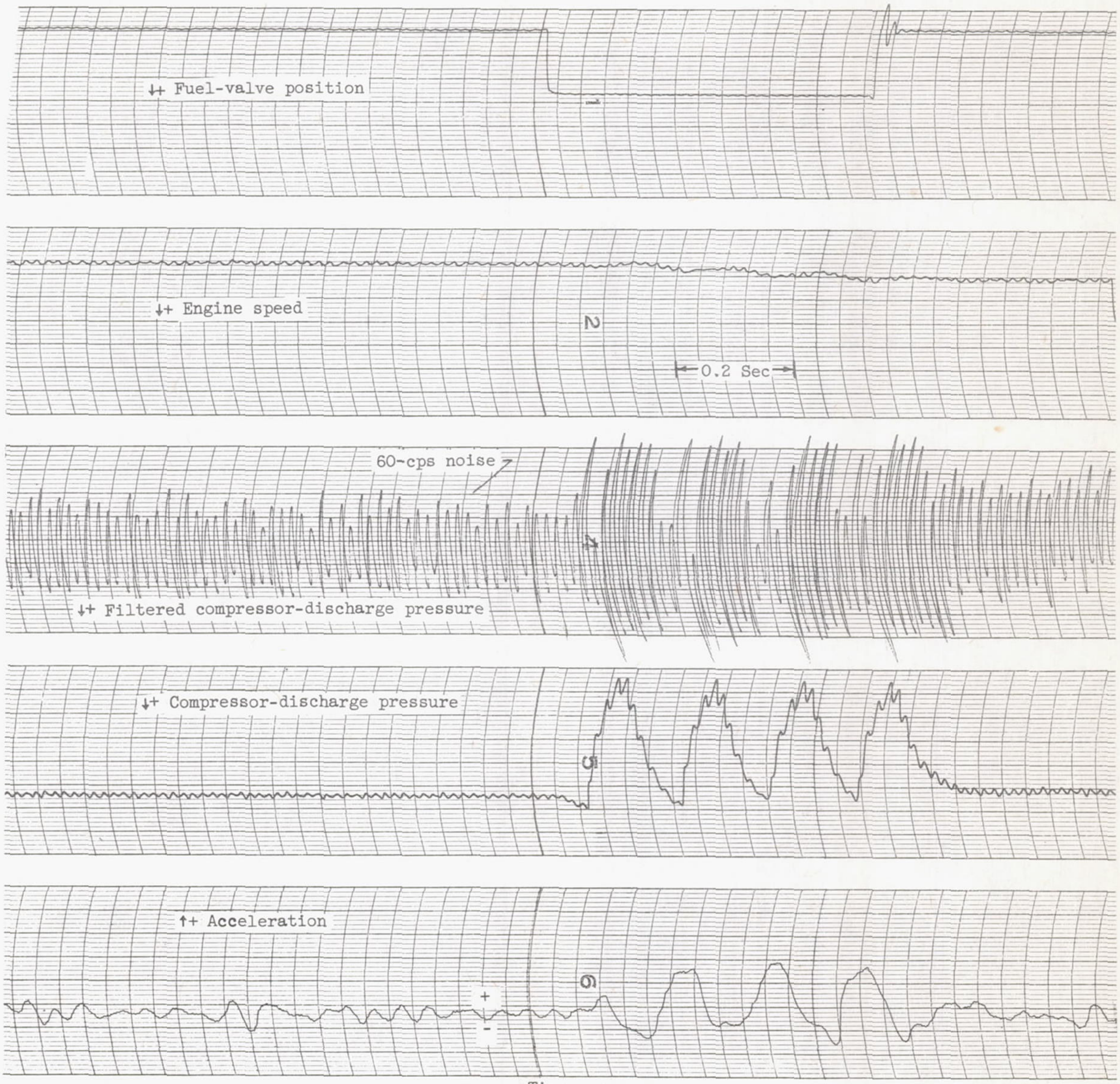

(b) Acceleration with 80-percent exhaust-nozzle area.

Figure 7. - Concluded. Survey of compressor-discharge-pressure frequencies.

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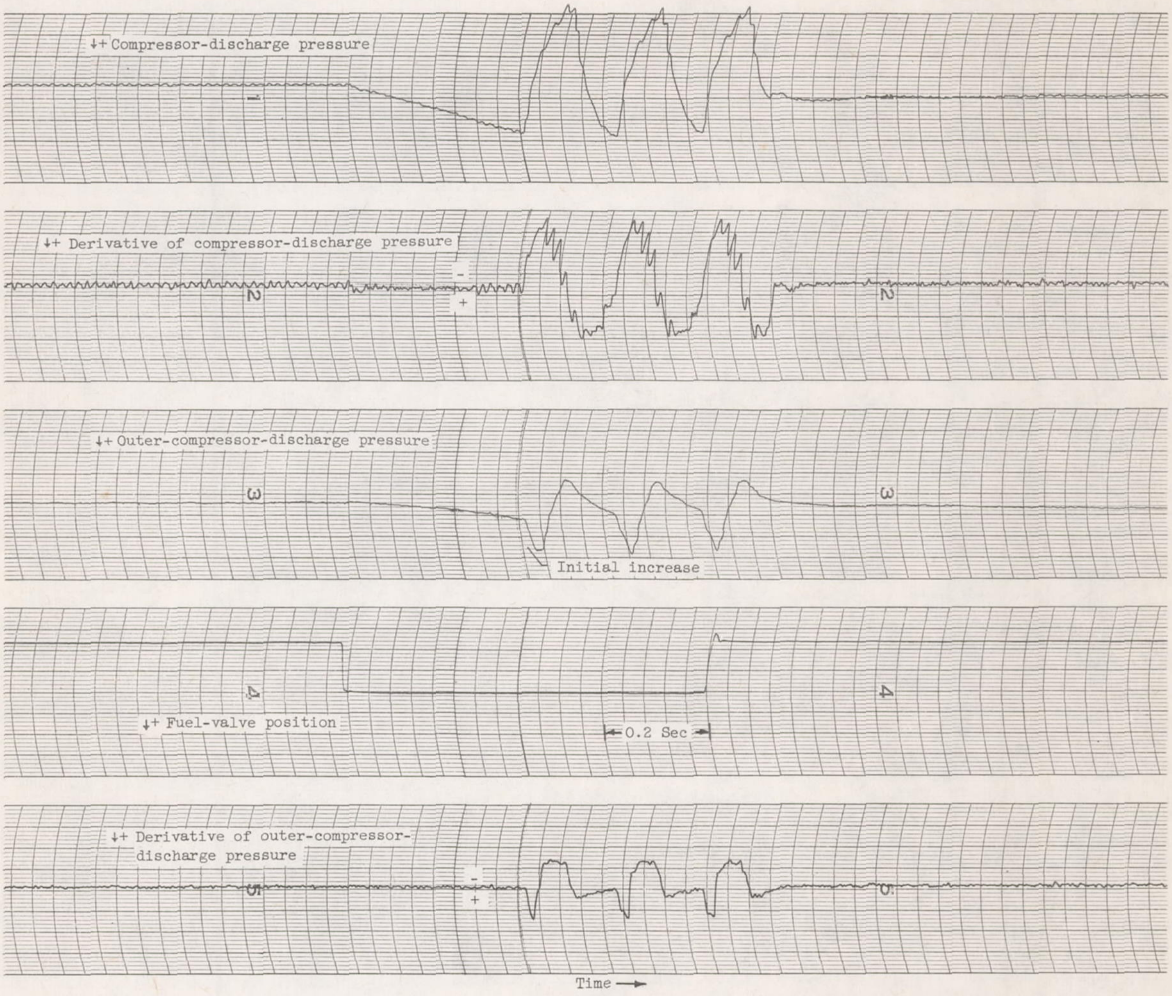

