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RESEARCH MEMORANDUM

A PROPOSED RAM-JET CONTROL SYSTEM OPERATED BY USE
OF DIFFUSER PRESSURE RECOVERY

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RESEARCH MEMORANDUM

A PROPOSED RAM-JET CONTROL SYSTEM OPERATED BY USE OF DIFFUSER PRESSURE RECOVERY

By Maxime A. Faget

SUMMARY

A ram-jet fuel-control system which effects direct control of the thrust coefficient by maintaining a desired ratio between the measured total pressure and the diffuser exit pressure is described. This system provides for control of the thrust coefficient so that there is no effect from variations in free-stream temperature and pressure and very little effect from variations of the free-stream Mach number. A method for scheduling the thrust coefficient for any desired variation with Mach number is also described. The use of zero-differential pressure switches to obtain the thrust control and Mach number control provides for a system which may be made highly sensitive. A control system using this type of sensing element will have a natural tendency to hunt. The degree of hunting may be made negligible, however, by proper design of the fuel-rate valve.

INTRODUCTION

The primary function of a ram-jet fuel regulator is to supply fuel to the engine at the proper rate so that the engine will produce the desired amount of thrust. In addition, the rich and lean fuel-air ratio (F/A) limits should not be exceeded, nor should the ram jet be operated in the region of diffuser "buzz." General practice has been to accomplish the regulation of fuel rate by some type of F/A meters; however, metering of F/A has many disadvantages. This is because the thrust of the engine is not a unique function of F/A. In fact, for a given F/A the thrust will vary with free-stream temperature, pressure, and Mach number, and combustion efficiency (which varies with temperature and pressure in the combustion chamber). Thus it becomes apparent that, unless adequate compensations for these effects are used, an F/A device will have a limited range of usefullness.

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Since the pressure recovery of the diffuser is closely related to the thrust coefficient, control of the diffuser-exit total pressure has been used in several types of fuel regulators recently introduced. Reference 1 describes a fuel regulator wherein maximum thrust coefficient is obtained by controlling the fuel rate to keep the diffuser-exit pressure at a maximum value. This is accomplished by imposing perturbations in the fuel rate and determining the phase relation of the responding pressure changes in the combustion chamber. This arrangement will provide for maximum power from the engine over a wide range of free-stream conditions, being limited only by the rich limit of the combustor in the upper Mach number range. This type of thrust control would be ideally suited for ram-jet-powered interceptor missiles or ram-jet boosters.

This paper describes some ideas for a system which will regulate the fuel rate in response to a proportion setup between the diffuser-exit pressure and the measured total pressure. This results in a thrust-control system in which there is no variation in thrust coefficient produced by variations in free-stream temperature and pressure and very little variation in thrust coefficient with Mach number. Any desired scheduling of thrust coefficient with Mach number may be accomplished with this system, making it adaptable for use in either an interceptor or long-range type of missile.

SYMBOLS

C_D drag coefficient, based on ram-jet combustion-chamber area

C_T thrust coefficient, based on ram-jet combustion-chamber area

F/A fuel-air ratio, weight rate of fuel flow to weight rate of air flow

H total pressure, pounds per square foot absolute

M Mach number

P static pressure, pounds per square foot absolute

Subscripts:

0	free stream
1	diffuser exit
c	surface of cone in the free stream
n	behind a normal shock in the free stream
x	downstream of first orifice of thrust-control pressure divider
y	downstream of first orifice of Mach number control pressure divider

TYPICAL RAM-JET ENGINE

In describing the functions of the regulator presented herein the computed performance of a typical ram-jet engine is used. This ram-jet performance is shown in figure 1 as a plot of thrust coefficient against Mach number. Shown on the plot are lines of constant pressure recovery and constant F/A. Included also is the curve of maximum diffuser recovery. Since the performance chart shown is computed for supercritical mass-flow conditions throughout, the region above the curve of maximum diffuser recovery is hypothetical. The conditions assumed in making the performance computations are as follows. A Ferri type of inlet with a 22° semiangle cone was used. The cowl lips were positioned so that the conical shock brushed the lip leading edge at the design Mach number of 2.25. The free-stream area of entering air for supercritical flow conditions was 50 percent of the combustion-chamber area. The exit-nozzle minimum area was 85 percent of the combustion-chamber area. A combustion efficiency of 90 percent and a burner pressure loss equal to twice the entering velocity head was assumed. The maximum diffuser recovery assumed for the computation was typical for a Ferri inlet and is shown in figure 2 plotted against Mach number.

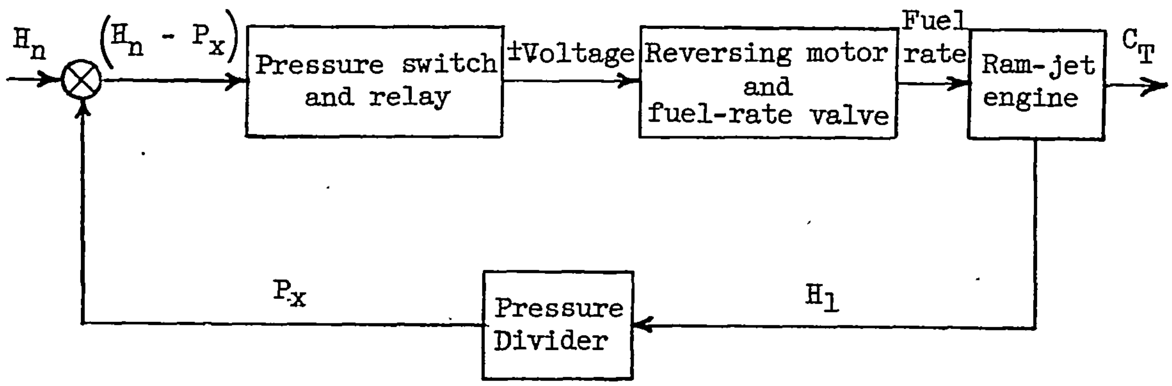
THRUST-COEFFICIENT CONTROL

In this scheme the thrust coefficient of the ram jet is controlled by controlling the pressure recovery. The diffuser-exit total pressure is controlled to be proportional to the stagnation pressure behind a normal shock wave (measured free-stream total pressure). In figure 3 thrust coefficient is plotted against pressure recovery for several free-stream Mach numbers. Cross-plotted are values of the resulting thrust coefficient when the pressure recovery is controlled to be proportional to normal shock recovery. Shown also are a family of curves for values of H_n/H_1 equal to 0.75, 0.80, 0.85, 0.90, 0.95, and 1.00. A value of H_n/H_1 equal to 1.00 is, of course, for the case when the pressure recovery is equal to normal shock recovery. It can be seen that the thrust coefficient controlled in this manner is very nearly constant over the range of Mach numbers from 1.8 to 3.0. Between $M = 1.8$ and $M = 2.25$ the thrust coefficient decreases slightly with increasing Mach number. In this range of Mach numbers the free-stream area of entering air is increasing as the free-stream Mach number increases. Above Mach number 2.25 the free-stream area of entering air is constant and the thrust coefficient increases slightly with increasing Mach number.

