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NACA MACH NUMBER INDICATOR FOR USE IN HIGH-SPEED TUNNELS

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SUMMARY

A device for indicating stream Mach number in a high-speed tunnel has been developed at Langley Memorial Aeronautical Laboratory. Based on the fact that Mach number is a function of the ratio of indicated dynamic pressure to static pressure, the NACA Mach number indicator consists of a mechanism for determining this pressure ratio. The ratio is indicated on a dial calibrated in terms of Mach number. This instrument is in service in the NACA 8-foot high-speed tunnel, and its accuracy has been found satisfactory for wind-tunnel requirements.

INTRODUCTION

At high airspeeds the lift, drag, and pitching-moment coefficients of aerodynamic bodies have been found to be dependent mainly on the Mach number rather than on the Reynolds number, which is the governing parameter at low speeds. The Mach number is defined as the ratio of the airspeed V to the speed of sound a in air at the same temperature and can be computed from the same pressure measurements used in the determination of airspeed.

It is desirable, in the operation of high-speed tunnels, to run tests at specific values of the Mach number rather than at specific values of the Reynolds number, velocity, or dynamic pressure. An instrument that would read Mach number directly would be valuable for adjusting the tunnel speed and eliminating the computation of Mach number. A direct-reading Mach number indicator has been developed and calibrated for use in the NACA 8-foot high-speed tunnel.

PRINCIPLE OF OPERATION

By simple compressible-flow relations it can be shown that stream Mach number M is a function of only the pressure ratio $H - p/p$ according to the following expression:

$$M = \frac{V}{a} = \sqrt{\frac{2}{\gamma - 1}\left[\left(1 + \frac{(H-p)}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

where

γ ratio of specific heats (for air, 1.40)

H stream total pressure

p stream static pressure

The Mach number indicator as developed for the NACA 8-foot high-speed tunnel (fig. 1) consists of two metal bellows for converting the pressures $H - p$ and p into forces and a mechanism for determining the ratio of these forces. The ratio is indicated on a dial, which is calibrated in terms of Mach number (fig. 2).

The instrument case (fig. 1) is airtight and is kept at stream static pressure. The large bellows is connected to the tube or orifice that measures stream total pressure and therefore measures the pressure difference $H - p$. The small bellows is evacuated and thus measures directly the stream static pressure. The two bellows are connected to opposite ends of the vertical balance beam, which is pivoted about a movable fulcrum. The fulcrum is driven along the beam by a lead screw and a reversible motor. Contacts are located at the ends of the balance beam. These contacts close when the beam is out of balance and actuate a sensitive relay, which causes the balancing motor to move the fulcrum in the direction of balance. When the fulcrum reaches the balance position, the bellows spring forces pivot the beam to open the contacts.

A simple force diagram is shown in figure 3. For the balanced condition the moment equation is

$$(H - p)\, A_1 L_1 = p A_2 L_2$$

$$\frac{H - p}{p} = \frac{A_2}{A_1}\,\frac{L_2}{L_1}$$

where

A_1 effective area of total-pressure bellows

A_2 effective area of static-pressure bellows

L_1 moment arm of total-pressure bellows

L_2 moment arm of static-pressure bellows

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Thus, for a given bellows area ratio, the ratio of the two pressures is indicated by the position of the fulcrum at balance.

Figure 4 shows the variation of Mach number and fulcrum travel with pressure ratio. These relations are nonlinear but have similar shapes. Figure 5 is a cross plot of figure 4 and shows the variation of fulcum travel with Mach number to be approximately linear within the operating range of the instrument.

SERVICE USE

It is standard practice in wind tunnels to determine Mach number from the pressure readings of calibrated static-pressure orifices located ahead of the test section. The calibration factor is dependent upon the ratio of the air-stream cross-sectional areas and the Mach number. Thus, for a given location of calibrated static-pressure orifices the calibration factor depends solely on the Mach number. The dial on the NACA Mach number indicator, shown in figure 2, has been constructed to include the static-pressure-orifice calibration factor for the NACA 8-foot high-speed tunnel, and the instrument case as now used in service is connected to these orifices.

In addition to use for tunnel-speed adjustment and determination of tunnel Mach number, the NACA Mach number indicator in its present form has other uses. With a dial that does not include a wind-tunnel calibration factor, the indicator can be used to determine local Mach numbers on aerodynamic bodies by connecting the static-pressure lead to the desired static-pressure orifice on the model. Local Mach numbers up to about 1.2 can be indicated with the present instrument.