(a) Compressor-discharge pressure and its derivative and outer-compressor-discharge pressure and its derivative.

Figure 8. - Investigation of possible surge-control parameters.

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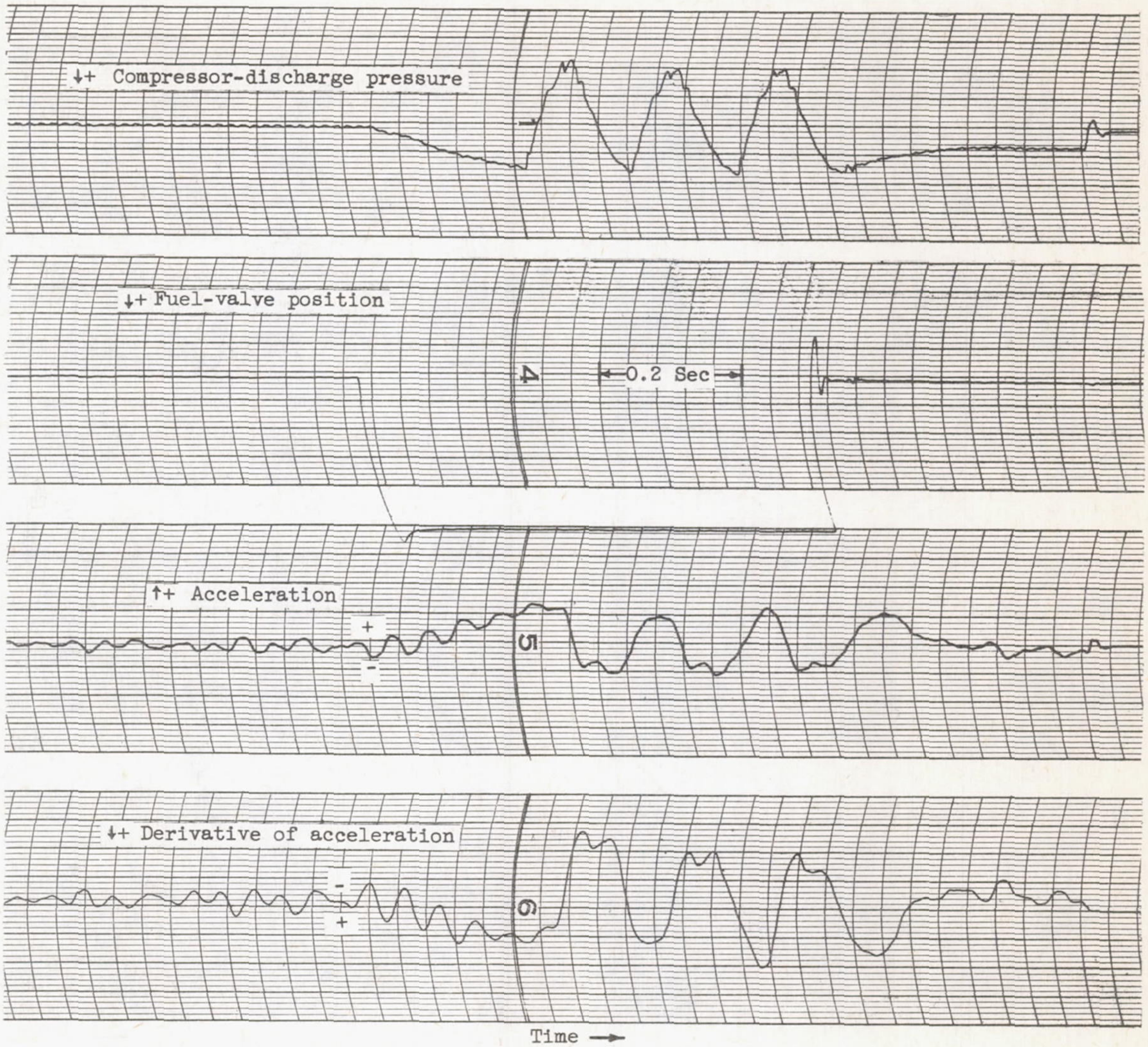

(b) Acceleration and its derivative.

Figure 8. - Concluded. Investigation of possible surge-control parameters.