In figure 4 thrust coefficient is plotted against Mach number for values of H_n/H_1 equal to 0.85, 0.90, 0.95, and 1.00. This curve is a cross-plot of figure 3. Also plotted on this figure are thrust limits on the ram jet. Below Mach number 2.05 the thrust is limited by the maximum recovery of the diffuser. At Mach numbers greater than 2.05 the thrust is arbitrarily considered to be limited to those values of thrust corresponding to stoichiometric F/A at sea level.

In figure 5 a control scheme is illustrated which is designed to control the thrust coefficient at constant values of H_n/H_1. This is accomplished by throttling the pressure H_1 through an orifice and balancing the resulting pressure P_x against H_n. The flow of air through the throttling orifice is regulated to a constant Mach number by the choking orifice downstream. Thus the pressure loss through this orifice is a constant percentage of H_1, and P_x/H_1 is a constant determined by the geometry of the orifices. Such a system of orifices will be referred to as a "pressure divider" in the remainder of this text. The pressure P_x is balanced against and made equal to H_n by controlling the fuel rate in response to signals from the zero-differential pressure switch. This is done by driving the fuel-rate control valve with a reversible motor controlled by the relay. With this arrangement the fuel-rate control valve is always opening or closing in response to signals from the zero-differential pressure switch, and controls the fuel rate so that H_n/H_1 is equal to the value of P_x/H_1. Thus the thrust coefficient of the ram jet will always tend to correspond to the chosen value of H_n/H_1 as shown in figures 3 and 4.

The thrust control scheme may be represented in block diagram form as a simple single-loop servomechanism, as illustrated below:



Since only open or shut signals can be given by the sensing element, with no inactive zone, this servomechanism will naturally hunt (ref. 2). By constructing the fuel-rate valve so that it opens and closes very slowly, the hunting may be reduced to a negligible amount. Actually, the valve need not open or shut any faster than what is required to provide changes in fuel rate corresponding to the maximum rate of change of climb and/or acceleration desired. If the ram-jet engine is to operate over a wide range of fuel rates, it is desirable to use a logarithmically tapered fuel-rate valve. This would give the valve the same response characteristics throughout its operating range and prevent the control system from being either sluggish at high fuel rates or oversensitive at low fuel rates.

The thrust-coefficient control system described presents the following advantages. The power output of the ram jet is controlled directly by the control system and there is no compensation required for changes in free-stream temperature, free-stream pressure, or combustion efficiency. There is only a small variation in thrust coefficient with Mach number.

The control system employs a zero-differential pressure switch arranged to set a proportion between two pressures. Thus, only a single highly sensitive sensing element is used. This results in a control system which is basically simple, rugged, and sensitive even at high altitudes.

The control system is limited in use to that range of ram-jet operation where an increase in fuel rate will result in an increase in diffuser pressure recovery. In general, this covers the useful operating range of most ram jets; however, there are some cases where additional thrust may be obtained with subcritical air-mass flow when an increase in fuel rate is not accompanied by an increase in pressure recovery. Obviously, the fuel control system described would not be sensitive to thrust increases in this range.

SPEED STABILIZATION

If a ram-jet-powered missile is to fly for an extended period, control of the thrust coefficient alone will be insufficient. Some additional control will be required to stabilize the missile at a desired cruising Mach number. The thrust-coefficient control previously described is easily adapted to Mach number control.

In figure 6 a typical drag-coefficient variation with Mach number is shown. Also on this curve is the thrust-coefficient variation resulting from two settings of P_x/H_1 in the thrust-control system. Below the cruising Mach number ($M = 2.25$) the thrust coefficient is regulated for $P_x/H_1 = 0.90$. Above this Mach number P_x/H_1 is equal to 1.00. Below $M = 2.25$ the thrust is greater than the drag and the missile will accelerate. Above $M = 2.25$ the reverse is true and the missile will decelerate. Thus the missile will be stabilized at the desired cruising Mach number.

A simple control scheme to accomplish this discontinuity in thrust coefficient at the cruising Mach number is shown in figure 7. The Mach number sensing system responds to the ratio between the cone surface pressure P_c and measured total pressure H_n. With a 15° semiangle cone, for example, H_n/P_c will be equal to 4.14 when the Mach number is equal to 2.25 (desired cruising Mach number). This ratio is set up in an additional pressure divider. This pressure divider is slightly different than the one used in the thrust control system in that the pressure ratio across the upstream orifice is great enough to cause choking. Since both orifices are choking, a simple relation can be used to determine the required orifice areas to give the desired pressure ratio

$$\frac{H_n}{H_y} = \frac{\text{Minimum area of downstream orifice}}{\text{Minimum area of upstream orifice}}$$

The pressure switch in the Mach number control circuit operates a solenoid valve which opens and shuts the bleed from the orifice system in the thrust-coefficient control circuit. At Mach numbers greater than 2.25 the solenoid valve will be shut and P_x/H_1 will be equal to 1.00. Below $M = 2.25$ the solenoid valve will be open and P_x/H_1 will be equal to 0.90. Thus the thrust-coefficient variation with Mach number shown in figure 6 has been accomplished.

IMPROVED CONTROL SYSTEM

While the Mach number control system shown in figure 7 may prove adequate in many cases, a more refined control of the thrust coefficient over the flight Mach number range may be desirable. In figure 8 the variation in thrust coefficient with Mach number is shown for a case where the value of P_x/H_1 is arbitrarily regulated so as to give what might be considered a desirable thrust scheduling. The thrust is nearly maximum at low Mach numbers and, as the cruising Mach number is approached, the thrust is decreased with Mach number. The thrust- and drag-coefficient curves cross at $M = 2.25$ without any discontinuity in thrust coefficient. This will, of course, result in better cruising economy than would be obtained with the previous scheme for Mach number control. In addition, the near maximum thrust at low Mach numbers will provide ample power for climbing and acceleration after booster separation.

On figure 8 there is also plotted the variation in P_x/H_1 with Mach number corresponding to the variations of the thrust-coefficient curve. To achieve this variation of P_x/H_1, the Mach number must be determined in flight and the thrust control system adjusted accordingly over the range of Mach numbers shown. Actually, this may be accomplished without a great deal of additional complication. A scheme to do this is shown in figure 9. It can be seen that the downstream orifices in both the pressure dividers of the thrust control system and the Mach number system have been made variable in area through the use of moving plugs. These plugs are linked together and driven by a reversible motor. The reversible motor is controlled through a relay by the zero-differential pressure switch in the Mach number control system. The arrangement is such that the pressure divider in the Mach number control system is continually being trimmed to maintain a pressure balance in the pressure switch. Thus the plug position (at balance) will change with Mach number and will therefore be an indication of Mach number. The plug in the thrust-control pressure divider will also be positioned with Mach number, since it is mechanically linked to the Mach number control plug. In figure 10 the ratio of H_n/P_c is plotted against Mach number. It can be seen that this is nearly a linear variation, thereby simplifying the design of the

Mach number control system. The plug position in the Mach number pressure divider should preferably be made to vary linearly with Mach number. To prevent excessive overshoot, the positioning motor should be geared down so that the plugs move very slowly. This movement need be only slightly faster than that which would correspond to the maximum rate change of Mach number expected.