GENERAL DESIGN CONSIDERATIONS

The instrument is essentially a static system. The bellows move only far enough to close the contacts and are returned to the neutral position at balance. This small deflection insures better accuracy than can ordinarily be realized with deflectional systems because errors due to hysteresis, spring forces, and friction are small when the bellows deflection is very small.

It is necessary that all constants be eliminated from the moment equation to insure indication of a pure ratio of the pressures. The bellows spring forces must be zero when the balance beam is in the neutral position. Prior to evacuation of the small bellows, the positions of the bellows were adjusted to give this condition. The balance beam is mounted vertically and supported directly under its center of gravity, so that the weight of the beam does not enter into the moment equation.

The sensitivity of the instrument is dependent upon the distance traveled by the fulcrum for a given change in pressure ratio. For a fixed length of balance beam, the travel can be increased by using a larger bellows for measuring the smaller pressure $H - p$. Using a larger bellows in effect increases the pressure-ratio range through which the instrument operates. In the present instrument, the ratio of effective areas of the two bellows is 3.46, which results in a fulcrum travel of about $4\frac{1}{2}$ inches out of a beam length of 8 inches, about twice the travel for an area ratio of 1.0.

In order to minimize the beam movement necessary to operate the instrument, a set of contacts is located at each end of the balance beam. The two sets are connected in parallel. The set farther from the fulcrum receives the larger deflection and operates the instrument at that point. All contacts are set with about 0.002-inch clearance.

The pressure $H - p$, which varies approximately as M^2 (see fig. 4), becomes very small at low Mach numbers, with the result that low Mach numbers cannot be determined from the pressure ratio with good accuracy. Furthermore, it is mechanically difficult to allow the fulcrum to approach the point of application of the pressure force p. However, compressibility effects at these low Mach numbers generally cannot be measured and determination of the Mach number is usually not required. The instrument was therefore designed to operate only for $M > 0.18$. A limit switch is provided to stop the mechanism when the fulcrum moves below the $M = 0.18$ position. As a safety device a second limit switch is located near the fulcrum-travel limit at the opposite end of the beam.

ACCURACY

During calibration of the indicator, the instrument error was determined. The error found in service operation is less than ± 0.003 at $M = 0.25$ and less than ± 0.001 at $M = 0.60$ or higher.

The lower accuracy found at low Mach numbers is inherent in the instrument. The moments are small; hence a larger change in Mach number is required to produce the unbalanced moment needed to pivot the balance beam and to operate the balancing motor. This necessary moment has been kept low by using "extra flexible" bellows of low spring constant, by making friction in the pivoting beam as low as practicable, and by making contact clearance as small as possible.

The accuracy of the indicator is adequate for ordinary wind-tunnel requirements, which are of the order of ± 0.01 at low Mach numbers and ± 0.005 to ± 0.003 at Mach numbers in the critical region. The accuracy might be increased in future designs by increasing the length of the balance beam, increasing the bellows area ratio, decreasing friction in the pivoting beam, and decreasing the bellows spring constants.

FLIGHT APPLICATIONS

It has been found necessary to placard some high-speed military airplanes because of certain severe compressibility effects. These effects always occur at the same Mach number for the same airplane. The placard limit is usually expressed in terms of airspeed, which has a different value - both indicated and true - at every altitude. It is therefore necessary that the pilot read two instruments plus a table of placard speeds and altitudes. A flight Mach number indicator, with the placard Mach number plainly marked on the dial, would enable the pilot to read directly his proximity to the limiting condition.

A simpler instrument might be used to operate a warning device when the pressure ratio corresponding to the limiting Mach number is reached. The principle involved in the wind-tunnel indicator can easily be applied to a warning instrument which can be designed to occupy no more space than an ordinary airspeed indicator. Such a device might be used to automatically extend dive brakes or flaps when the limiting condition is reached and thus prevent further increase in speed.

Study and development of flight Mach number indicators and warning instruments are being continued at Langley Memorial Aeronautical Laboratory.