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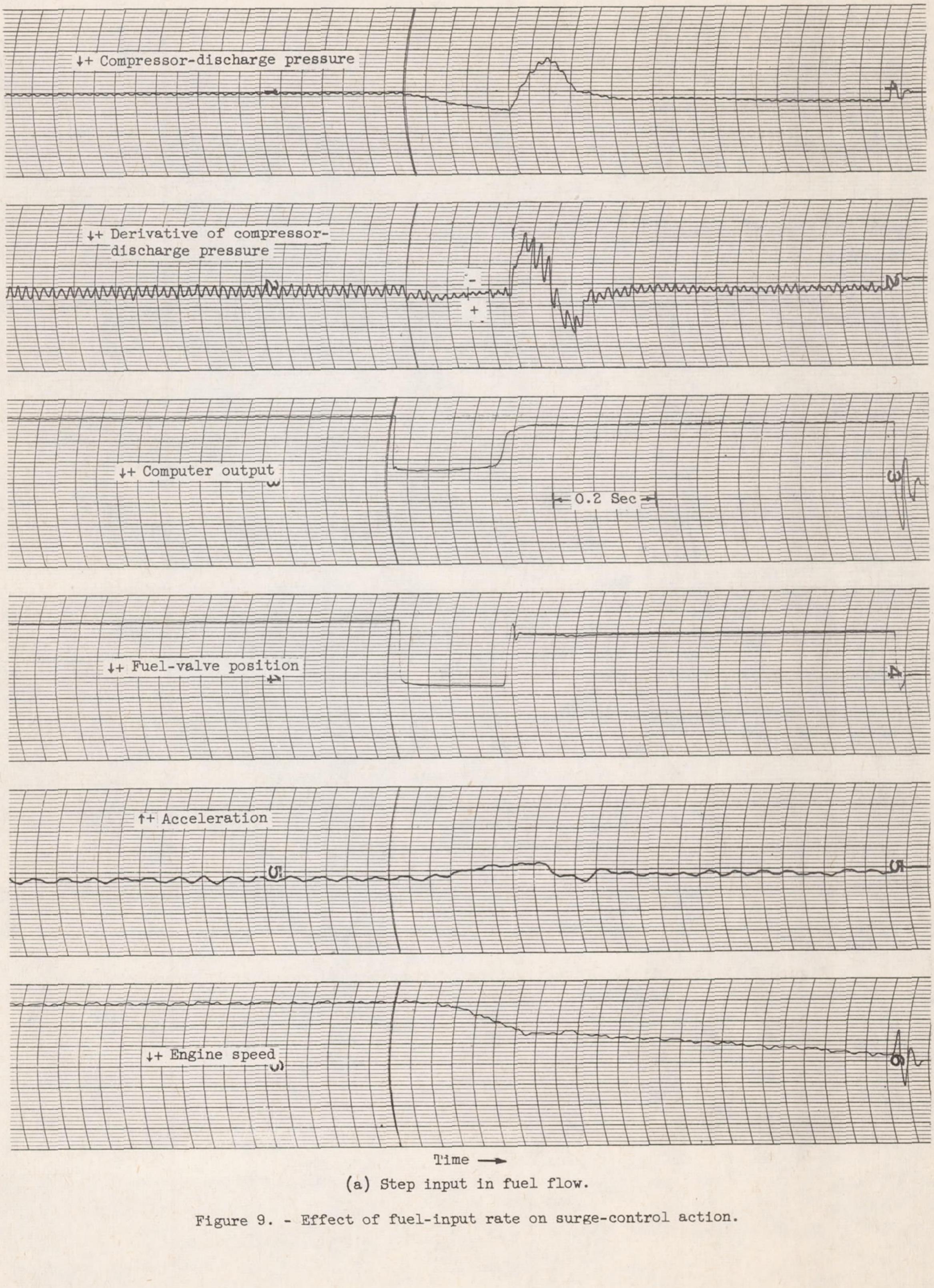

(a) Step input in fuel flow.

Figure 9. - Effect of fuel-input rate on surge-control action.

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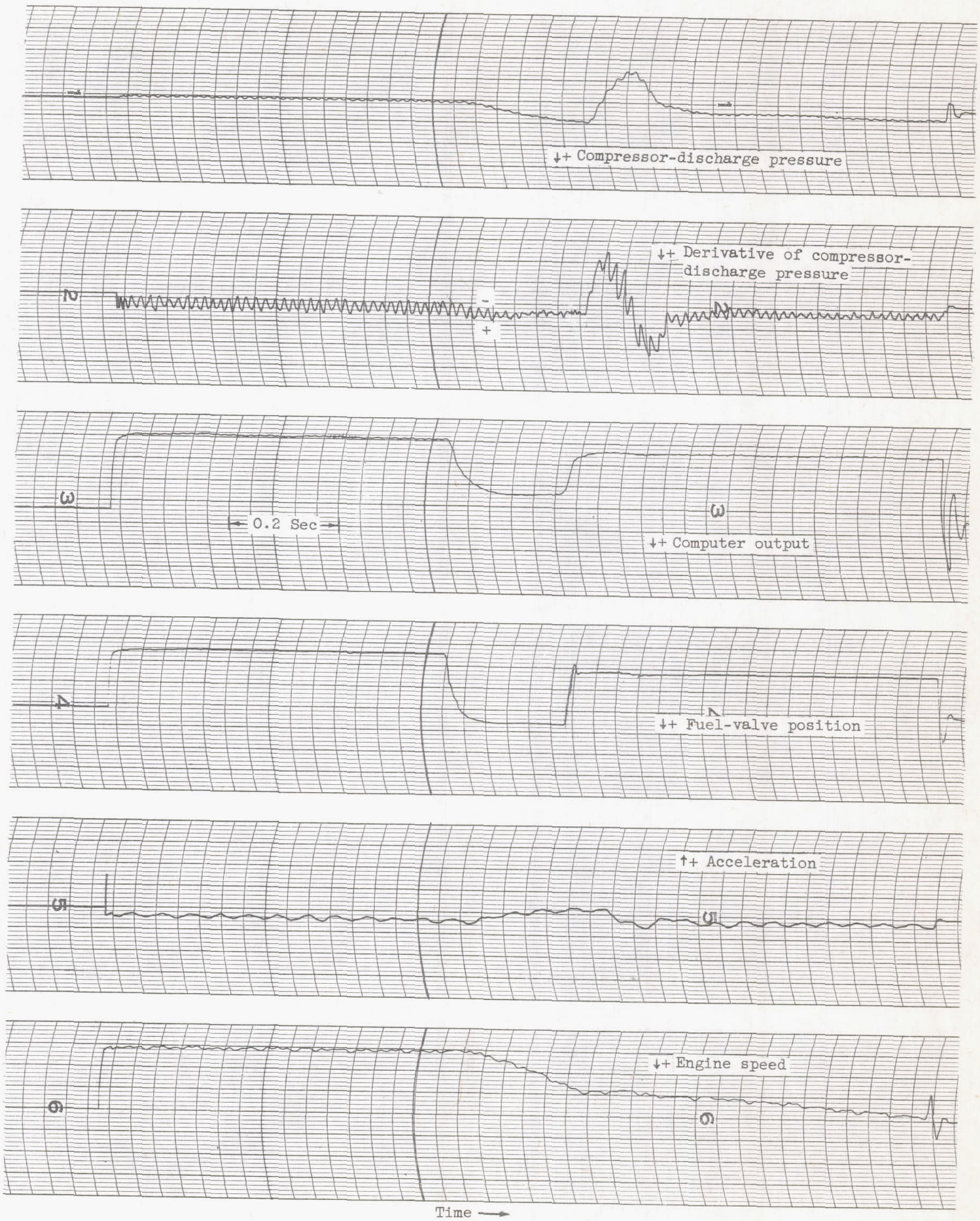

(b) Ramp input in fuel flow.