The plug in the thrust-control pressure divider may be made to vary the thrust coefficient with Mach number in any desired manner. The variation shown in figure 8 is, of course, accomplished by designing the plug to vary P_x/H_1 in the manner plotted in the upper portion of that figure.

Variable-geometry ram jets may also be regulated with this system by the addition of a few components. This may be done in a manner which will give maximum economy at any thrust coefficient chosen over the operating range of the engine. First, the thrust-coefficient variation with Mach number should be chosen. Then the engine geometry and total-pressure recovery corresponding to maximum economy should be calculated. The geometry of the engine must then be rigged (through use of suitable cams, linkages, and power servos) to vary with the Mach number position of the pressure-divider plug in the Mach number control system. The pressure recovery should also be set to vary with Mach number in the desired manner by the method previously described.

CONCLUDING REMARKS

A ram-jet fuel-control system has been described which effects direct control of the thrust coefficient by maintaining a ratio between the measured total pressure and the diffuser-exit pressure. This control system has the following characteristics:

1. The controlled thrust coefficient for any given value of H_n/H_1 is unaffected by changes in free-stream pressure or temperature and varies only slightly with free-stream Mach number.

2. The thrust coefficient may be scheduled to vary with Mach number in any desired manner within the operating limits of the ram-jet engine.

3. The control system is incapable of controlling the fuel rate in the region of subcritical mass flow when an increase in fuel rate is not accompanied by an increase in diffuser exit pressure.

4. The use of a simple sensing element capable of giving only open or shut signals with no inactive zone results in a control system that will naturally hunt.

5. The use of zero-differential pressure switches to operate the fuel valve and Mach number control system provides for high sensitivity and simplicity.

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2. Kochenburger, Ralph J.: A Frequency Response Method for Analyzing and Synthesizing Contactor Servomechanisms. Trans. AIEE, vol. 69, pt. I, 1950, pp. 270-283.

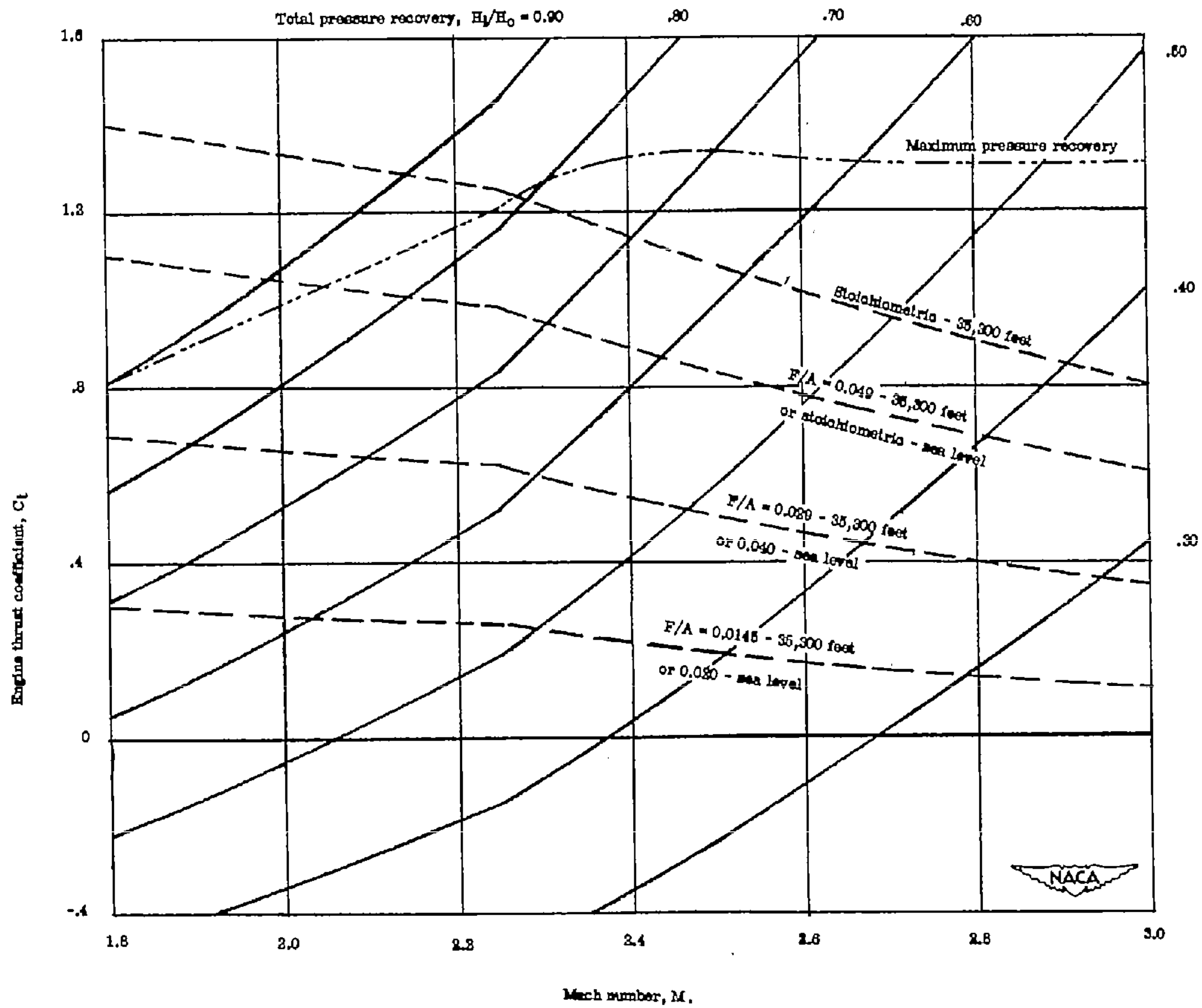

Figure 1.- Performance of typical ram-jet engine.

