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The Operation of the N.P.L. 18″ x 14″ Wind Tunnel in the Transonic Speed Range

By

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SUMMARY

A brief description of the slotted liners used is given together with the power requirements and some flow surveys.

Some observations are made on wall interference on a half-model of a swept wing tested in the wind tunnel.

Notation

A_S	injector slot area
A_W	cross-sectional area of working section
b	width of tunnel working section
C_D	drag coefficient
H	stagnation pressure
h	height of tunnel working section
M	Mach number
ΔM	Mach number increment
ΔM_L	$\frac{1}{2}(\Delta M_{upper} - \Delta M_{lower})$
ΔM_B	$\frac{1}{2}(\Delta M_{upper} + \Delta M_{lower})$
ΔM_{upper}	Mach number increment at upper wall
ΔM_{lower}	Mach number increment at lower wall
P	blowing pressure, absolute
S_m	planform area of wing

U/

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U	tunnel velocity
δu	velocity increment
V_n	volume of wing
x	distance downstream of beginning of slots
α	incidence of wing
$\Delta\alpha$	increment in incidence
β	$\sqrt{M^2 - 1}$
$\frac{\partial C_L}{\partial \alpha}$	lift-curve slope

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1. Introduction

With solid liners, the N.P.L. 18" × 14" wind tunnel has been operated satisfactorily at subsonic speeds (up to choking) and at supersonic speeds corresponding to Mach numbers of 1.24, 1.41, and 1.60. The installation of a pair of slotted liners has enabled the tunnel to be operated at Mach numbers in the transonic range; its maximum Mach number is 1.22 in the absence of a model.

The working section of the 18" × 14" wind tunnel is two-dimensional and the shaped liners occupy the shorter (14 in.) sides. The actual distance between the liners varies with different sets of liners; for the slotted liners it is approximately 17 in. in the working section. The longer sides are flat and consist of interchangeable panels. The tunnel is driven by the injector principle[1,2] using compressed air as the driving fluid. At present the compressed air storage plant has a total capacity of 38,000 cubic feet and can be pressurized to 350 lb per sq in. above atmospheric pressure. The reservoir pressure can be throttled to produce the desired "blowing pressure" just upstream of the injector slots. The slots extend around the perimeter of the tunnel (73 in. at the slots) and their width can be varied up to 0.5 in. The tunnel can be pressurized up to stagnation pressures of 3 atmospheres.

During the past few months the slotted liners have been used for testing in the transonic speed range. In order to make the present experience generally available a description of the liners and a preliminary calibration of the slotted working section are given below.

2. Construction of the Slotted Liners

The general arrangement of one of the slotted liners is shown in Fig. 1. Each liner was made in three sections, a contraction in the form of a solid wooden block, a slot entry section, and a constant-slot-width section. This last section is integral with the slotted expansion where the liners diverge at a total angle of 9°. The slotted sections were each built up from eleven slats and their associated webbing (Fig. 2), made from aluminium alloy. These were bolted to a steel liner rail and cross-braced. The sections were bolted together with lapped joints.

Originally/

Originally the slats were not cross-braced since they were not expected to sustain any appreciable side force. In fact, the supporting webbing was made as small as possible to avoid constraint in the plenum chamber. However, experience in the N.P.L. 36" × 14" wind tunnel showed that this design was not stiff enough laterally, and each of the liners was cross-braced at five points along the tunnel, two inches below the liner surface, by 3/8 in. diameter rods with spacers to locate the slat positions accurately. This was fairly satisfactory in preventing large amplitude vibration but it was found necessary to make frequent checks on the tightness of the bracing.

Another source of trouble was found at the joints between sections of the liners. The bolts tended to work loose and in one case a fatigue failure was found at a bolt-hole. These mechanical difficulties caused small steps (of the order of 0.002 in.) to occur at the joints and shock waves from the joints were detected on the centre-line of the working section. From this experience it is recommended that all bolts, particularly those which are not immediately accessible, should be fitted with a locking device. In addition it would probably be beneficial to sweep the individual joints so that the disturbances from steps at the joints may be reduced.

The original expansion had a total expansion angle (between the two liners) of 9° with slots of the same width as the working section. At its downstream end it was attached to a wooden block so that all the air extracted from the plenum chamber came through the slots. This design was used to obtain the results from the "unmodified liners".

In order to make use of the 18" × 14" tunnel at stagnation pressures greater than atmospheric it is necessary to have independent control of Mach number and stagnation pressure. Chinneck and North[5] found that satisfactory Mach number control could be achieved using a sonic throat downstream of the working section. To incorporate this in the 18" × 14" liners the expansion was cut off as shown in Fig. 1 and an adjustable sonic throat was inserted. The throat consists of two leaves on each of the shorter sides of the tunnel. The front leaves are approximately 16 in. long and are hinged at approximately 11 in. from the centre-line of the tunnel.

3. Aerodynamic Design

The aerodynamic design of the slotted liners was based mainly on previous experience at the N.P.L.[3,5].

At the end of the slot-entry section and throughout the constant-slot-width section the slot to total area ratio is 0.091 for each liner.

The depth of the plenum chamber is $6\frac{1}{2}$ in. (0.38 tunnel heights) and the maximum blockage, due to webbing is 17 per cent of the cross-sectional area of the chamber. Previous experience and the present experiments show that this depth is sufficient.

Although the early experiments[3] showed the "unmodified" expansion to be the most satisfactory in comparison with others tested at that time, more recent work[5] has suggested improvements. In fact, the modifications necessary to instal the sonic throat resulted in a reduction in power required. No arrangements were made for using auxiliary suction to assist in extracting air from the plenum chamber[11].

The/

The slotted walls each diverged by 9 minutes (0.002 in. per in.) from the centre plane of the tunnel to allow for boundary layer growth. No provision was made for varying the wall divergence.

4. Power Requirements

The power required to drive the empty tunnel, with slotted liners, is discussed below in terms of the blowing pressure, P (i.e., the stagnation pressure of the injected air). Three configurations were tested for a range of injector slot widths. These configurations were:-

(a) the unmodified liners (with the expansion as shown by the dotted line in Fig. 1)

(b) the modified liners with the sonic throat fully open

(c) the modified liners using the sonic throat.

The variation of blowing pressure with Mach number is shown in Fig. 3. Approximate mean curves are drawn to show the trends more clearly. These are found to be very similar to the results obtained in the N.P.L. 9" x 3" tunnel[5]. The results from the two tunnels are shown in Fig. 4 for the same value of A_S/A_W, the ratio of injector slot area to working section area. The differences can probably be attributed to differences in the flow downstream of the sonic throat which have a considerable effect on the injector efficiency. The reasons for the peculiar shape of the 18" x 14" curve near $M = 1.05$ are not known but the measurements are fairly closely repeatable.

Comparison of the blowing pressures for cases (a) and (b) shows that the modified liners are more efficient (Fig. 5). Unfortunately the gauzes in the return circuit were cleaned between the two series of tests and this might account for a small part of the difference.

There was a marked increase in the maximum obtainable Mach number (from 1.14 to 1.22) due to better ejector suction in the expansion section.

5. Flow Surveys

As a preliminary calibration of the working section with slotted liners, the static pressure distribution was measured along the centre line of the tunnel and along the centre slat of each liner. The sonic throat was used to control the Mach number in all the tests reported in this section. When the second throat was not used the results were similar but the pressures were more unsteady.