Figure 9. - Concluded. Effect of fuel-input rate on surge-control action.

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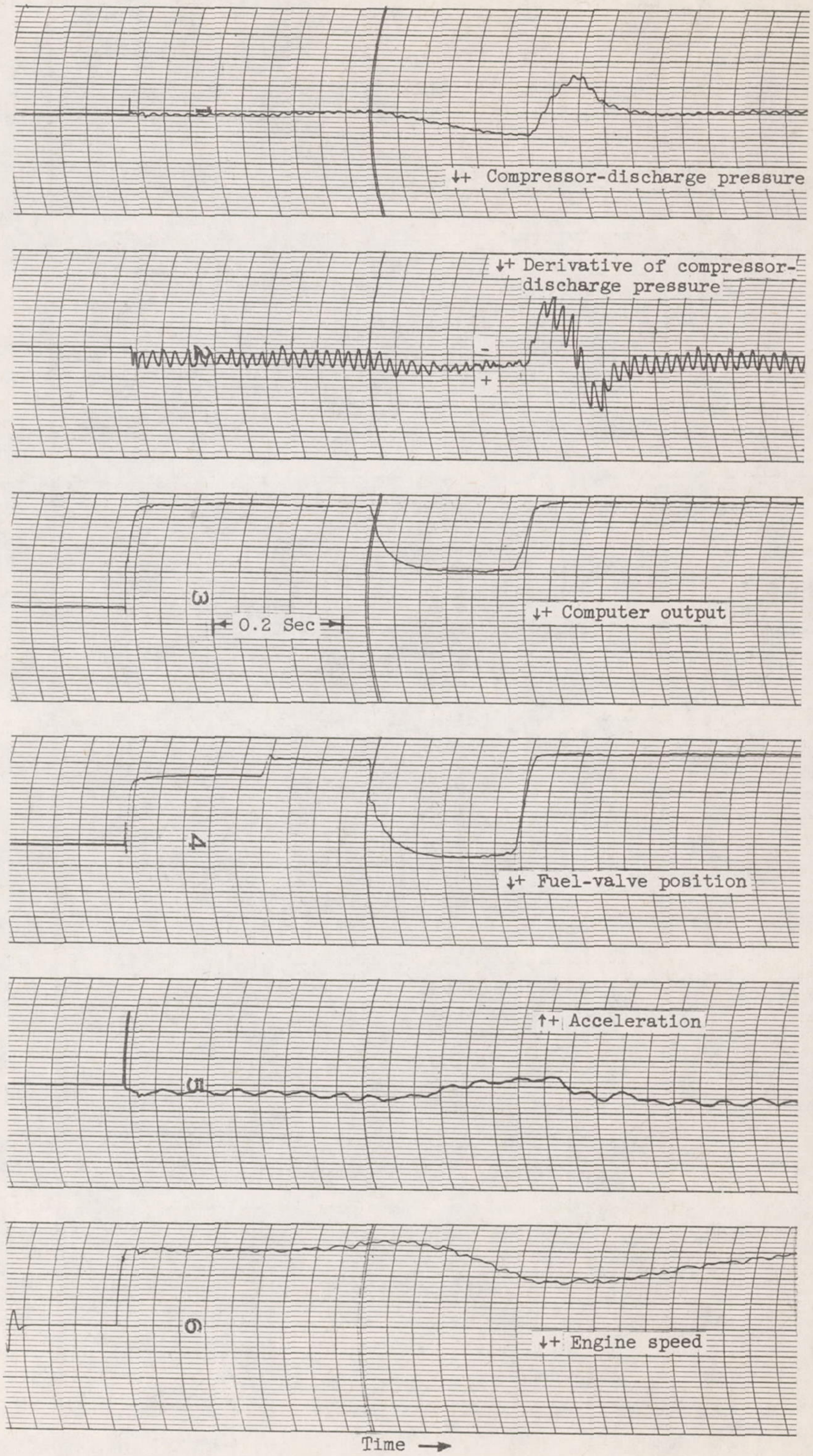

(a) Fuel cut-back with surge.

Figure 10. - Effect of fuel cut-back timing on surge-control action.