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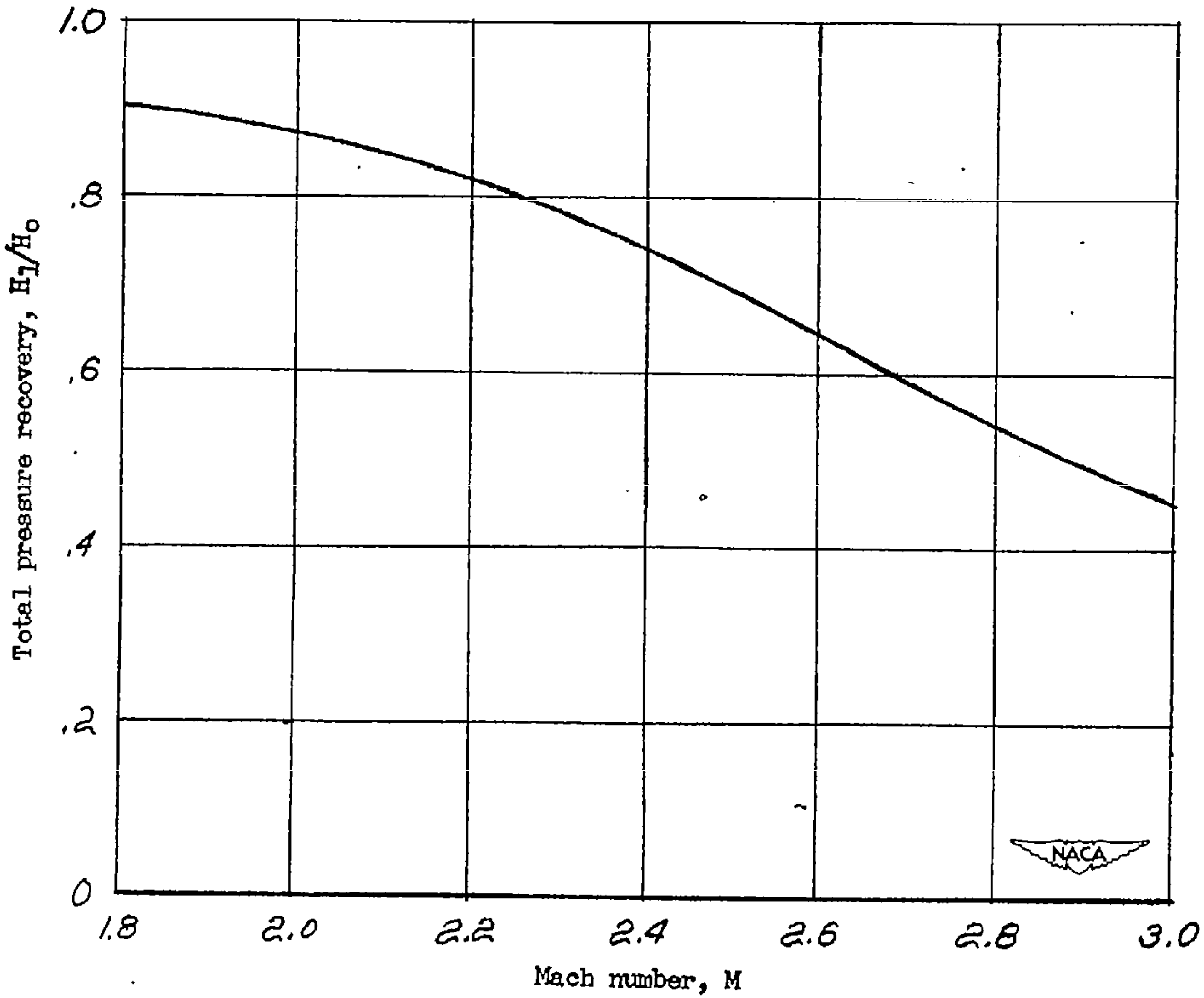

Figure 2.- Maximum pressure recovery H_1/H_0 for typical ram-jet engine.

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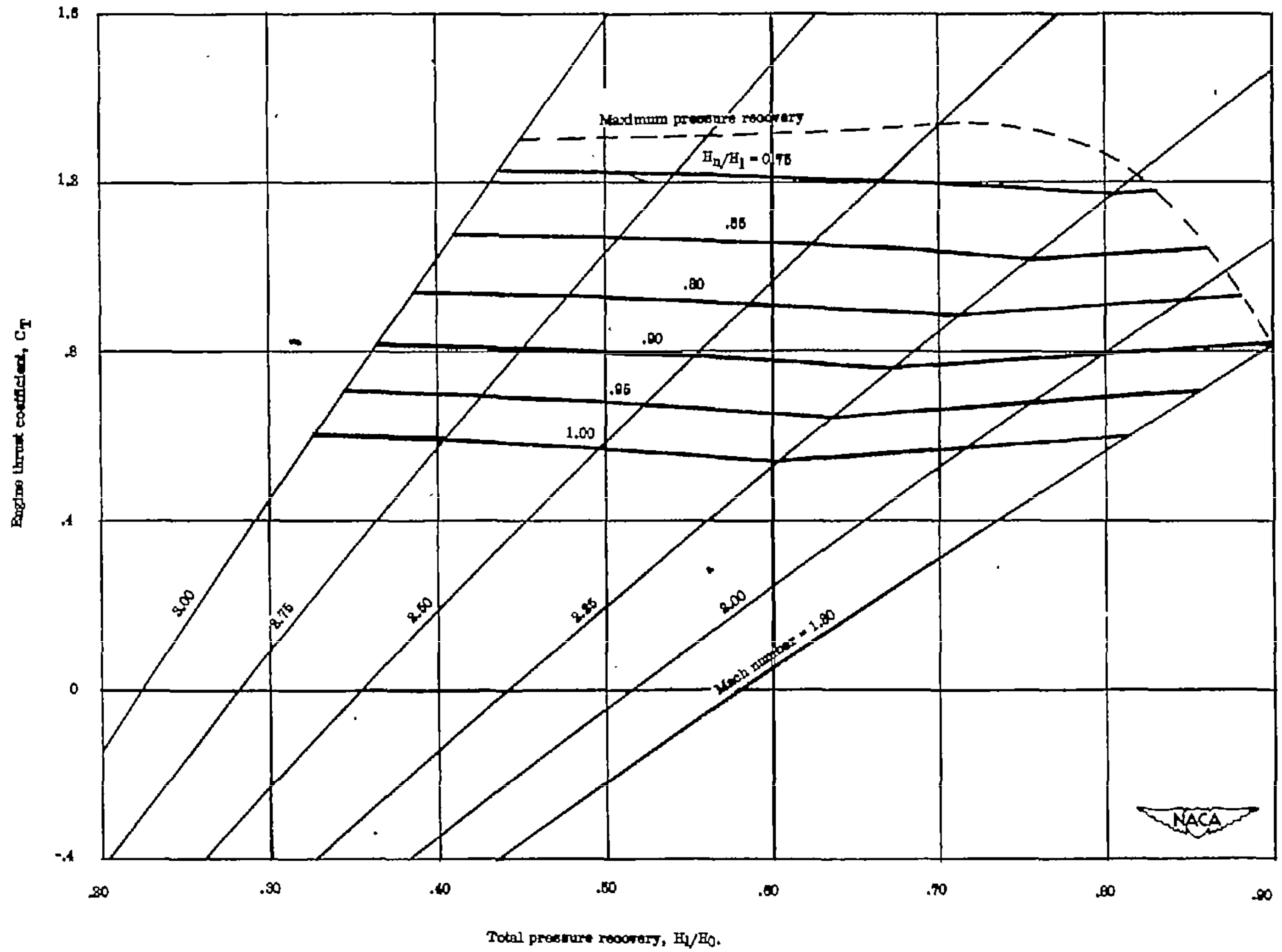

Figure 3.- Variation of thrust coefficient with pressure recovery for several Mach numbers, with values of H_n/H_1 cross-plotted.