The centre-line distributions were measured with a 0.08 in. diameter ogival nose static tube with the holes at 22 diameters downstream of the nose. The corresponding Mach number distributions are shown in Fig. 6. When the flow is subsonic, the Mach number is constant to within ±0.002 over a length of 15 in. In the supersonic case the discontinuities are considerably larger and over the same length the maximum deviations from the average are about 0.015. There is no overall Mach number gradient along the tunnel at any of the speeds tested but there are several local gradients. Some of these are fairly large at supersonic speeds and are probably associated with weak waves from the side wall junctions and their reflections.

The Mach number distributions along the centre slat of each liner are shown in Fig. 7. The readings at $x = 19$ in. (upper surface) and at $x = 52$ in. (lower surface) are always high, probably due to badly shaped pressure holes.

At/

At subsonic speeds the Mach number is constant to within ±0.002 from $x = 25$ in. to $x = 45$ in. Downstream of the latter position there is a small but gradual increase of Mach number which becomes more marked near the beginning of the expansion ($x = 58$ in.). This is an upstream effect of the low pressure region in the expansion and it decreases as the Mach number is increased. In the slot entry region there is a small Mach number gradient. This increases with the Mach number in the working section but is always small for $M \leqslant 1$. At $M = 1.05$ there is a pressure increase around $x = 5$ in. which is probably due to shock waves from the joints between the contraction and slot entry sections. At the maximum obtainable Mach number, 1.22, the flow expands considerably in the slot entry region. There is no evidence of shock waves in this region. However, the Mach number does not increase smoothly and it is quite possible that weak shock waves are masked (or cancelled) by the rapid expansion.

Yawmeter traverses were made along the centre line of the tunnel at $M = 0.95$ and 1.15. The probe was a Conrad yawmeter made from two 0.065 in. diameter tubes. It is difficult to decide on the actual zero but the variation of yaw was less than ±0.08° over 15 in. of tunnel length. The symmetry of the surface pressures on a wing placed at geometrically zero incidence suggests that the observed scatter in the flow direction is probably centred about a mean very close to zero.

6. Wall Interference

The first model to be tested in the slotted-wall working section was a half-span model of a swept wing. The position of the model in the wind tunnel is shown in Fig. 8 which also shows the positions of the wall static pressure holes. The geometrical properties of the wing are

Aspect Ratio	= 2.83
Taper Ratio	= 0.33
Leading Edge Sweep	= 53.5°
Streamwise section;	6% thick RAE 102
Frontal blockage ;	0.5% of tunnel cross-sectional area.

The pressure distribution along the centre slat of each wall was measured with the wing at incidences of 0° and 12° at several Mach numbers in the transonic range. Some of the results are shown in Figs. 9, 10, 11 and are discussed briefly in relation to interference effects on the model.

The distributions of Mach number at the walls at the maximum obtainable Mach numbers are shown in Fig. 9 for several configurations. This case of maximum Mach number is one extreme which must be considered in selecting a reference hole to determine the tunnel Mach number. Consideration of the distributions with the empty tunnel and with the wing at zero incidence suggest that the pressure hole at $x = 34$ in. is the only suitable one. However, when the wing is at an incidence of 12°, there is a difference between the local Mach numbers at $x = 34$ in. on the upper and lower surfaces. Fig. 10 shows that this difference increases as the Mach number decreases and suggests that a hole at $x = 31$ in. or further upstream should be used as a reference hole. From the blockage effects shown in Fig. 11 it was decided that the pressure hole at $x = 25$ in. was the most suitable since at this position blockage effects were negligible at subsonic speeds. Since the maximum Mach number is not reached until $x = 34$ in. the tunnel

Mach number corresponding to the pressure measured at $x = 25$ in. is too low and a correction must be made to the indicated Mach number. The variation of this correction with Mach number is shown in Fig. 12.

The presence of a model in the working section reduces the maximum obtainable Mach number (Fig. 9). When the model is at zero incidence the reduction in tunnel Mach number is negligible (about 0.002), but the extra blockage at $\alpha = 12°$ causes a reduction in Mach number of about 0.04.

The effects of the wing at other Mach numbers are shown in Figs. 10 and 11. These figures were constructed from the measured wall pressures when the wing was at twelve degrees incidence. The wall pressures with the wing absent are subtracted to eliminate tunnel variations and the differences are converted to Mach number differences ΔM_{upper} and ΔM_{lower}. Measures of the lift and blockage interference effects are obtained as ΔM_L, ΔM_B where

$$\Delta M_L = \tfrac{1}{2}(\Delta M_{upper} - \Delta M_{lower})$$

$$\Delta M_B = \tfrac{1}{2}(\Delta M_{upper} + \Delta M_{lower}.)$$

Wall interference at supersonic speeds has been studied in Refs. 7 and 8 and the present experiments do not contribute materially to this. However, one relevant problem is well illustrated in Fig. 9. The minimum Mach number at the lower liner is only slightly supersonic and therefore reflected waves from this wall are initially at small angles to the normal and some of them may interact with the model. This suggests that there may be some advantage in placing a lifting model asymmetrically in a slotted wall tunnel.

At slightly supersonic Mach numbers (between 1 and 1.03) there is evidence from some tests on static tubes that Mach interactions between weak shock waves associated with the model and extraneous shock waves from the tunnel walls may be important. The interaction may alter the flow pattern (e.g., change the shape of the bow shock wave) although it may not have a large effect on pressures on the body.

As the Mach number is decreased the magnitude of the disturbance at the wall decreases and moves upstream (Fig. 11). It also decreases in size as the incidence is decreased and at zero incidence at $M = 0.85$ the model has no measurable effect on the wall pressure distribution. It seems reasonable to assume that results obtained at zero incidence at $M \leqslant 0.85$ are free from blockage interference; this is supported by the theory of Maeder and Wood[4] which gives the velocity increment, δu, due to blockage as

$$\left|\frac{\delta u}{U}\right| \simeq 0.00003$$

for a square tunnel. (The actual height to width ratio of 0.6 for the 18" × 14" tunnel should not increase the order of the correction.)

Pressure measurements on the wing are available at $M = 0.6$ and 0.85 with both solid and slotted liners. The differences between the two sets of results were examined and compared with simple interference corrections. The Mach number and incidence corrections ΔM and $\Delta\alpha$ respectively, necessary to make the two sets of results coincide are shown in Table I together with the theoretical estimates.

TABLE I./

TABLE I

The Mach number and incidence corrections required to make the results from the solid liners coincide with those from the slotted liners

M	ΔM		$\Delta\alpha/\alpha$	
	Theory	Expt	Theory	Expt
0.6	0.002	0.003	--	--
0.86	0.011	0.012	0.16	0.16

It is thought that the slotted wall results do not require any blockage correction. Therefore the second column shows the theoretical value of the solid and wake blockage correction for the solid-wall results. This is given by

$$\frac{\Delta M}{M} = \left(1 + \frac{1}{5} M^2\right)\left(0.62 \frac{V_m}{h^2 b \beta^3} + \frac{C_D}{4\beta^2} \frac{S_m}{bh}\right).$$

Column three shows the difference between the slotted and solid wall results found experimentally. There is good agreement between theory and experiment.