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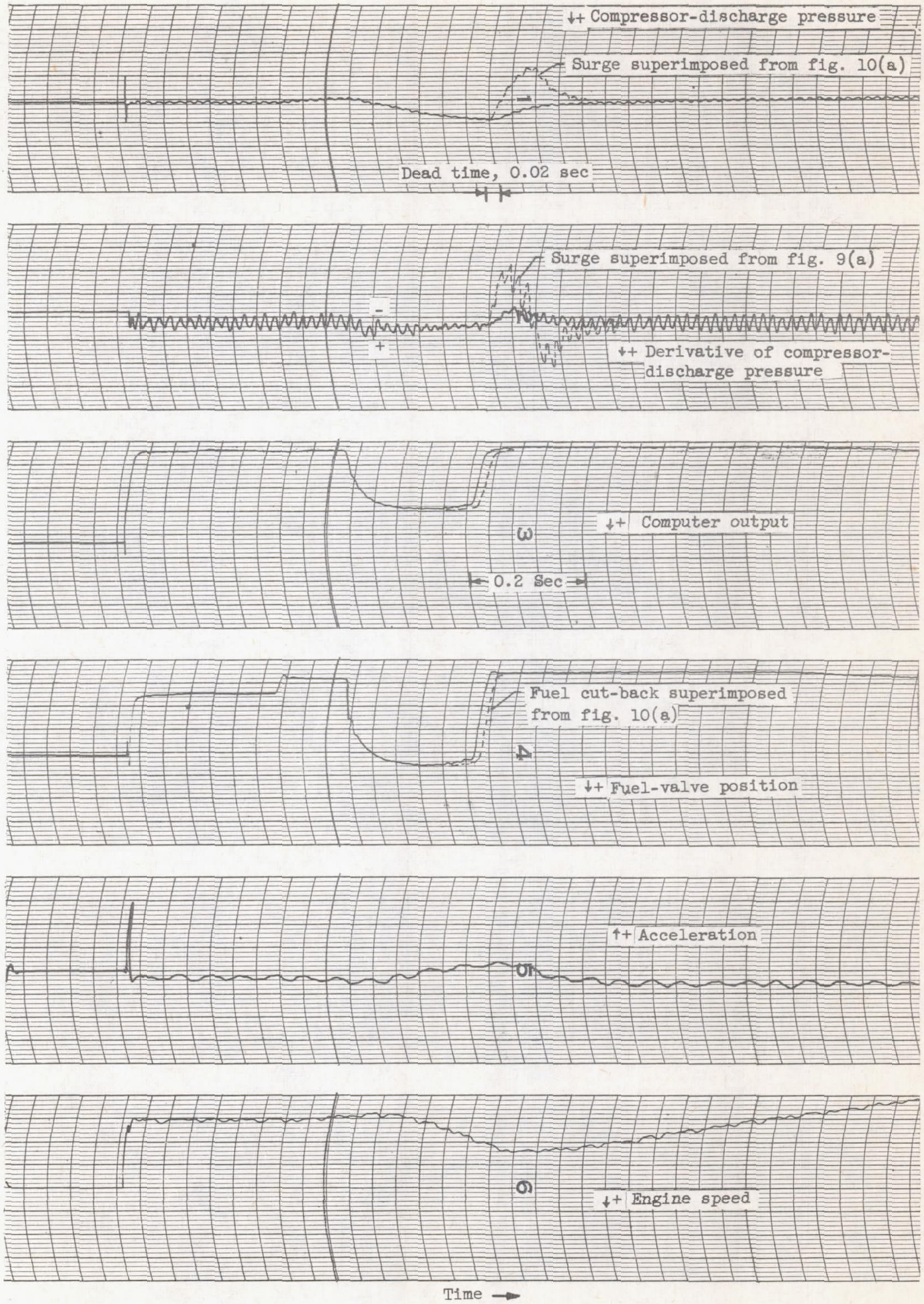

(b) Fuel cut-back without surge.

Figure 10. - Concluded. Effect of fuel cut-back