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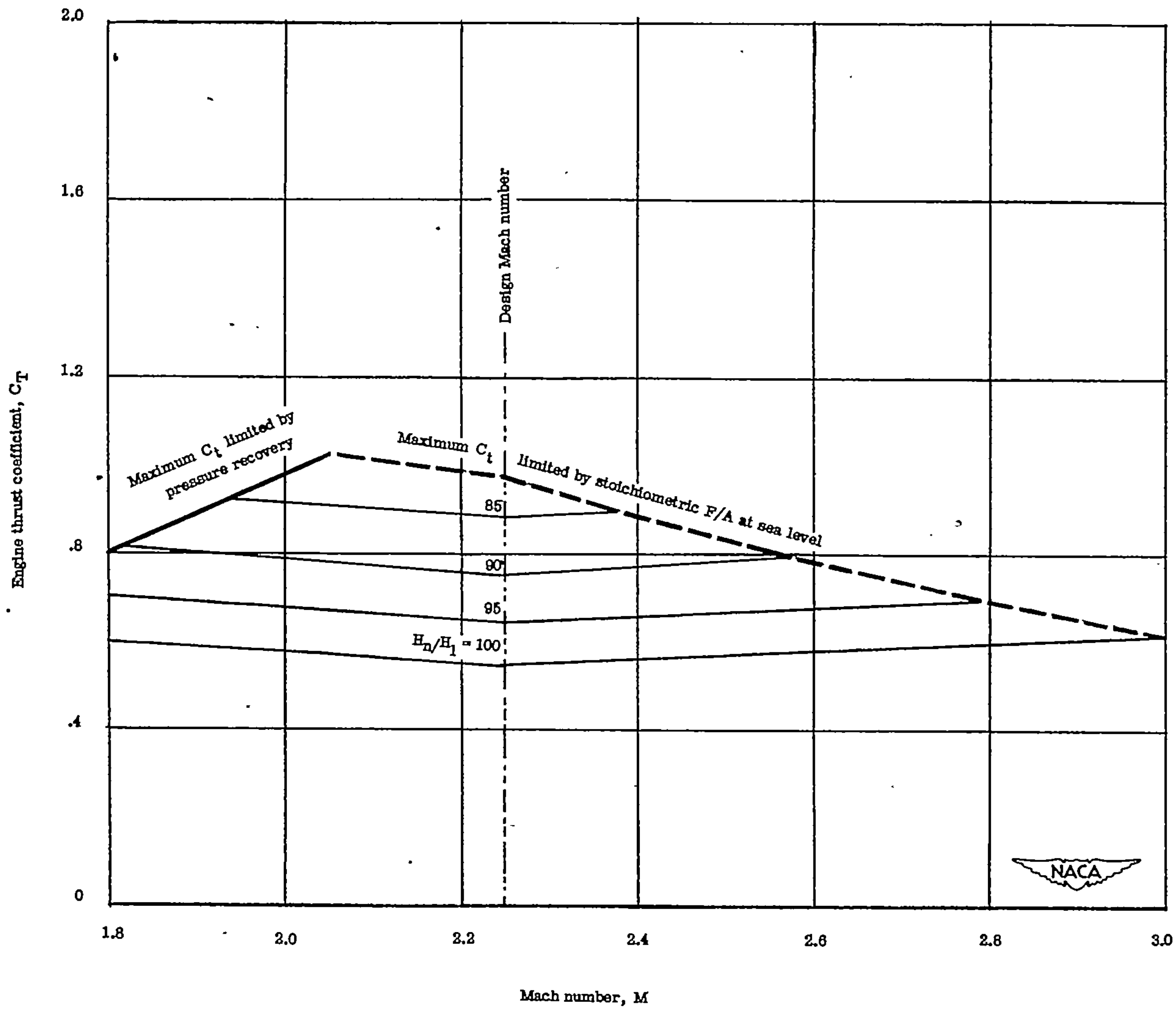

Figure 4.- Variation of thrust coefficient with Mach number for various values of H_n/H_1.