The correction, $\Delta\alpha$, to the incidence of a wing in a solid-wall tunnel is given by

$$\left(\frac{\Delta\alpha}{\alpha}\right)_{solid} = 0.12 \frac{S_m}{bh} \frac{\partial C_L}{\partial\alpha}.$$

The correction for the wing in the slotted working section is given by Maeder and Wood[4] and is approximately equal and opposite to the above correction for solid walls. Therefore the difference between the solid and slotted wall results is expected to be equivalent to an incidence correction of $\Delta\alpha$, where

$$\frac{\Delta\alpha}{\alpha} = 0.24 \frac{S_m}{bh} \frac{\partial C_L}{\partial\alpha}.$$

The value of this expression is shown in column four of Table I and the experimental difference is shown in the next column. The agreement may be fortuitous because the correction seems to increase from leading to trailing edge and the figure given represents an average value. It should be noted that the correct results at incidence lie approximately halfway between the slotted-wall and solid-wall results after the latter have been corrected for blockage.

7. Concluding Remarks

Preliminary calibration showed that the slotted working section was satisfactory for testing at all Mach numbers up to the maximum obtainable. At subsonic Mach numbers the Mach number distribution in the working section was constant to ±0.002. The equivalent figure at supersonic Mach number varied up to ±0.015 at the maximum Mach number.

Wall/

Wall interference was negligibly small at subsonic speeds for a model of 0.5% blockage. The differences between measurements made with solid and slotted walls at a Mach number of 0.85 were found to agree closely with the theoretical corrections which should be applied to the solid wall results.

The power required was decreased by an alteration to the slotted expansion. The general trend of the power required to obtain a given Mach number was found to agree with results obtained in the 9" × 3" tunnel[5].

8. Acknowledgements

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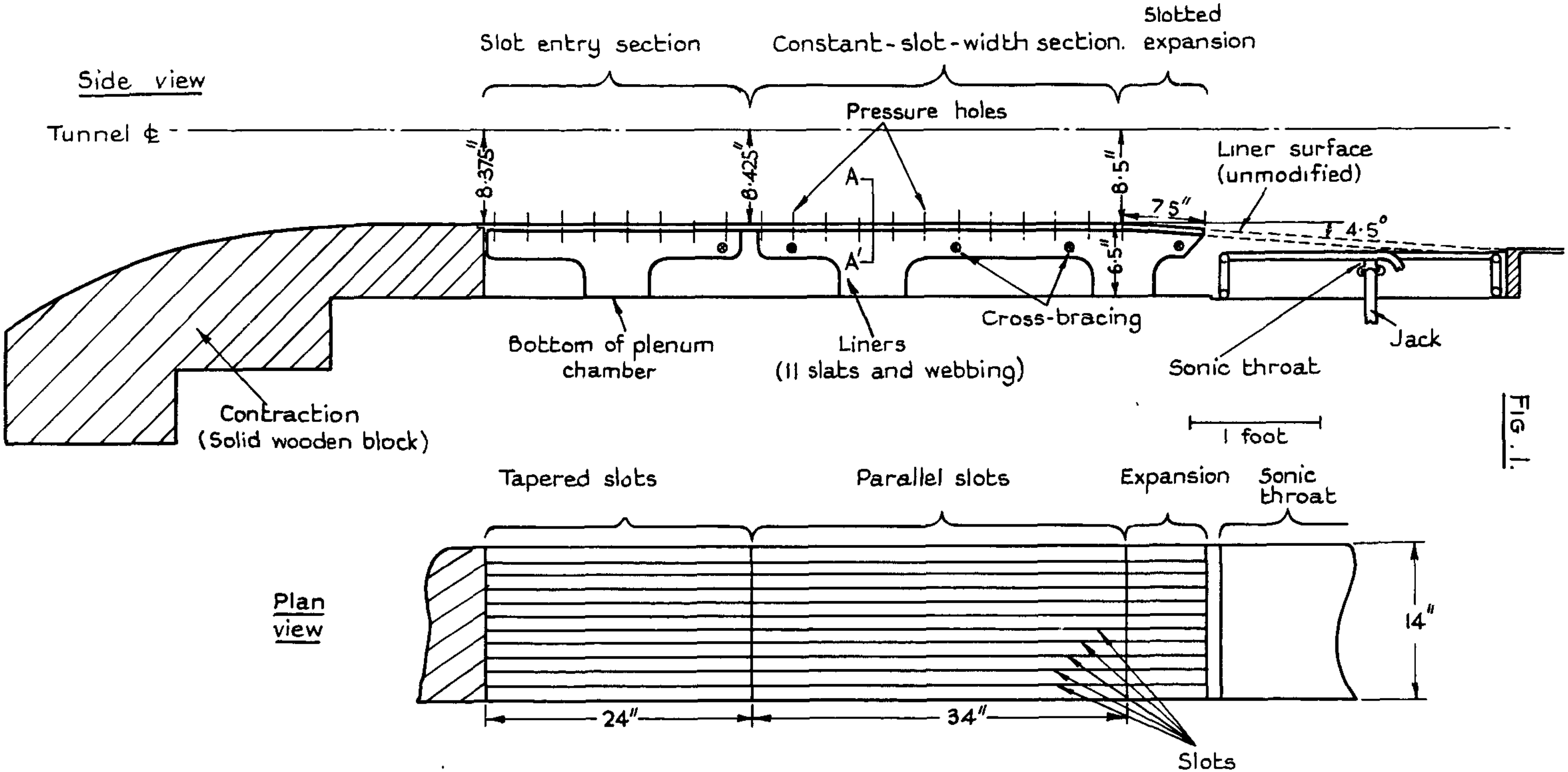
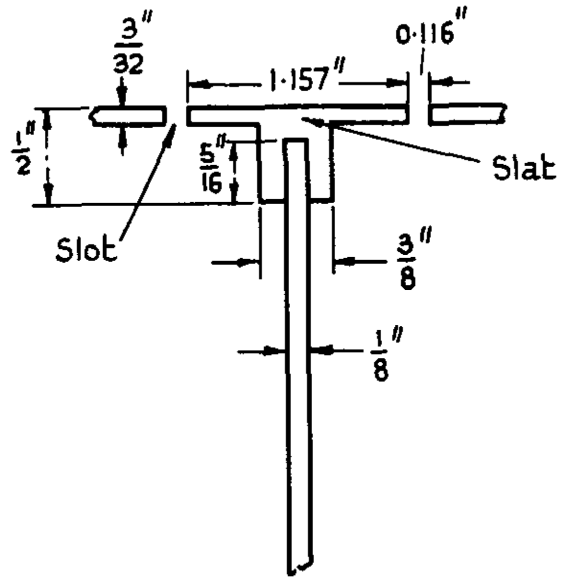


FIG. 1.