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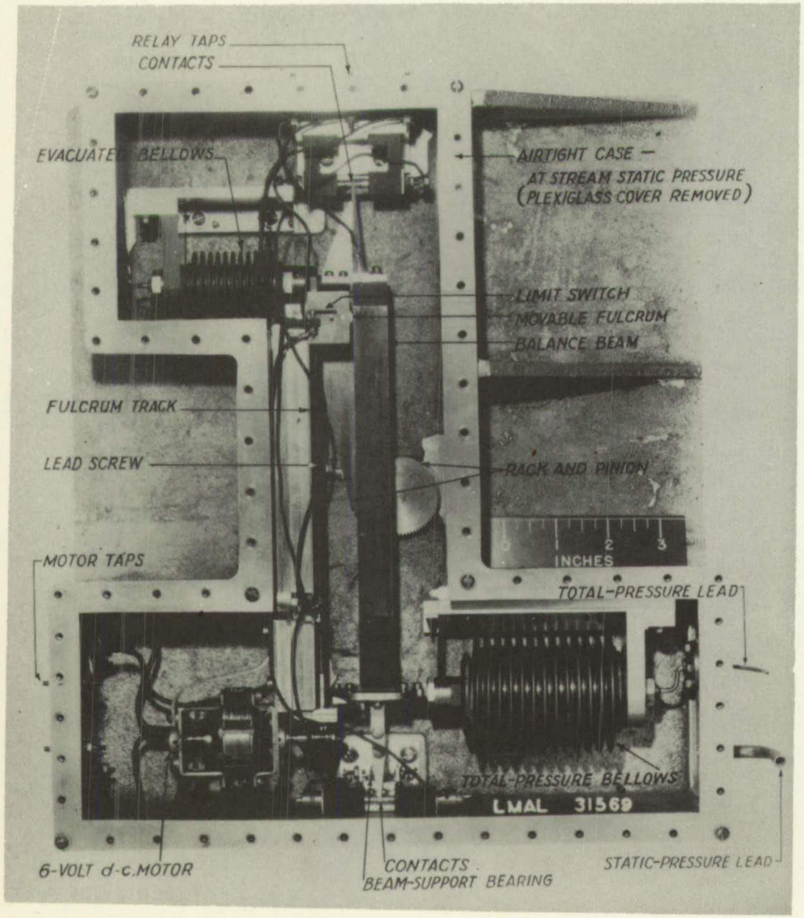

Figure 1.- Details of mechanism of the NACA Mach number indicator.