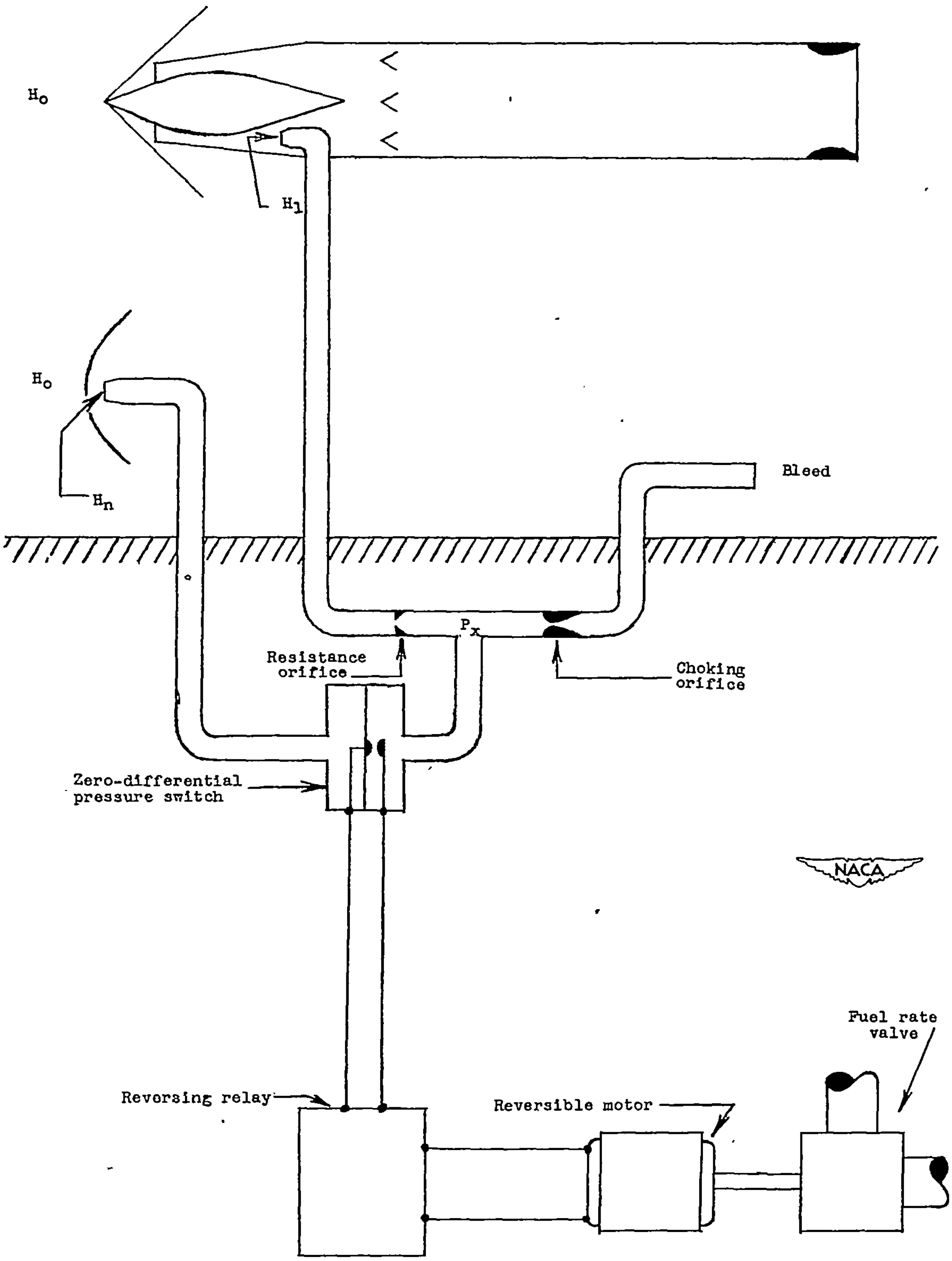

Figure 5.- Scheme for controlling the thrust coefficient by regulation of the fuel rate in response to the diffuser-exit pressure.

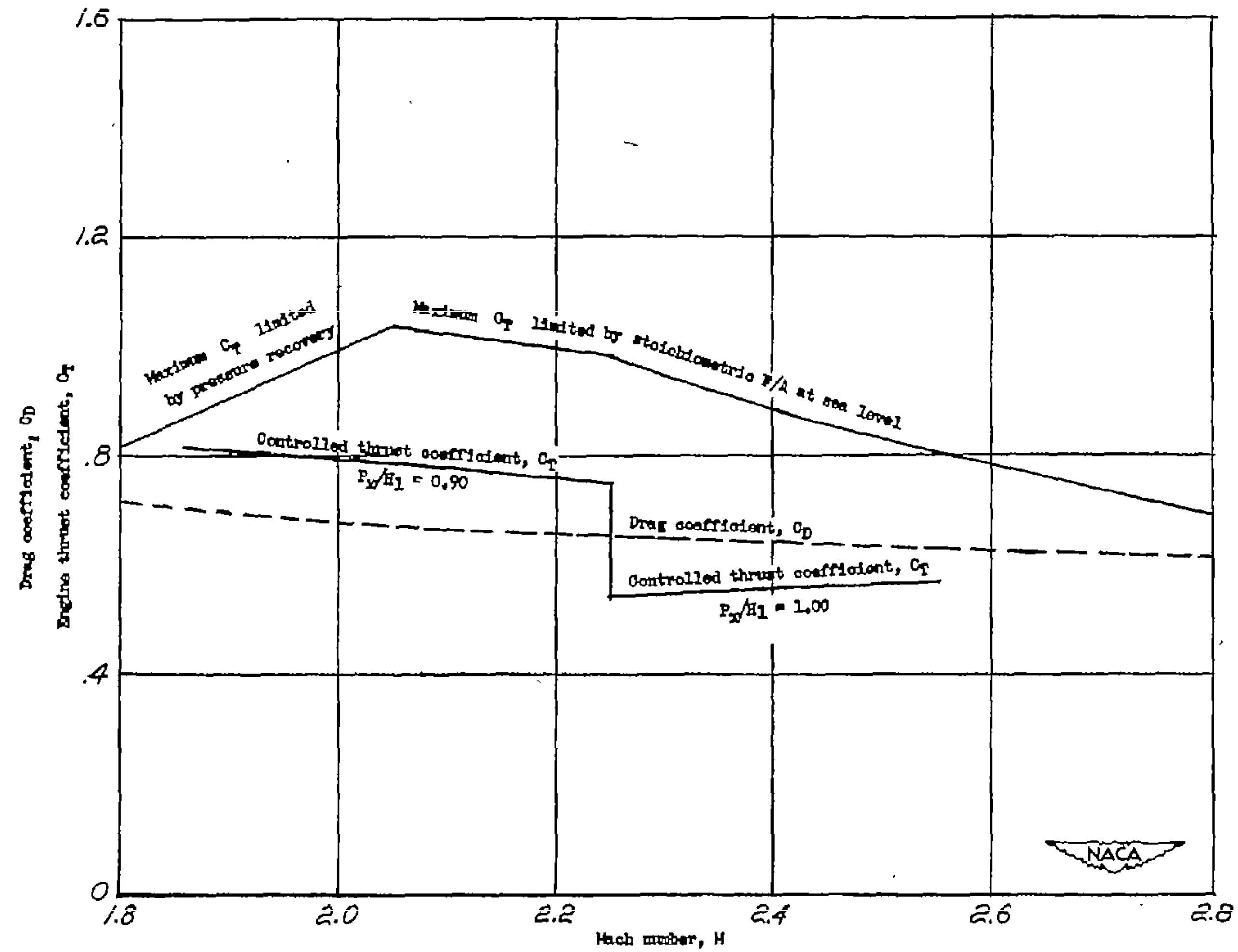

Figure 6.- Variation of controlled thrust coefficient with Mach number with a discontinuity to obtain speed stabilization at $M = 2.25$.