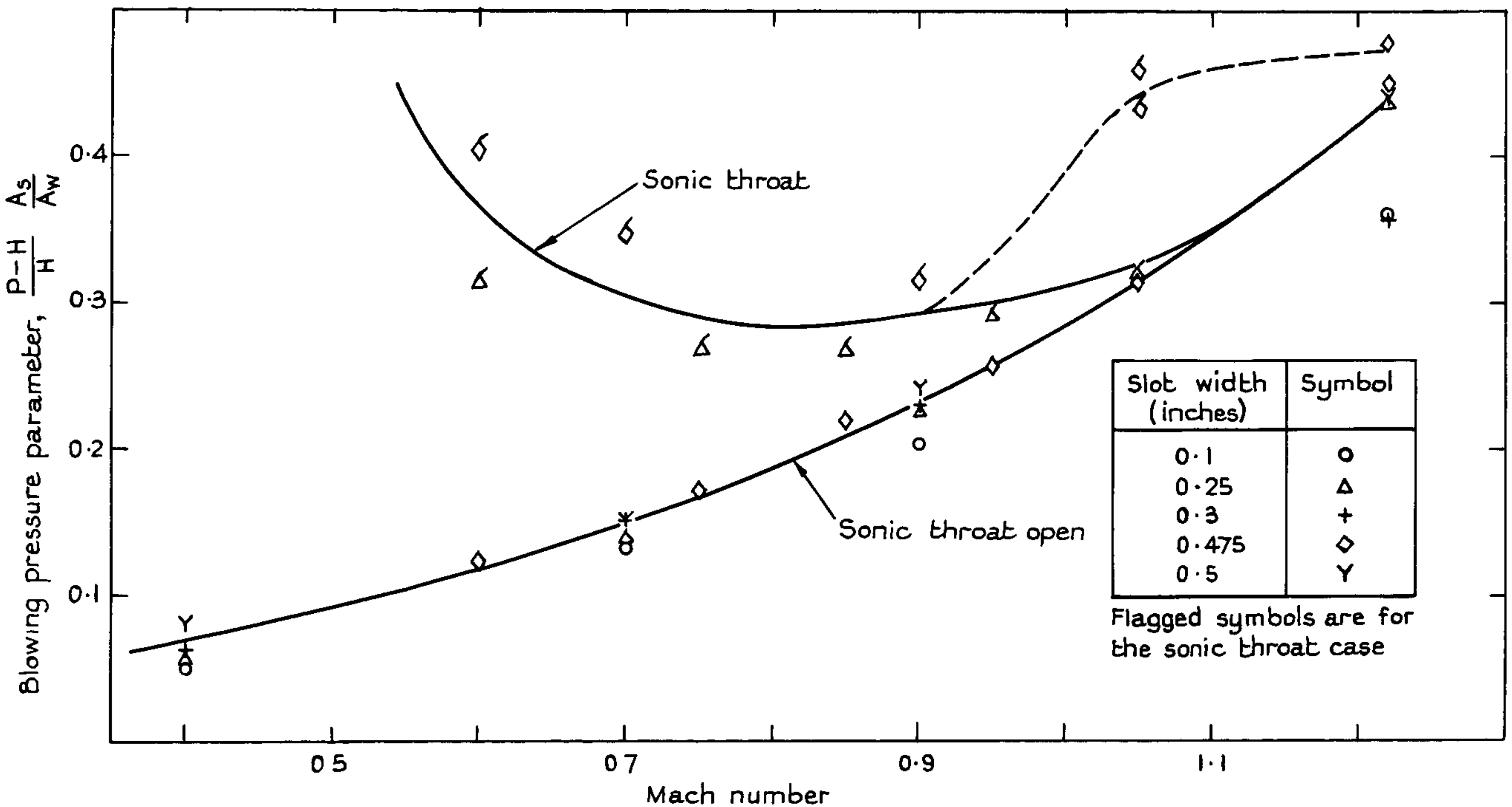
General arrangement of the slotted liners (See also fig. 2)

FIG. 2



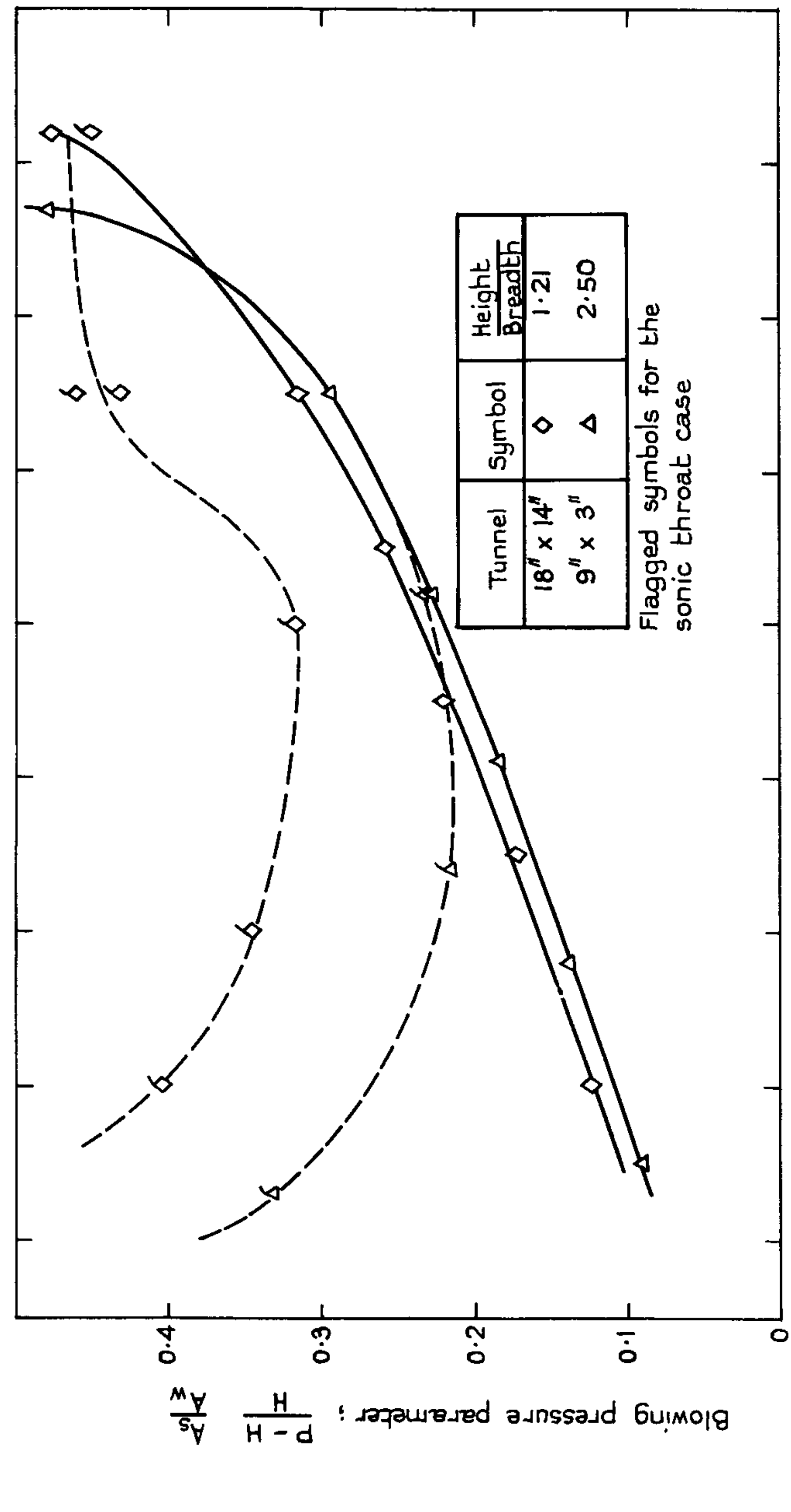
The detail design of a slat. Cross-section taken perpendicular to the tunnel axis at AA' (see fig 1)

FIG. 3.