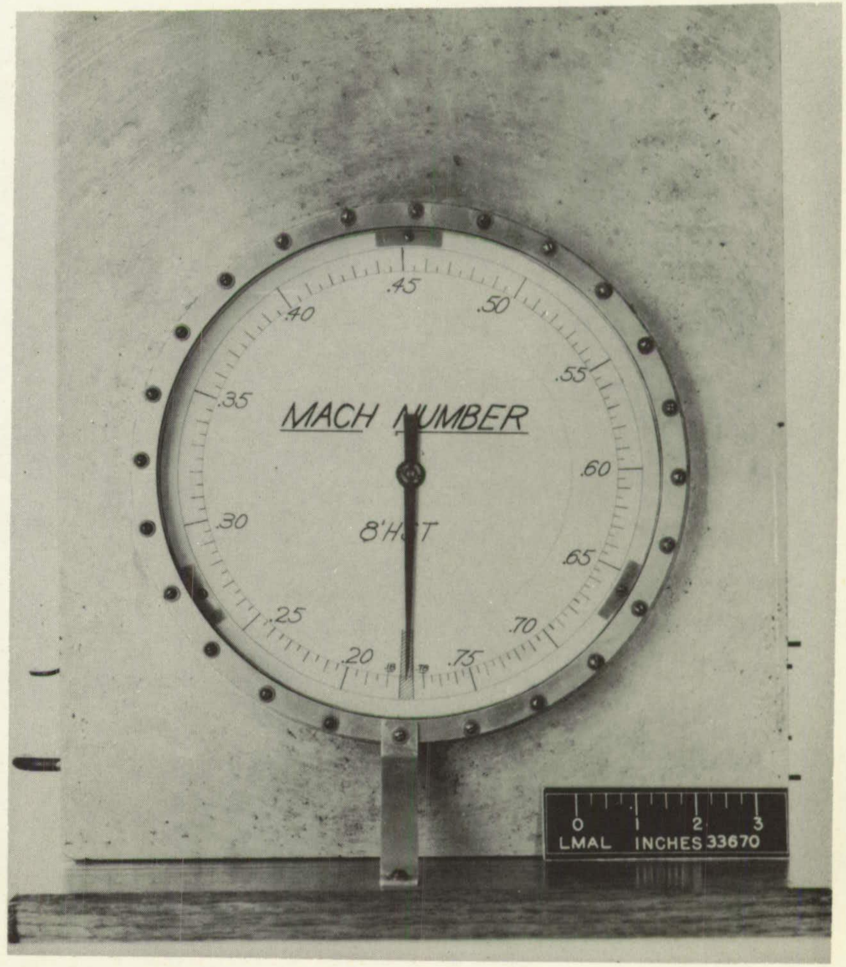

Figure 2.- Dial face of the NACA Mach number indicator.

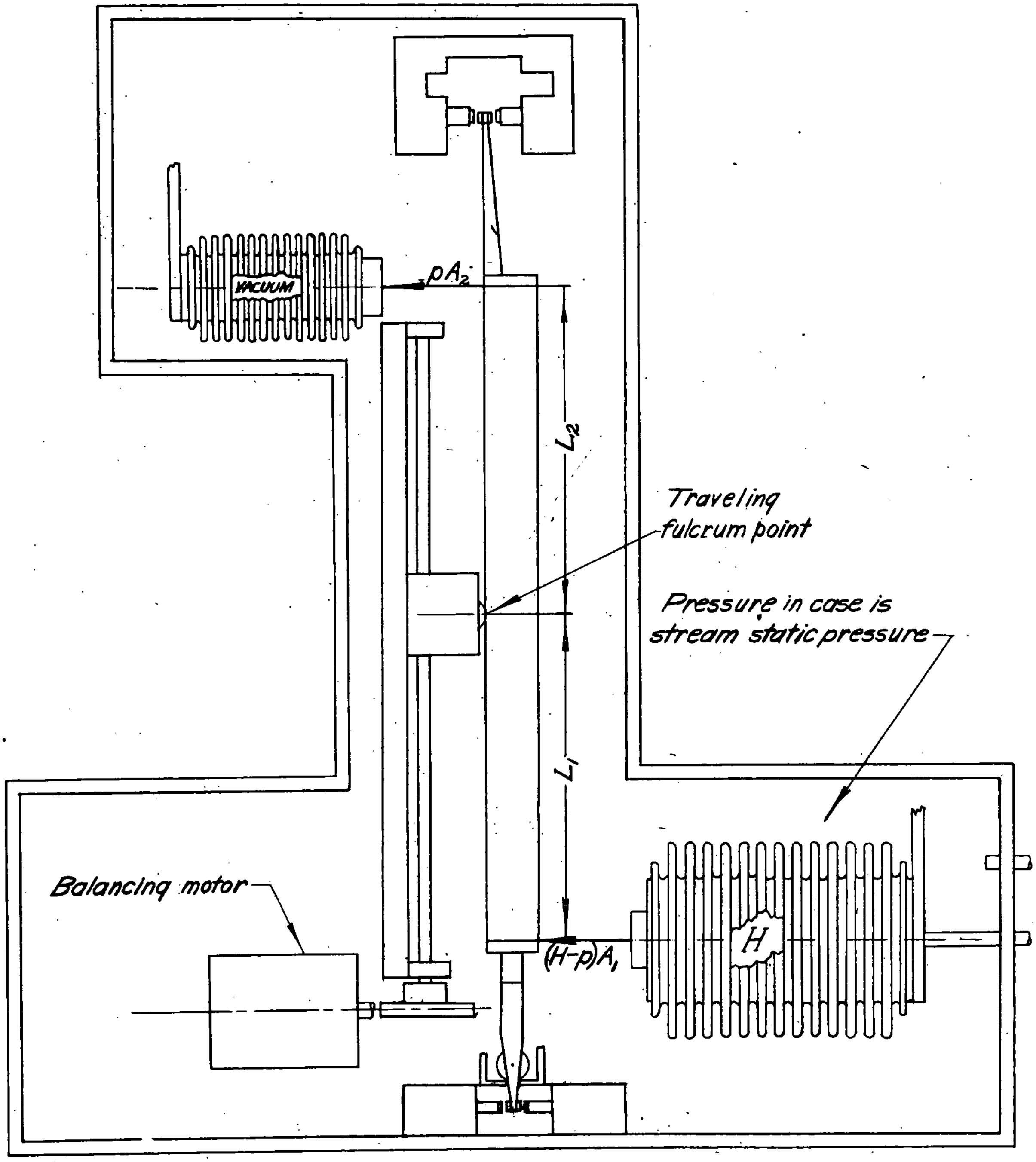

Figure 3.- Schematic diagram showing forces at balance.