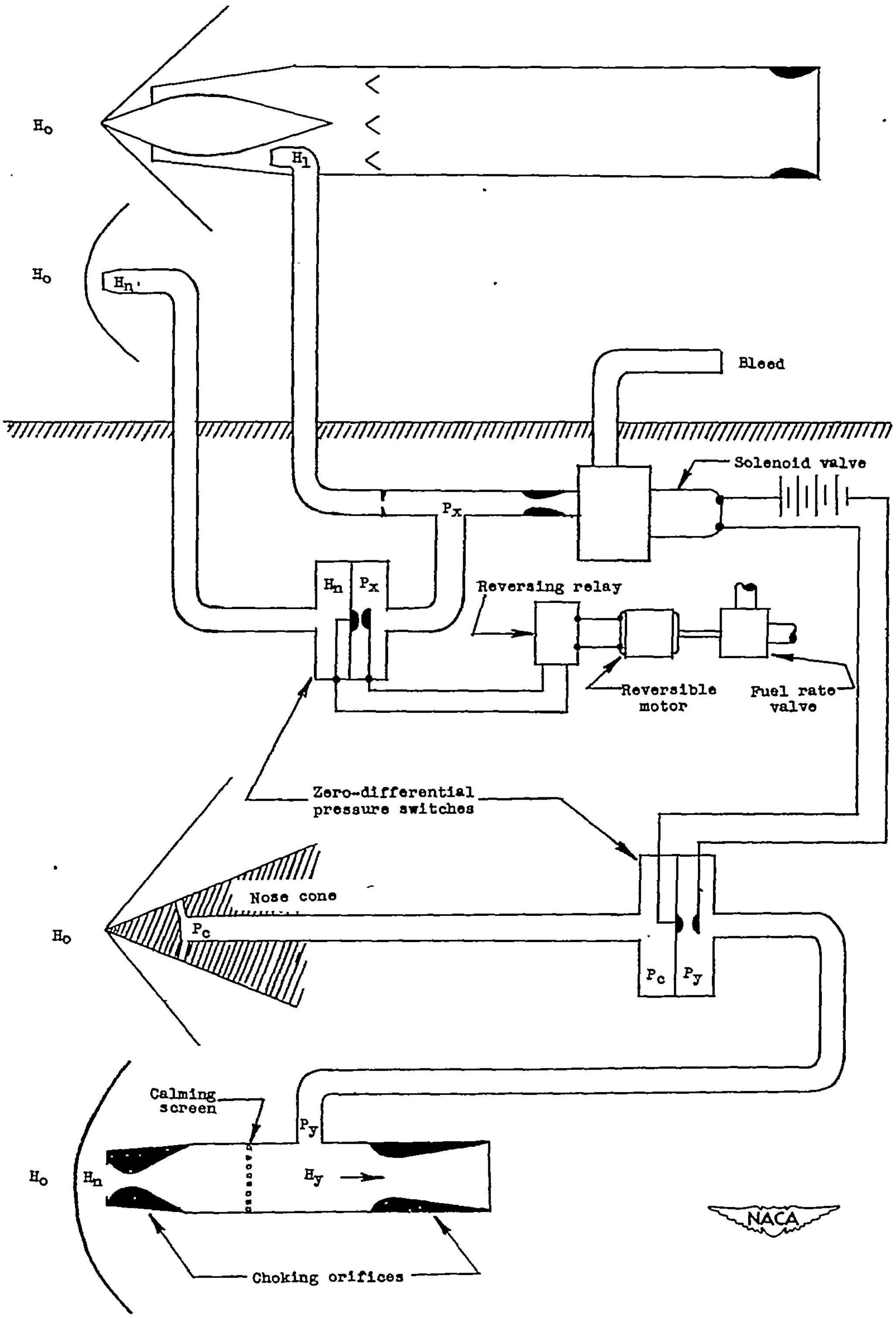

Figure 7.- Scheme for controlling thrust coefficient with two values of P_x/H_1 to obtain speed stabilization.

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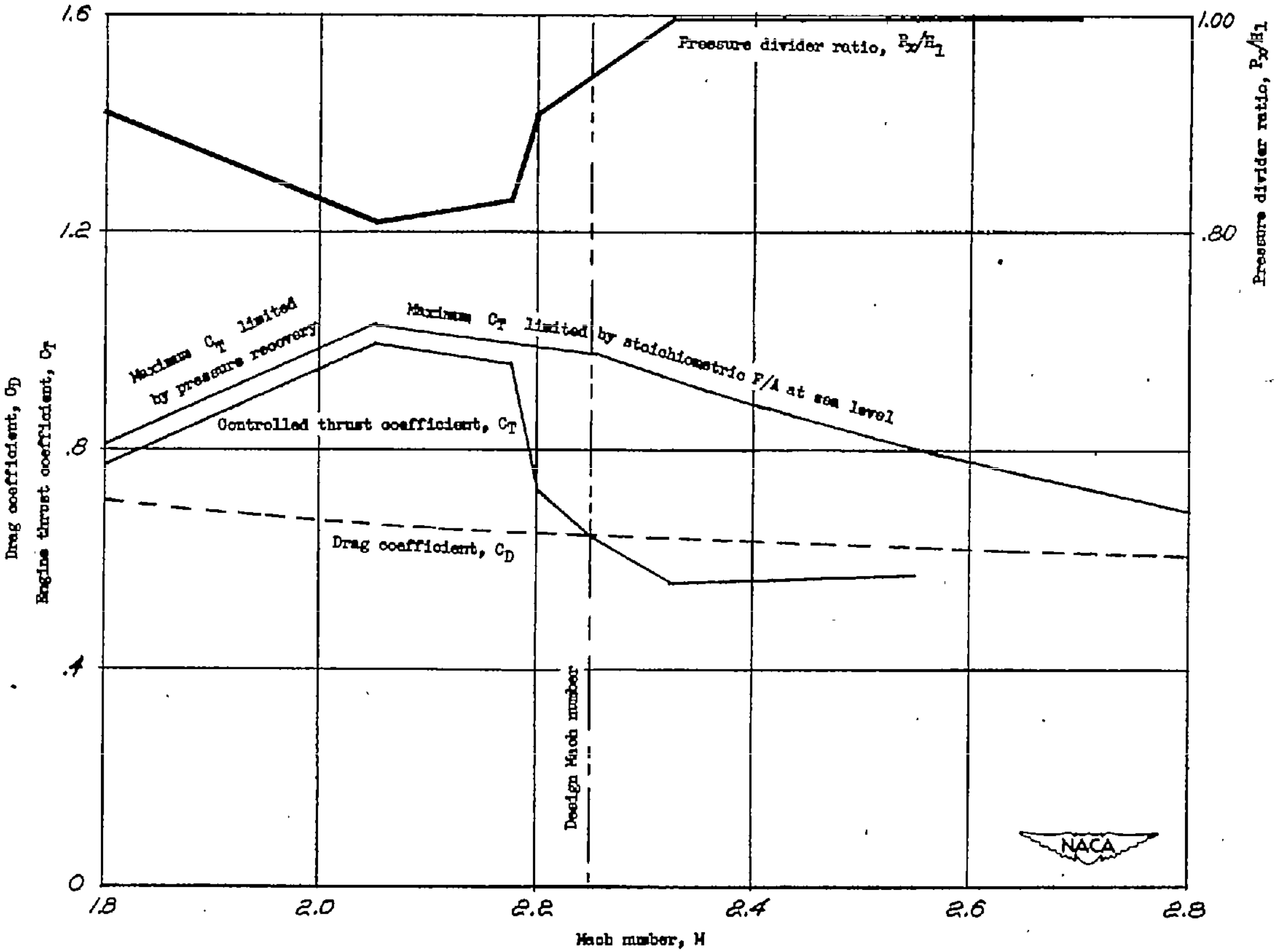

Figure 8.- Variation of controlled thrust coefficient with Mach number when P_x/H_1 is varied continuously with Mach number.