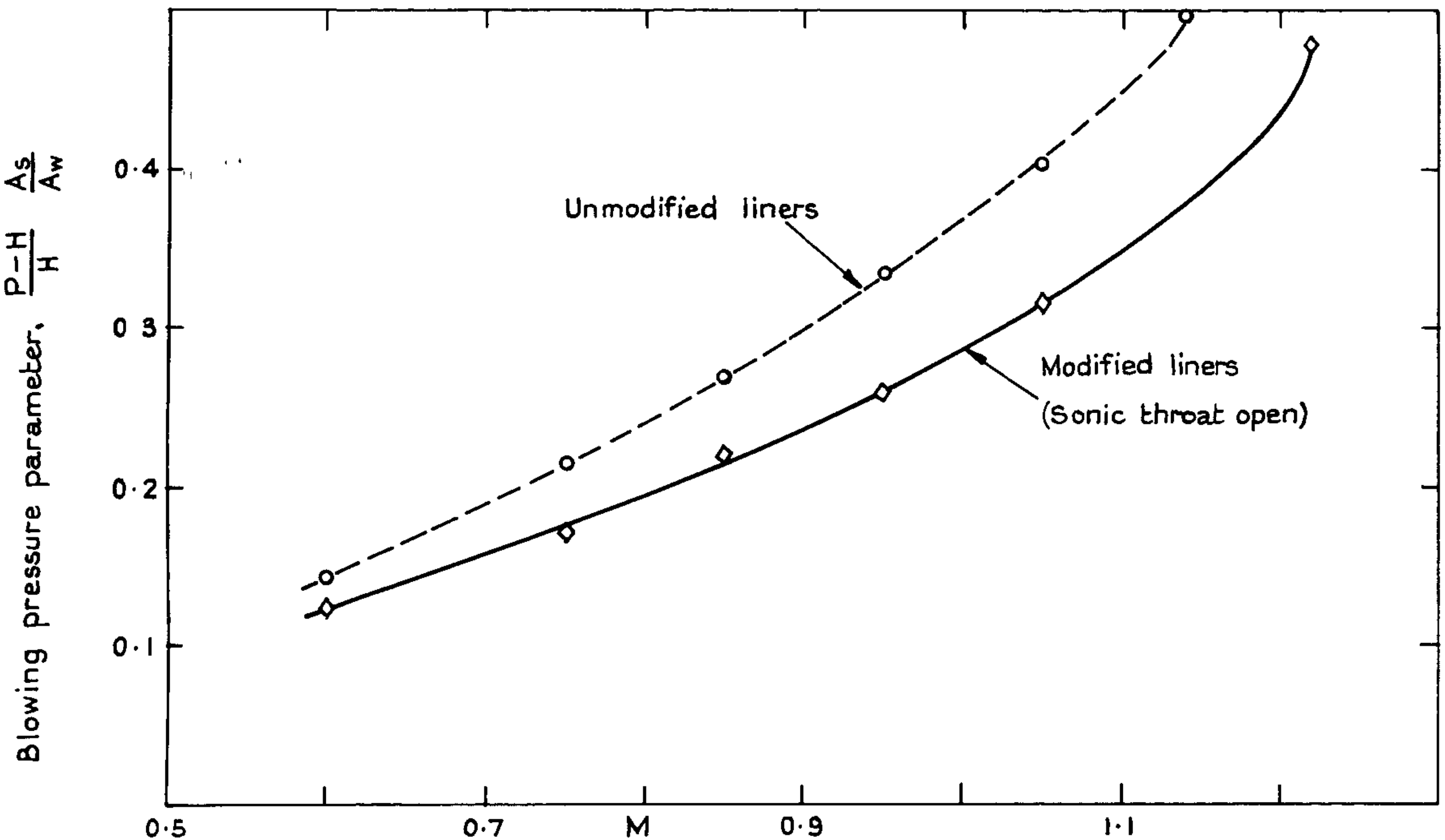
Blowing pressure v Mach number for modified liners

FIG. 4



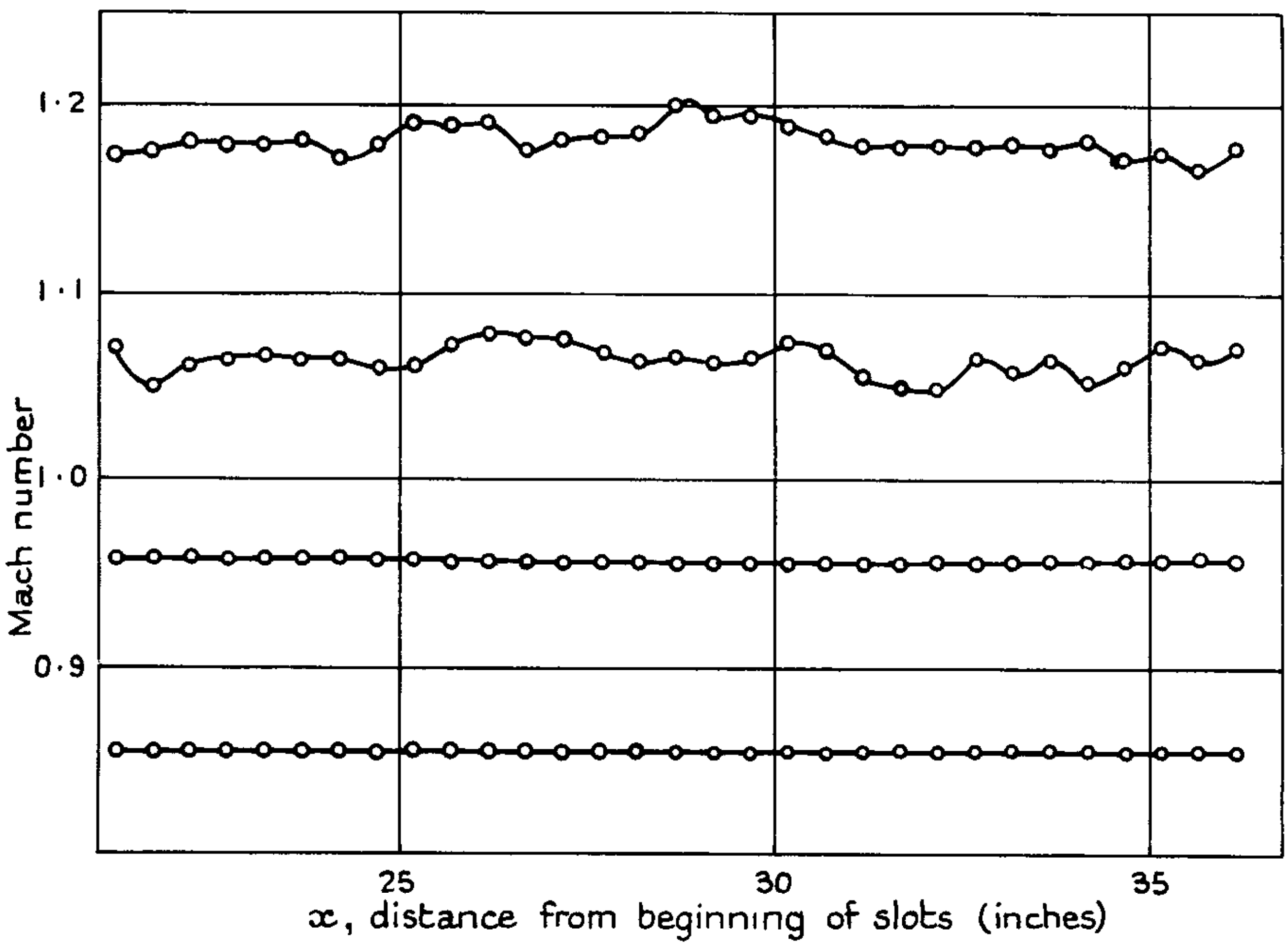
Comparison with results from 9" x 3" tunnel, $\frac{A_s}{A_w} = 0{\cdot}14$

FIG. 5.