timing on surge-control action.

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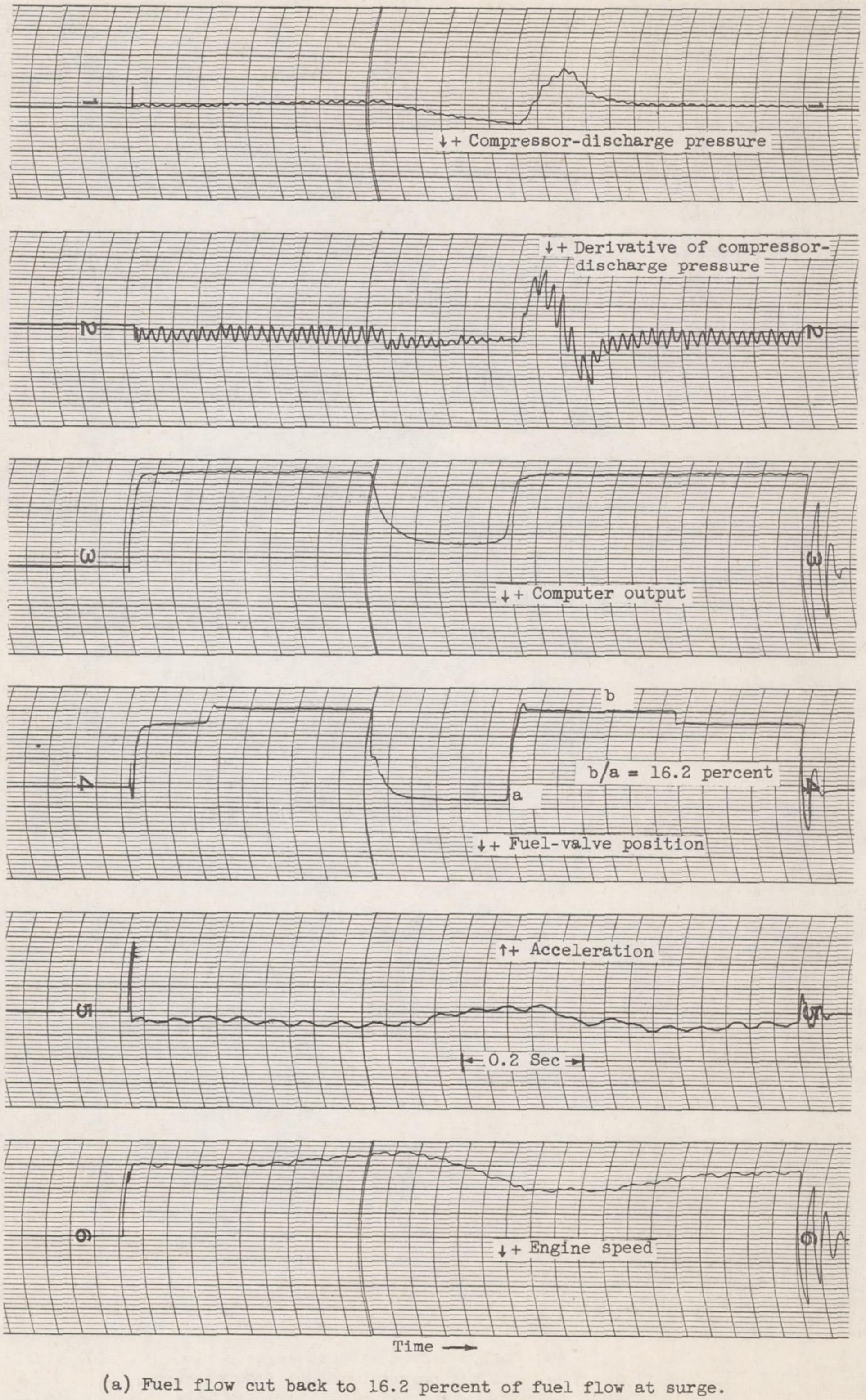
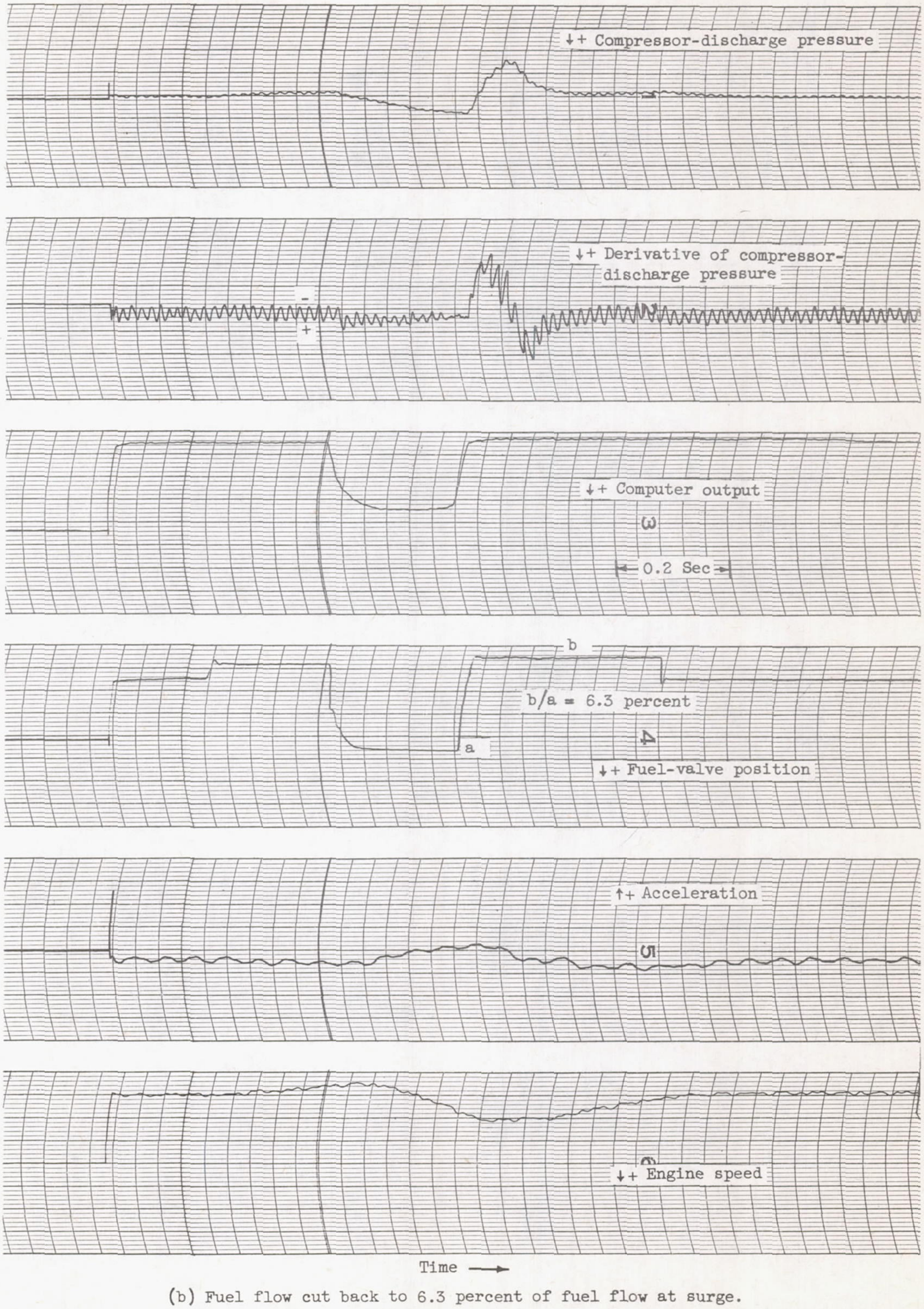
CB-4 back



