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The Manufacture of Aerofoil Models by Tangent Plane Milling

By

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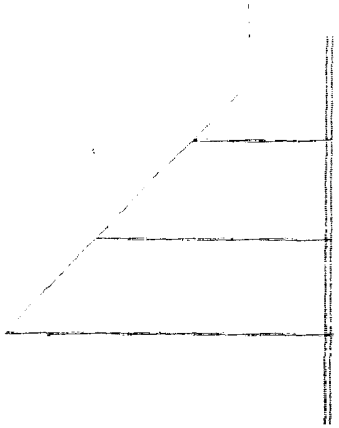

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ADDENDUM

Since this paper was written a number of models have been made, by milling and surface grinding, using the tangent plane tecnique. It has been found that, given good milling or surface grinding machines, accurate jigs, and constant checking by means of the simple measuring tecniques described, adequate control of the process can be maintained. By grinding, the simpler models such as a half delta wing, can be made within ±0.0005 in. of nominal size with a variation over large areas of only 0.0003 in.

The main difficulty in producing accurate models is, of course, the instability of the material of the model during manufacture and a number of materials have been tried with varying degrees of success. So far the most successful appear to be Ledloy for models made entirely by milling and S11 for those made by grinding, although neither of these materials is entirely free from distortion when machined. It is the opinion of the author that any good quality steel, heat treated by standard methods appropriate to the steel, can be used satisfactorily and the solution to the problem of instability is to be sought in the method of machining rather than in a search for an ideal material. It has been found that trouble due to distortion is negligible if, from the early stages of roughing out, metal is removed as nearly as possible uniformly from the whole surface. For example, when making a symmetrical half delta model of roughly 4 in. base chord and 4 in. span in S11 steel, the procedure was to choose six planes for each of the two surfaces and, working alternately from side to side, machine these twelve planes until each was within 0.002 in. of finished size. This particular model was finished by grinding and the complete program of machining was as follows. By milling, each of the twelve planes was taken down to about 0.050 in. of size, then to 0.030 in. and finally to 0.020 in. of size. The blank was then transferred to the grinding jig and each plane ground first to 0.015 in. of size, then to 0.010 in., to 0.005 in. and finally to 0.002 in. of size. Finally all finishing planes, 25 per side, were ground to within 0.0005 in. of nominal size. It was found that as each plane was cut the model distorted away from the cutter when milling and towards the wheel when grinding. Most distortion occurred when grinding from 0.020 in. to 0.015 in. of size and it was evident that the previous milling operations had work hardened the surface setting up surface stresses. Subsequently the amount of distortion diminished, until in the final stages the maximum movement as any one plane was cut was within the 0.001 in. tolerance and by grinding alternately from side to side the residual distortion of any one plane was within only a few ten thousandths of inch.

There appear to be no reasons why this procedure should not solve the problem of distortion while maching, and with experience, the amount of distortion can be anticipated, and the number of stages reduced. With good jigs and careful measurement it should be possible to mill within 0.010 in. of size and so reduce the time for grinding.

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The Manufacture of Aerofoil Models by Tangent Plane Milling.

- By -
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Communicated by Mr. A. Fage, F.R.S.

1st June, 1953

Introduction

The increased use of high-speed tunnels has led to an increasing demand for small metal aerofoils of high precision. In addition to two-dimensional aerofoils of constant section there is a particular demand for "three-dimensional" aerofoils of the delta wing type where the section progressively diminishes from root to tip.

Experience had shewn that attempts to produce the required form by methods which relied mainly on hand work failed to provide the precision required, final inspection revealing errors of form which made the models unacceptable to the limits imposed. It was therefore decided to try a machining process which would generate the form required by cutting a large number of enveloping tangential planes. Apart from its sound geometrical principle, this technique provided the considerable advantage that a simple form of inspection could be carried out during the actual manufacturing process, so eliminating a lengthy and elaborate final inspection. The Metrology and Aerodynamics Divisions of the N.P.L. collaborated in the trials and the results, with details of the method, are described in this paper. Part I deals with the construction of a two-dimensional aerofoil and Part 2 a three-dimensional one.