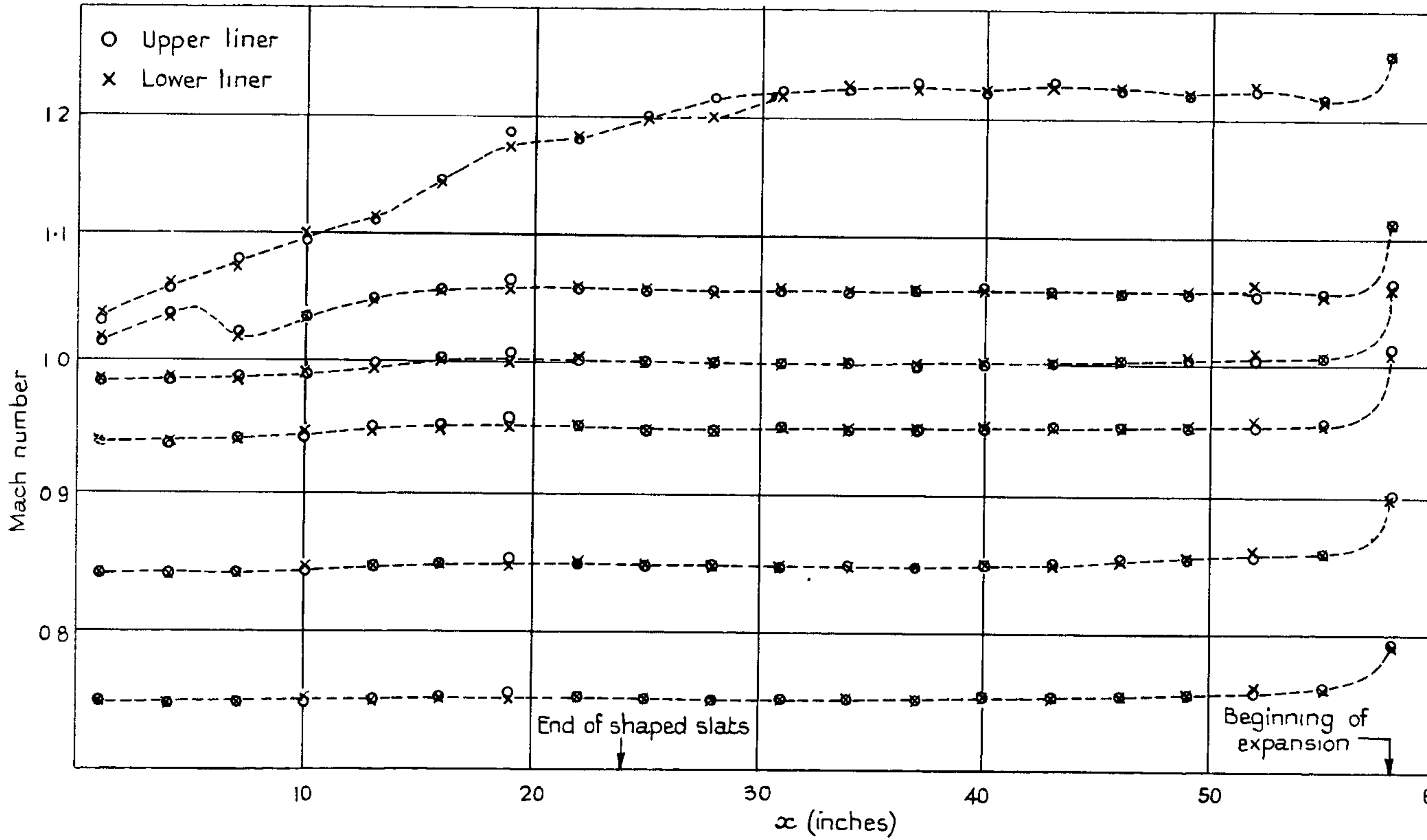


The effect of expansion shape on blowing pressure, $\frac{A_s}{A_w} = 0 \cdot 14$