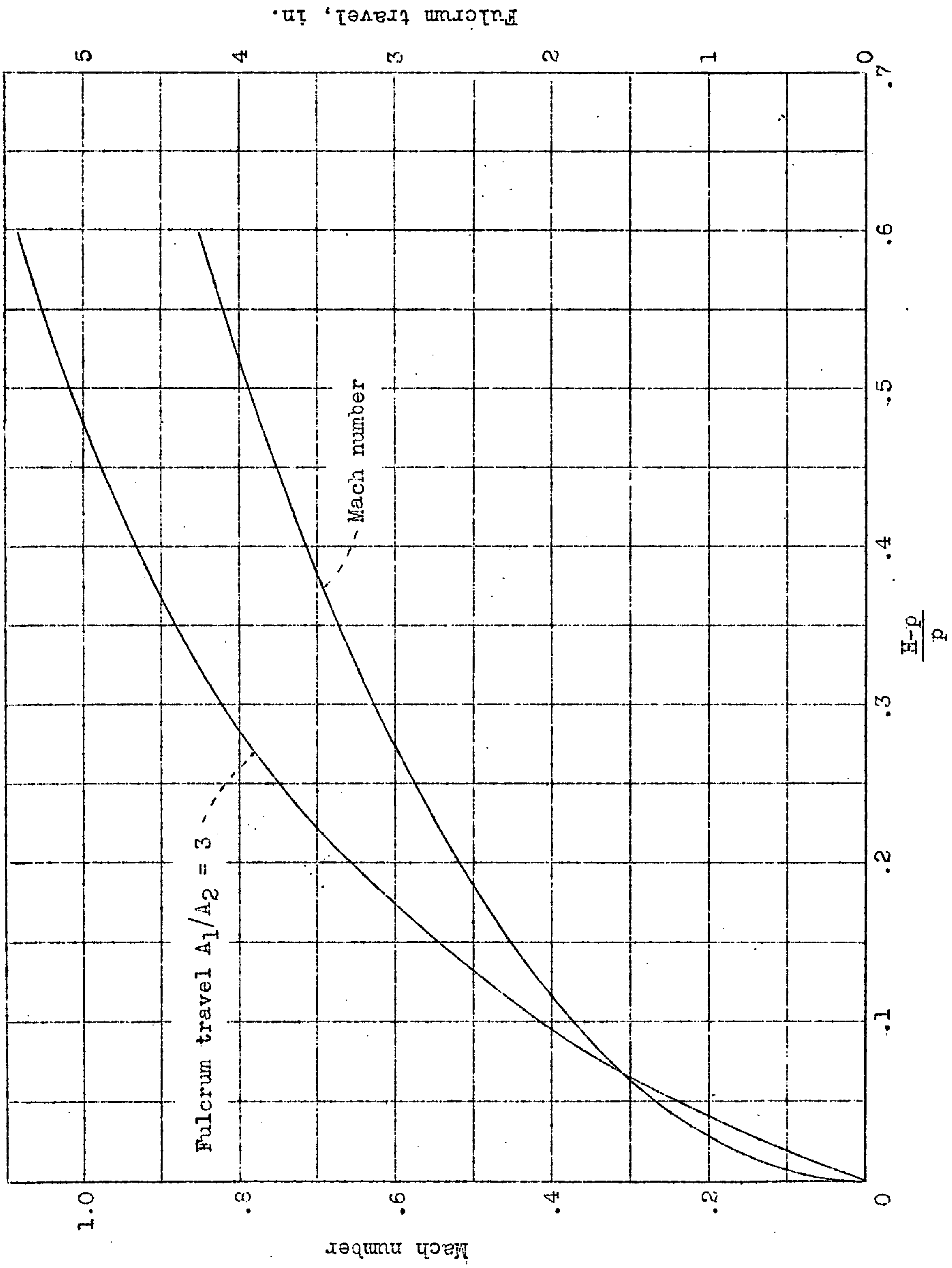

Figure 4.- Variation of Mach number and fulcrum travel with pressure ratio.