The method described in this paper is a milling process followed by a minimum of hand finishing to ensure a smooth blending of the tangential planes. The use of milling methods was prompted by the fact that the standard dividing heads and tilters available were suitable only for use on large machines. The high precision of form required had naturally suggested that the models should be made by grinding, but the construction of the necessary special fixtures would have introduced appreciable delay. Subsequent to the completion of the two models described, it was learned that Messrs. Rawlings and Partners, Kenilworth, Warwick had independently and with complete success applied a similar technique to the manufacture of aerofoil models by grinding. With the experience gained from milling aerofoils and the benefit of discussions on this work with Mr. Rawlings it is proposed, as soon as the necessary fixtures can be made, to grind hardened steel aerofoils at the Laboratory.

Since the production of the models described, others have been made successfully and a roughing jig has been introduced which facilitates the early stages of manufacture. It is believed that with practice, and some further simple measuring equipment to avoid the use of slip gauges, the double objective of eliminating final inspection and shortening the time of manufacture compared with previous methods will be achieved.

PART I/

PART I

Two-dimensional Model

The object of this trial was to manufacture a two-dimensional aerofoil as closely as possible, with existing equipment, to the nominal sizes given in Fig.1. The form of the section comprised a 1:16 ellipse followed by a parallel section followed by a tapered tail finishing at a sharp edge. The work was carried out on a universal milling machine using a Zeiss dividing head for rotating the aerofoil.

Principle of Method and Data Required

The method of manufacture comprised precise rotation of a blank under a precisely set milling cutter which would generate planes tangential to the form required. Fig.2 shows the section and a typical tangential plane.

In practice a blank was mounted between centres and could be rotated precisely under a cutter which, at any particular setting, moved in a plane parallel to the line of centres. By suitably adjusting the height of the cutter above the line of centres for a particular rotational setting of the blank, it could be made to remove all metal above a plane tangential to the section required.

To make the necessary settings on the machine to form the elliptic section it was required to know the inclination ψ of the tangential planes with the plane of symmetry and the perpendicular distances p of these planes from the line of centres. Values of ψ and p at 2 degree intervals on the auxiliary circle were provided by the Mathematics Division of the Laboratory correct to 0.2 minutes of arc and 0.0001 in. respectively. In addition the corresponding values of x and y (Fig.2) correct to 0.0001 in. were provided for final inspection purposes.

In practice it proved to be unnecessary to use all the data provided. Only sufficient planes were cut to ensure that the excess metal l (Fig.3) at the intersection of any two successive planes was less than 0.0002 in. With this condition only 22 planes per side were required, ranging from 2 degree auxiliary circle intervals at the leading edge to 6 degree intervals towards the blend with the parallel section.

Preparation of Blank

The blank was made from bright rolled mild steel bar which was heat treated after removing the scale. It was made $5\frac{1}{2}$ in. long which ensured adequate clamping allowance at the dividing head end and about $\frac{1}{4}$ in. excess at the tailstock end. This excess metal at the ends was not cut in the subsequent machining and gave the aerofoil rigidity in the final stages when the metal at the leading and trailing edges was thin. The surfaces and edges of the blank were surface ground to give a rectangular section leaving at least 0.020 in. on each face to be removed in the final milling operations.

Set Up and Operation of Machine

The vertical head of the milling machine was assembled and adjusted so that the axis of the $\frac{1}{2}$ in. diameter two-fluted Clarkson cutter was perpendicular to the work table. The Zeiss dividing head and tailstock were clamped to the work table and adjusted so that the traverse of the cutter relative to the work table was parallel to the line of centres within 0.0001 in. over 6 in. (Fig.4).

A 0.0001 in. reading micrometer head with a spherical contact point was rigidly attached to the milling head and could register (when the work table was traversed to a particular position, known as the "setting position") on a pile of robust end bars and slip gauges placed at a fixed position on the work table.