FIG. 6



Mach number distributions on tunnel centre-line



Mach number distributions along liners

FIG 7

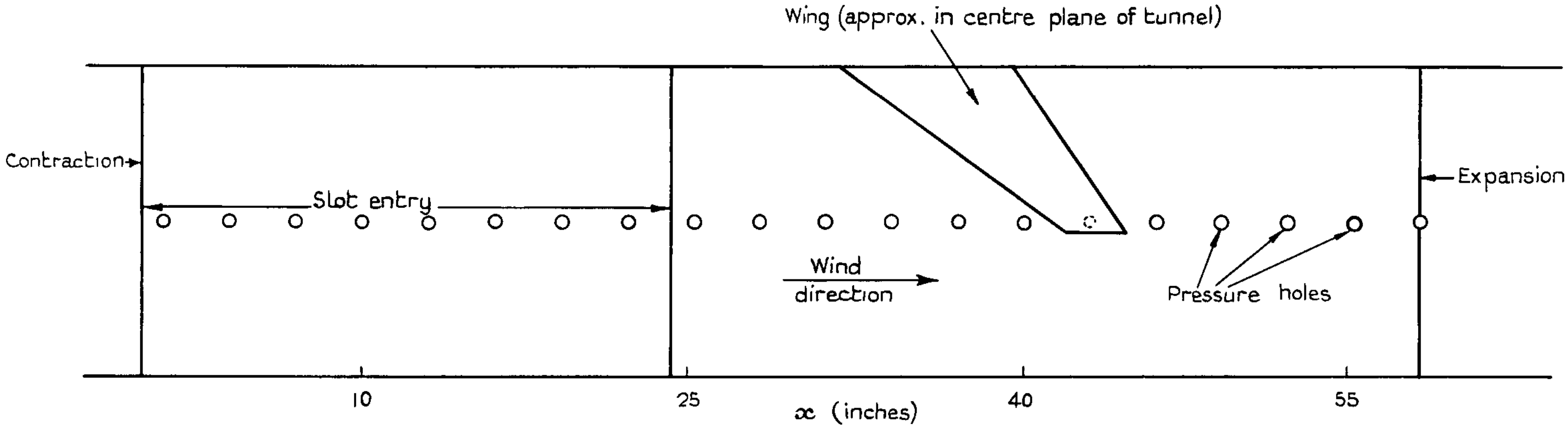


FIG 8

Position of wing in tunnel

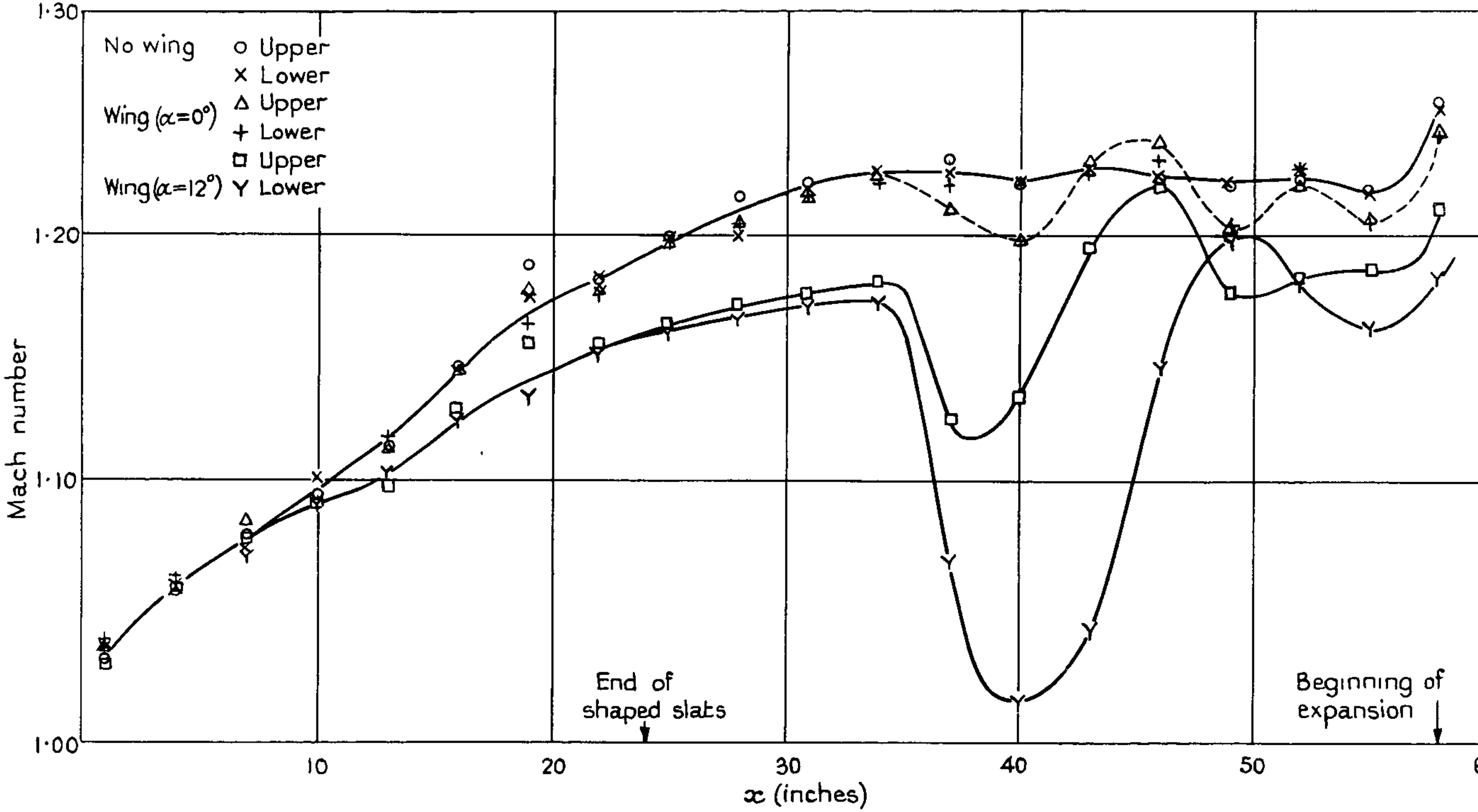
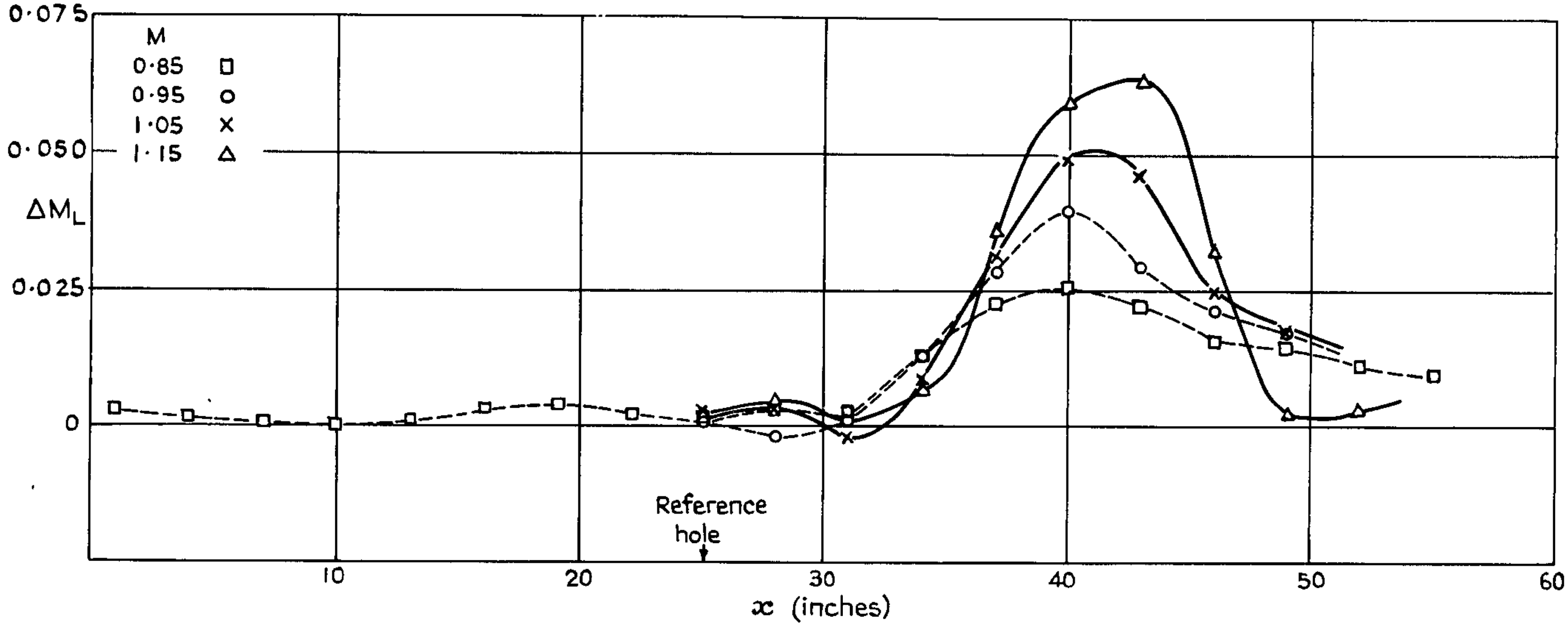


FIG. 9.