(a) Fuel flow cut back to 16.2 percent of fuel flow at surge.

Figure 11. - Effect of size of fuel-flow cut-backs on surge-control action.



(b) Fuel flow cut back to 6.3 percent of fuel flow at surge.

Figure 11. - Concluded. Effect of size of fuel-flow cut-backs on surge-control action.

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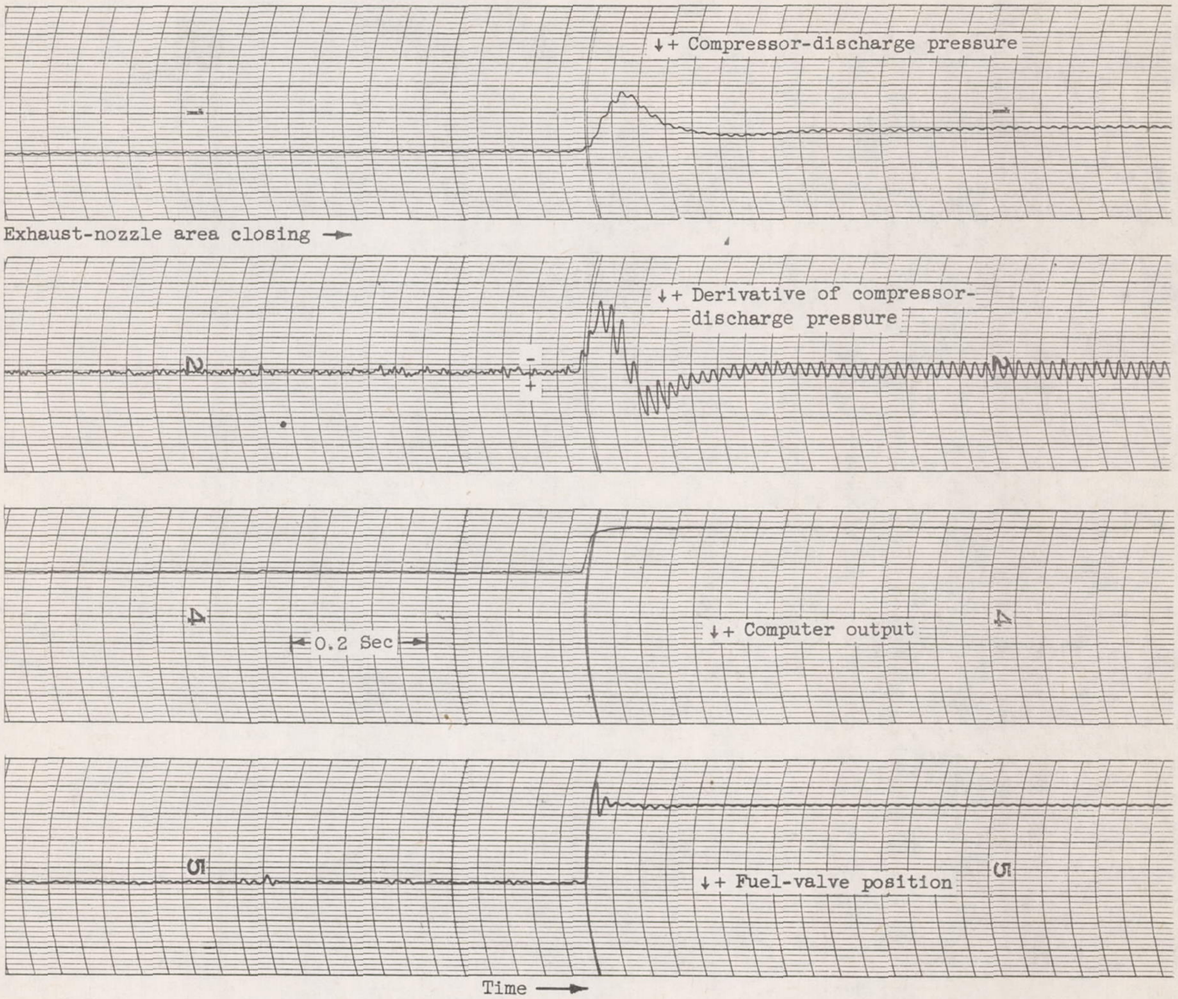
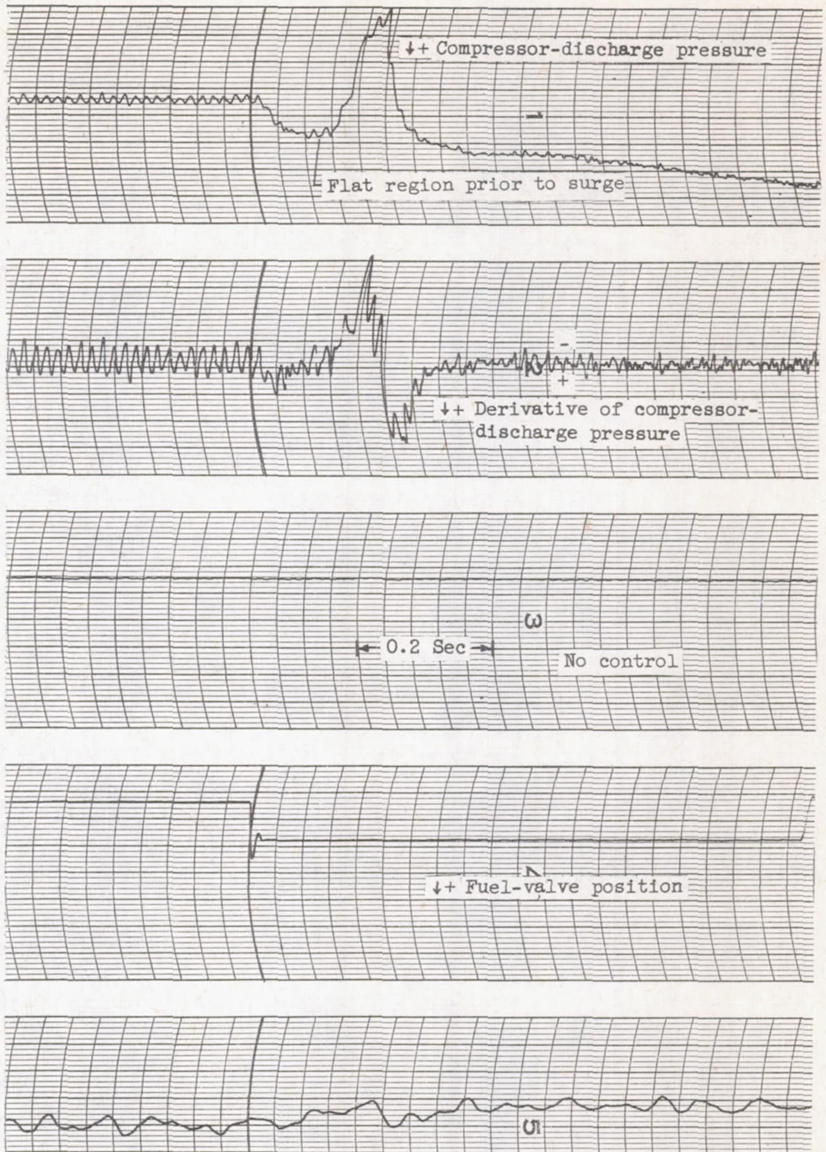


Figure 12. - Surge-control action following surge initiated by closing exhaust-nozzle area.



(a) Surge cycle without control action.

Figure 13. - Surge-control action at speed below idle.