This/

This auxiliary measuring arrangement, as will be shown later, enabled the cutter to be set at precise distances above the centre line of the dividing head. Because the micrometer was attached directly to the milling head and the slip gauge pile was always placed at the same position on the work table the precision of setting the cutter was nearly independent of the thermal expansion of the machine* and the lack of flatness of the work table.

To establish the "zero" of the micrometer two light cuts were made across the blank, the first with the dividing head set to 0° and the second with it set to 180°. Neither the longitudinal setting of the work table nor the vertical setting of the cutter were moved during this operation. The work table was then traversed to the "setting position" and the micrometer reading on a suitable slip pile recorded. From half the thickness of the blank measured between the two cuts and the recorded micrometer reading, the slips and micrometer setting required to set the cutter at the centre line of the dividing head were determined. This latter setting constituted the "zero" for the micrometer and hence the slips and micrometer setting necessary to set the cutter at any of the desired positions, p, above the centre line could be readily determined**.

At this stage, it was considered essential to establish a datum surface so that the "zero" of the micrometer could be checked periodically in the course of the three to four days required to mill the aerofoil. This was done by clamping a block of metal to the work table and milling a flat on the top surface parallel to and approximately at the same height as the line of centres. The actual height of this datum surface above the line of centres was measured by traversing to the setting position immediately after the surface was cut and recording the micrometer reading.

Subsequently, at regular intervals during the course of the final machining of the aerofoil, the cutter was lightly touched on this datum surface and the corresponding micrometer reading noted. Any departure from the original reading was recorded and subsequent settings of the cutter were corrected by this amount. In this manner compensation was made for the movement of the milling spindle in its bearings due to thermal expansion and for the slight wear of the cutter. Corrections up to 0.0005 in. had to be made for this cause. It was invariably found, after 1 to 2 hours running, that the spindle had risen slightly in its bearings.

Roughing/

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*The thermal expansion of the milling machine during the course of a day's continuous running was large compared with the accuracy to which aerofoils are required. As a check on this thermal expansion, the corresponding readings of the vertical movement as shown on the machine's scale were recorded at the same time as the vertical settings made with the auxiliary measuring equipment. It was found in the course of a day's running that the error in the machine's scale was as much as 0.005 in. This is due to the fact that the macine is analogous to a caliper gauge, the overhanging milling head and work table corresponding to the anvils and the main body of the machine, which becomes hot due to the circulation of oil, corresponding with the bow.

**In future work the setting of the cutter could be simplified in the following manner. The micrometer head used should be graduated like a depth gauge, i.e., the graduations should be in the reverse direction as compared with a standard micrometer head. The cutter would then be set to the centre line of the dividing head as described above and the micrometer clamping adjusted so that the micrometer read zero on a slip pile comprised of an integral number of inches. Any setting of the cutter in the range 0 to 1 in. above the centre line could then be read directly from the micrometer. For settings beyond 1 in. the slip pile would be changed by the appropriate number of inches and the decimal part still read directly from the micrometer.

Roughing Out

Eight tangential planes per side were cut to roughly form the elliptic section. Each cut was set to leave 0.010 in. excess metal to be removed by the finishing cuts. The parallel and tail sections were also roughed out to within 0.010 in. of size. At this stage the aerofoil was again heat treated. It was packed in alumina, raised to 700°C and allowed to cool over night.

Finishing

The aerofoil was remounted between centres and clamped to the dividing head centre. No difficulty was found in adjusting the clamping so that the dividing head read zero when the parallel portion of the aerofoil was parallel, within 0.0001 in., to the plane of traverse of the cutter.

The dividing head was then set to 90° so that the plane of the aerofoil was vertical and the leading edge uppermost. The cutter was set to be 1.5000 in. above the centre line and a cut made longitudinally along the leading edge starting at the tail-stock end.