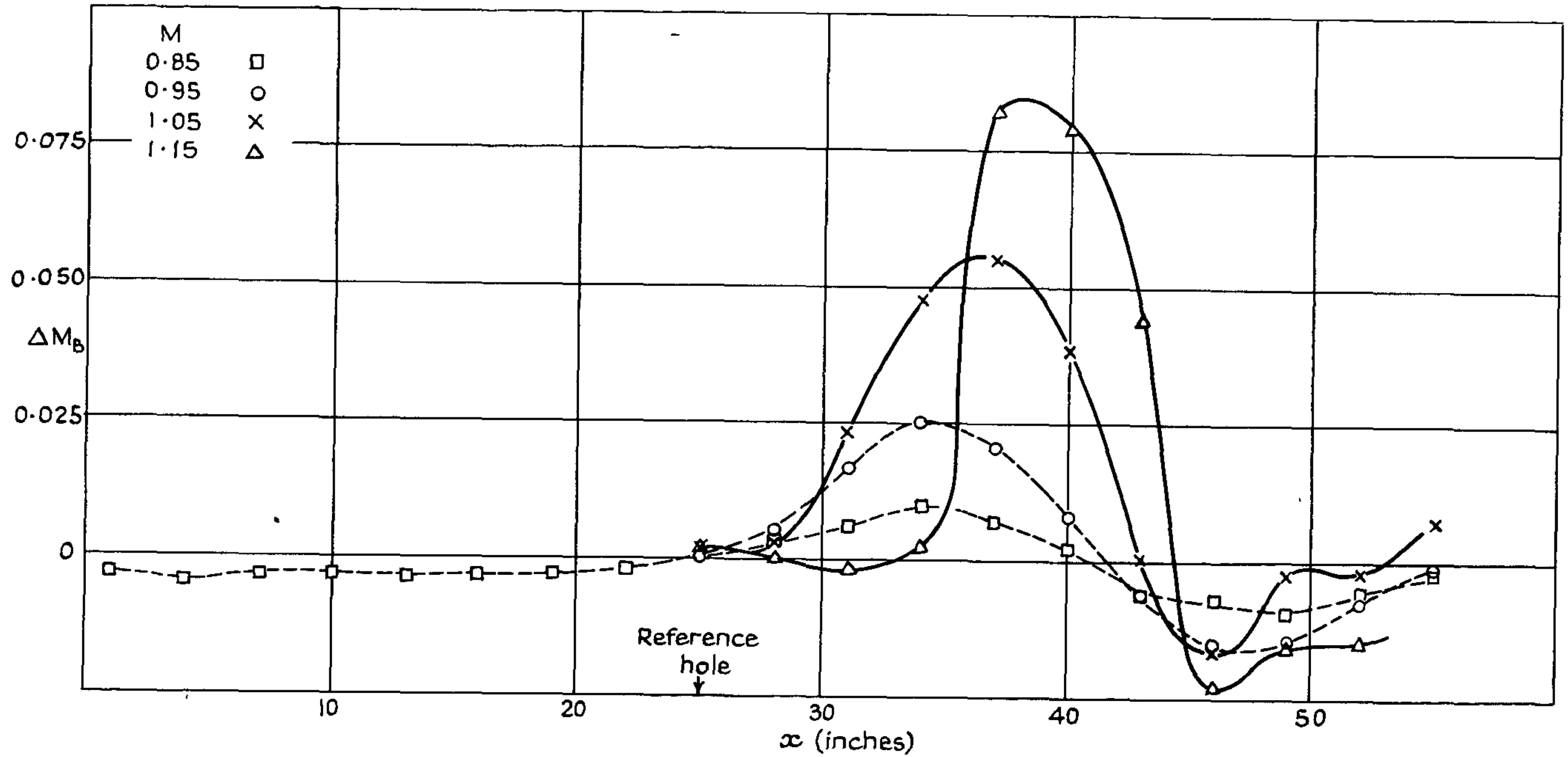
Effect of the wing on the wall distribution at the maximum Mach number

FIG 10.



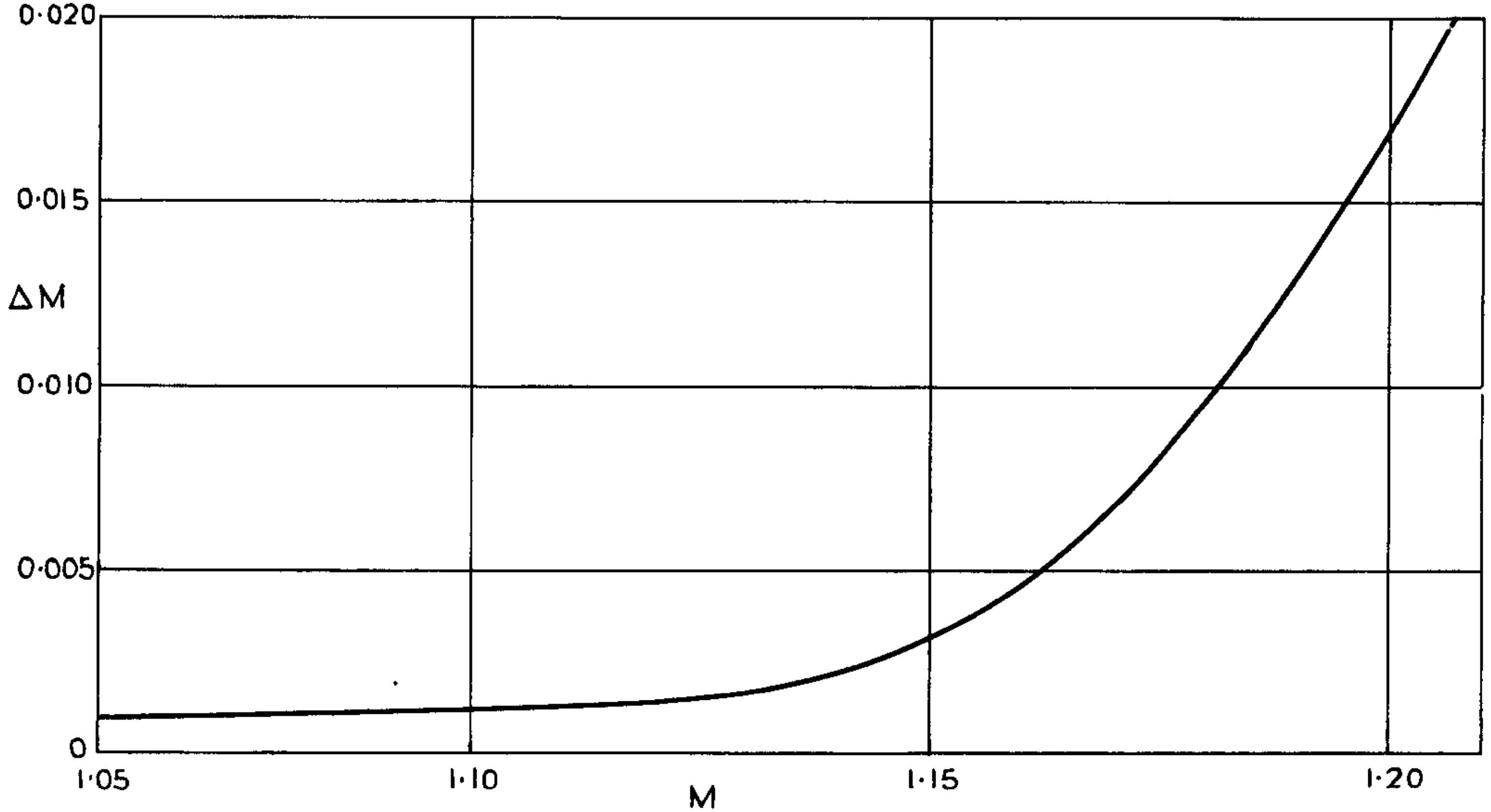
Lift interference at the tunnel walls. ($\alpha = 12°$)

FIG 11



Blockage interference at the tunnel walls. ($\alpha = 12°$)

FIG. 12



Correction to the indicated Mach number due to the pressure gradient between the reference hole and the model position

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