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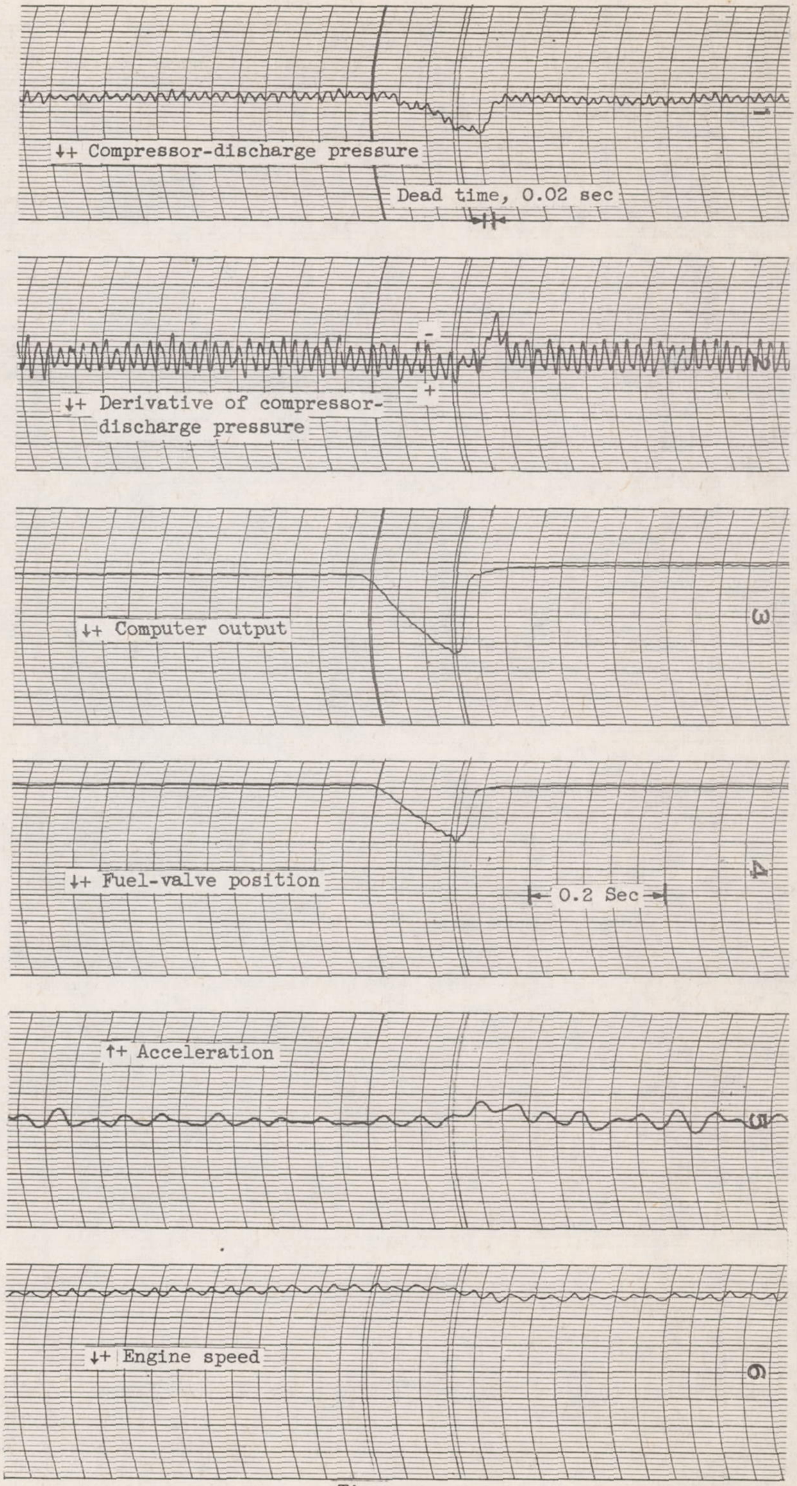

(b) Control action with surge prevention.

Figure 13. - Continued. Surge-control action at speed below idle.

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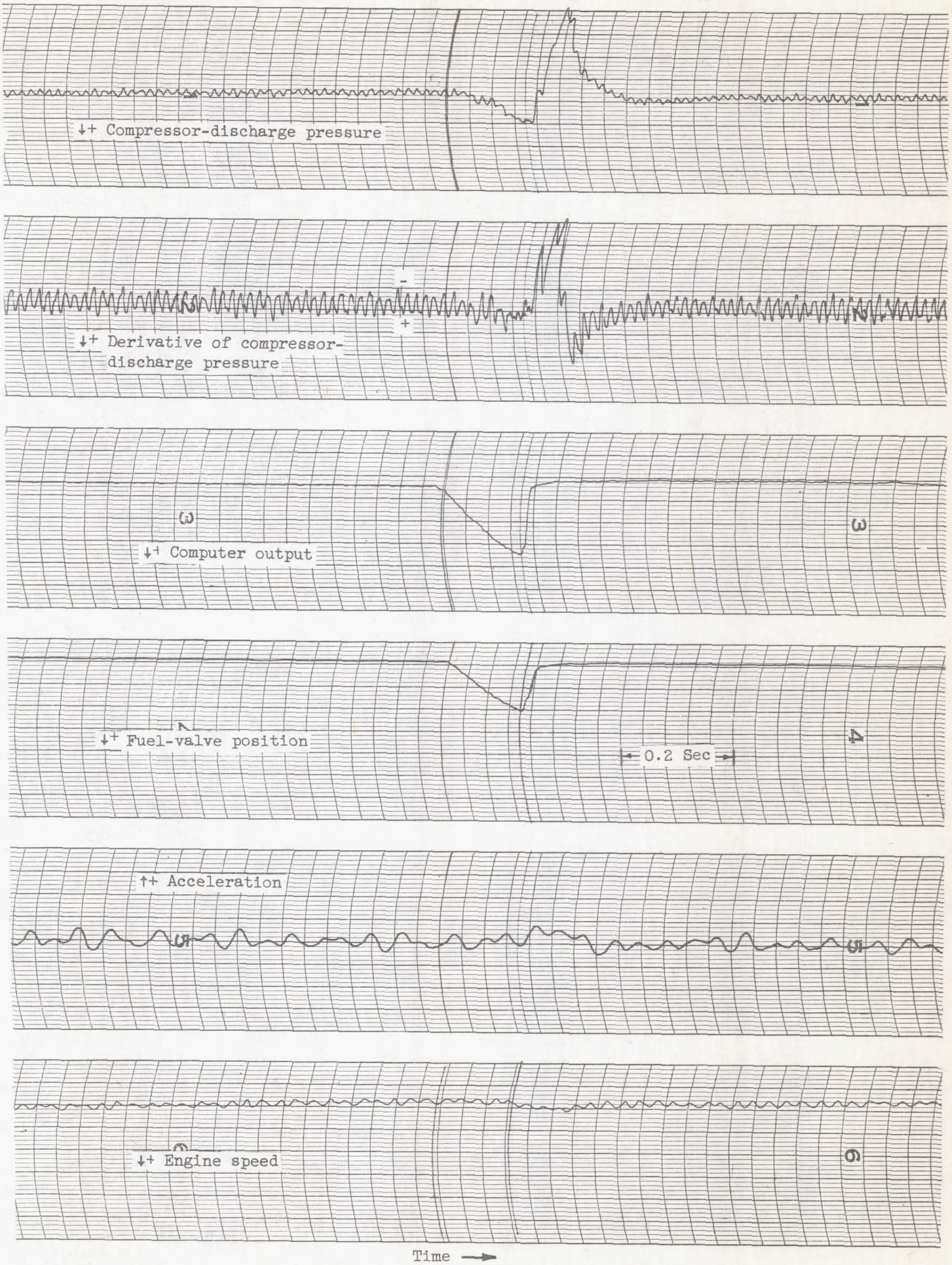

(c) Control action at engine speed 1 percent higher than in figure 12(b).

Figure 13. - Concluded. Surge-control action at speed below idle.