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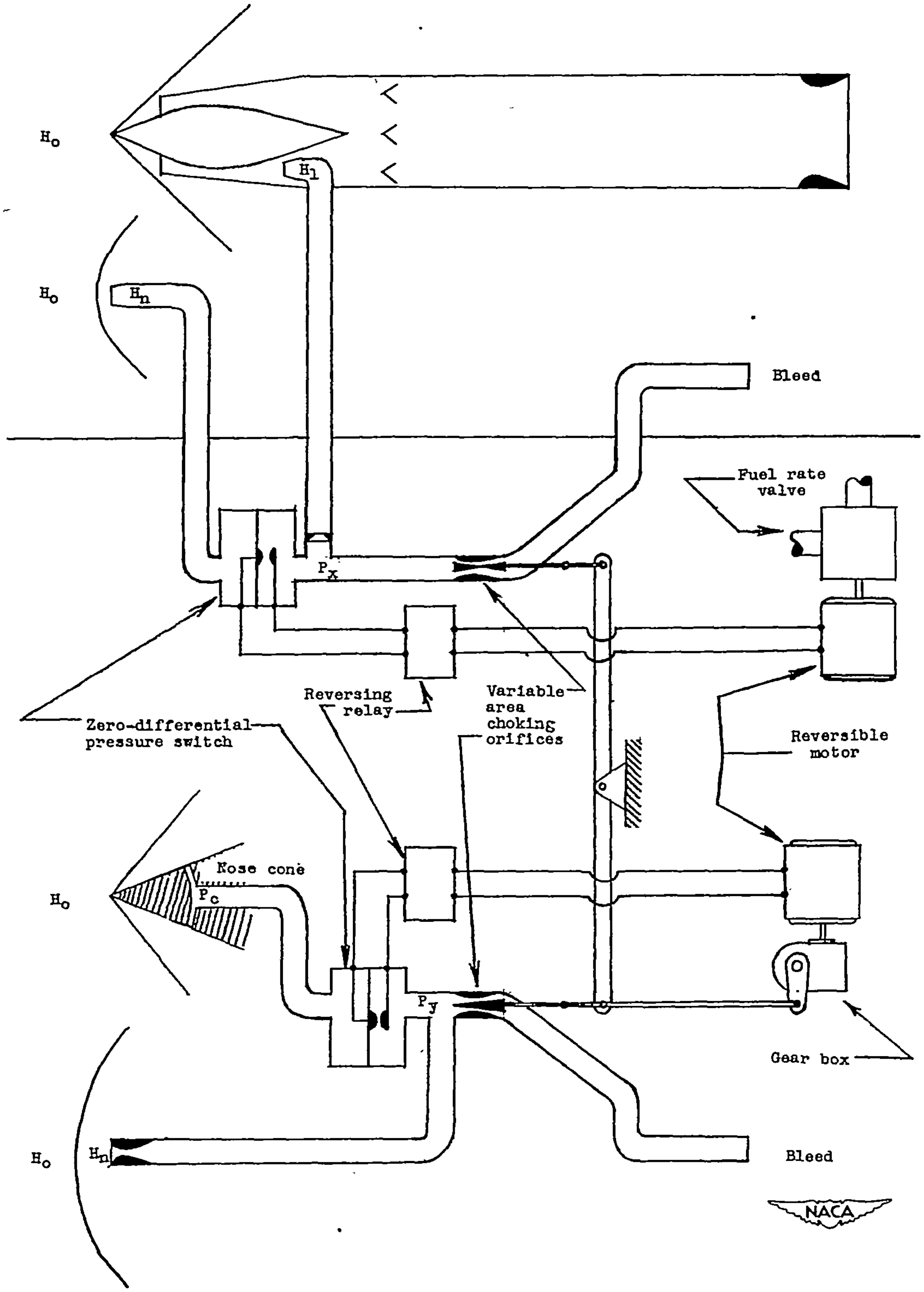

Figure 9.- Scheme for controlling the thrust coefficient when P_x/H_1 is to be varied continuously with Mach number.

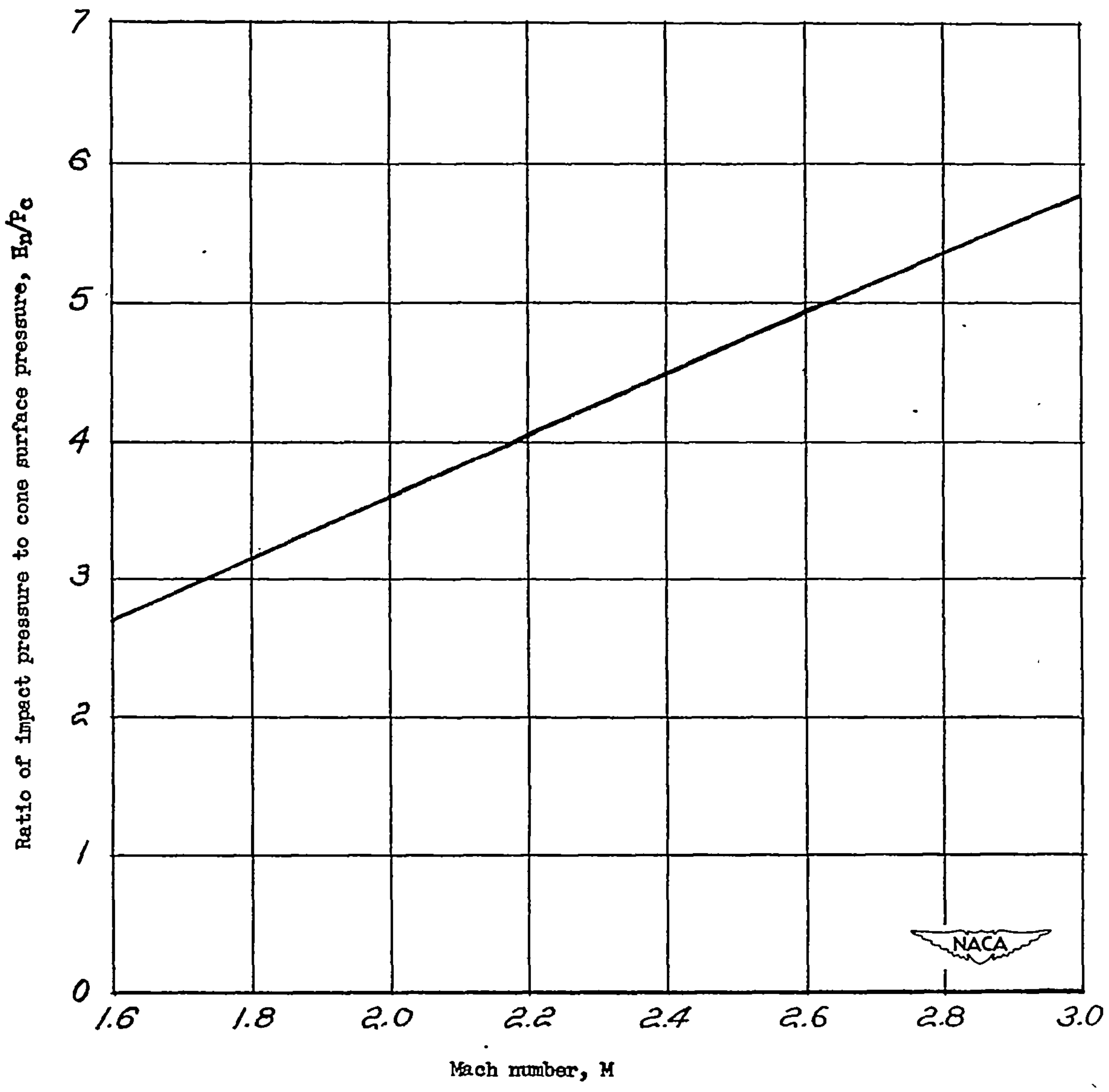

Figure 10.- Impact pressure divided by cone surface pressure H_n/P_c against Mach number for a 15° semiangle cone.

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