The first tangential planes adjacent to the leading edge were then cut in the following manner. The cutter was set to the appropriate height, p_1, above the line of centres and the dividing head set to $90^\circ + \psi_1$. The cutter was then run in transversely by hand near the tailstock end, but clear of the $\frac{1}{4}$ in. excess metal mentioned above (Fig.5). The automatic longitudinal traverse was engaged and the cut allowed to run to within $\frac{3}{4}$ in. of the dividing head end when the automatic traverse was stopped and the cutter fed out transversely by hand. Without moving the vertical setting of the cutter, the dividing head was set to $90^\circ - \psi_1$ and a similar cut made on the opposite surface of the aerofoil. This process was repeated for each of the 22 tangential planes required to form the elliptic section. It should be noted that each vertical setting of the cutter was used to cut two planes symmetrically disposed relative to the 90° rotational setting and thus symmetry of the two surfaces of the aerofoil was assured.

It was found that a different depth of cut and finish were produced according to the direction of traverse of the cut and that therefore excess metal should always be left at each end of an aerofoil to allow the cutter to be fed in and out.

The trailing edge, which was inclined to the plane of symmetry by approximately $10\frac{1}{2}^\circ$, was cut in a similar manner to the tangential planes of the elliptic section. Care had to be taken when cutting near the feather edge as the thin metal tended to spring away from the cutter. The broken excess metal at the feather edge was finally removed by setting the dividing head to 270°, i.e., feather edge uppermost, and the cutter traversed longitudinally by hand at the correct height but without rotation of the cutter. In this manner the feather edge was planed or shaved off thus obviating the burring over which a milling action would have had.

After a preliminary inspection the aerofoil was finished by rubbing with fine emery cloth to remove the light milling marks and slight excess metal at the intersections of the tangential planes. Finally the excess metal at the ends of the aerofoil was removed by milling and the mounting lugs formed.

Inspection

Measurements perpendicular to the plane of symmetry were made on both surfaces of the aerofoil along three chords. The chords were spaced at mid length and 0.5 in. from each end. The measured departures from the nominal form are shown in Fig.6. It will be seen that the form of the elliptic section and parallel portion is within ±0.001 in. from nominal while the tail portion is convex and has excess metal up to 0.002 in. per side. These errors are not considered excessive and the aerofoil was acceptable for use.

It will be noted from Fig.6 that

1. The errors of the two surfaces are symmetrical.
2. The errors are periodic in nature.
3. The line of symmetry of the tail is inclined to that of the parallel section.

The symmetry of the errors is, of course, attributable to the method of cutting corresponding tangential planes at the same cutter setting.

The periodic nature of the errors (excess metal at 0.1 in., 0.75 in. and 3 in. and metal missing at 0.3 in. and 2 in. from the leading edge) is surprising as all cutter settings were made to an accuracy of ±0.0002 in. If the observations near the leading edge are ignored it would appear that the periodicity is related to the time of cutting as the first 0.2 in. was cut on the first day, up to 2.5 in. on the second day and the tail finished on the third day. There is therefore an indication that cuts became progressively heavier in proportion to the machine's running time.

No periodic check was made on the relationship of the zero setting of the dividing head with respect to the plane of traverse of the cutter and it is probable that the 'zero' of the dividing head shifted with respect to the cutter in proportion to the running time due to thermal expansion of the machine. This would account for the inclination of the tail with respect to the parallel portion as the latter was cut at the end of a day's running while the former was cut after a short warming up period.

Plaster casts were made in the neighbourhood of the leading edge before and after finishing with emery cloth. These casts were optically projected at a magnification of 50x and the results are shown in Figs.7 and 8. A number of the tangential flats with the slight excess metal at their intersections can be seen in Fig.7.

The asymmetry of opposite flats near the leading edge may have been caused by a shift in the vertical setting due to the easing of the thrust bearing of the vertical traverse as the heavily loaded work table was traversed. It was noted several times that the setting of the micrometer had appreciably altered after the work table had been traversed from the setting position and back. Fig.8 shows the smooth form achieved after the removal of the excess metal by emery cloth.

A comparison of measurements made along a chord near the end of the aerofoil directly after milling with those made in the final inspection, showed that very little metal was removed by the emery cloth and no distortion occurred when forming the lugs.