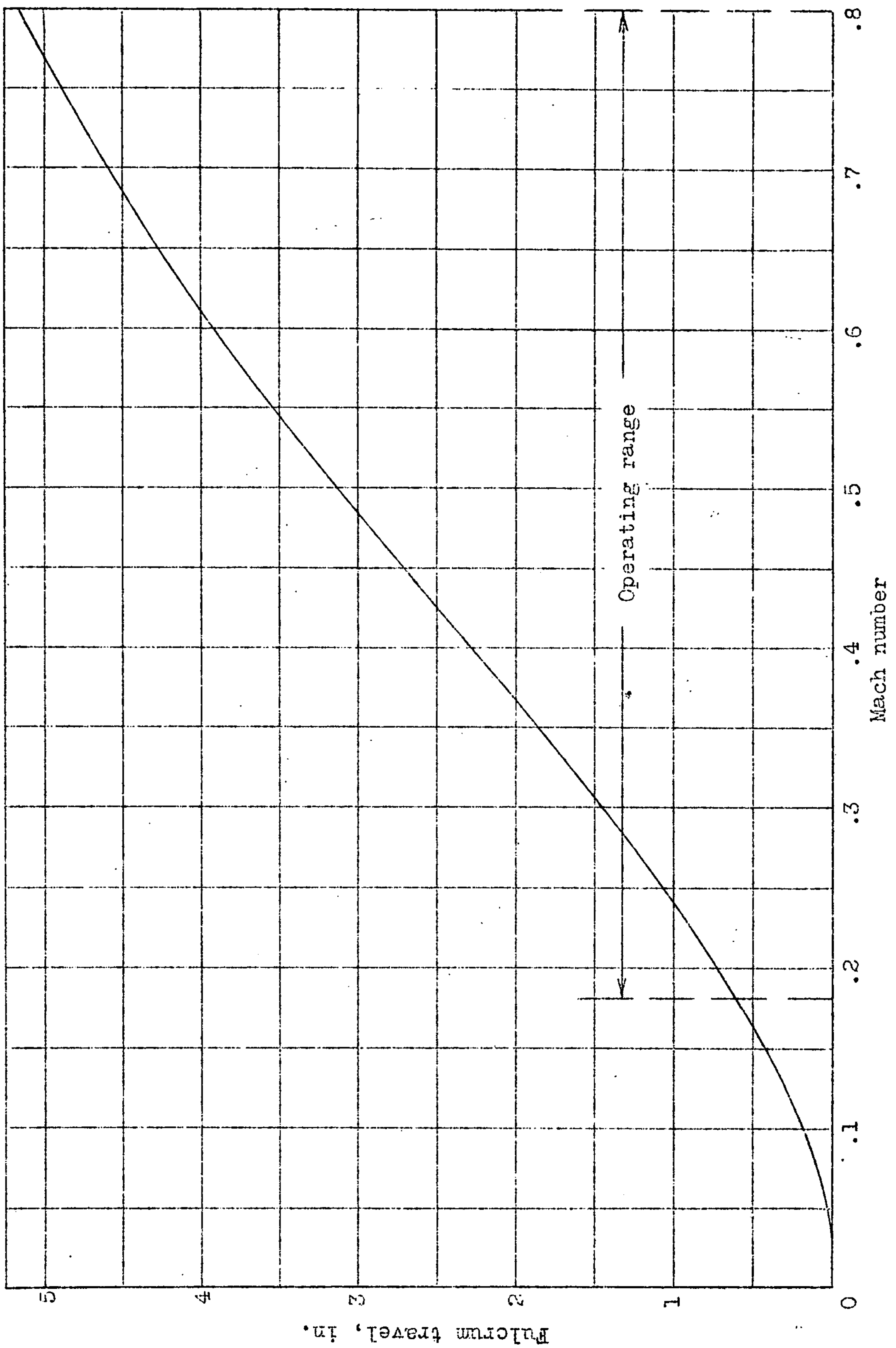

Figure 5.- Variation of fulcrum travel with Mach number.