Conclusions

The accuracy achieved in the manufacture of this aerofoil was considered very satisfactory in view of the large errors that could have been introduced by the thermal expansion and inaccuracies of the traverses of the machine used.

It is considered that greater accuracy in the manufacture of aerofoils by this method would be achieved, and more readily, on a machine tool which could provide the following:-

(a) a work-table, with automatic feed, moving in a fixed horizontal plane to an accuracy of the order of 0.0001 in.

(b) a vertical milling head which can be set in relation to the work-table to an accuracy of the order of 0.0001 in.

(c) a "zero" relationship between work-table and milling head, both linear and angular, unaffected by continuous running of the machine.

PART 2/

PART 2

Three-dimensional Model

One of the simplest types of three-dimensional aerofoil used in high-speed tunnels is the half-delta wing and for this reason a half-delta wing, having an RAE 102 6% aerofoil section at the root chord, was chosen for this trial.

Geometrical Considerations

Fig.9 shows a typical half-delta wing model. The surface is defined by the locus of a straight line which passes through a vertex S and sweeps out a previously defined aerofoil section LRTQ in the root plane. In other words, the half-delta wing model is a cone with an aerofoil section as base. The simplicity of this type of model, from the manufacturing aspect, lies in the fact that, provided the aerofoil section has no points of inflection, each generator of the surface lies in a plane which is tangential to the surface and which meets the surface only along the generating line. Fig.10 shows a typical tangential plane which contains the generator RS and intersects the plane of symmetry in CS.

By cutting a large number of these enveloping tangential planes in an oversized blank the required model can be produced. The practical problem of cutting these enveloping planes can be resolved into

(1) providing a means of cutting a plane parallel to, and at any required distance from, a datum surface,

(2) presenting the blank to the cutter in such an aspect that any specified tangential plane is parallel to the datum surface and at a known distance from it.

The Bryant-Symons jig-borer, used as a milling machine, was adapted to achieve (1) above; while an S.G. dividing tilter mounted on the work table of the jig borer was used to achieve (2).

Adaptation and Control of Jig-borer

The basic features of the jig-borer used are a 28" × 19" work-table having a longitudinal traverse and a boring head traversable on a cross beam supported at its ends on two vertical columns. The longitudinal traverse of the table and the transverse movement of the boring head are manually controlled by hand wheels operating lead screws.

To make the machine suitable for milling it was necessary to provide a slow power feed to the work-table. Accordingly a $\frac{1}{2}$ h.p. motor was coupled by a belt drive to the hand wheel which traverses the work-table of the machine thus providing a power feed for milling purposes. A 2-fluted end mill of $\frac{1}{2}$" diameter was inserted in the boring head and the distance of the cutting edges from the work-table was measured by means of slip gauges and a ten-thousandth reading dial gauge mounted on a stand. With the vertical feed of the boring head locked, it was found that a predetermined distance of the cutting edges of the end mill from the work-table could be maintained within 0.0002 in. independently of longitudinal traversing of the table or cross traversing of the head, provided the spindle was run for about 20 minutes to allow it to warm up. Thus planes could be cut parallel to the work-table or datum surface, and at any desired distance from it to an accuracy of 0.0002 in.

Presentation of Blank to Cutter

Fig.11 shows the essential features of the S.G. dividing tilter used for mounting the blank. The circular rotatable face plate AB is normal to its axis of rotation PO. By means of a hand wheel the face-plate can be rotated about PO through any angle from 0-360° and set to 1 second of arc.

The/

The axis PO intersects normally an axis of tilt XY which is parallel to the base of the instrument and thus to the work-table or datum surface on which it is mounted. By means of a second hand wheel the face-plate AB can be rotated about XY. The range of this rotation is 90° and the axis PO can be set at any angle in the quadrant O'PO" where PO' is parallel and PO" perpendicular to the base. The accuracy of setting by means of the vernier scale provided is 1 minute of arc.

Let it be supposed that a perfect half-delta wing model as shown in Figs.9 and 10 is mounted on the face-plate AB so that the root chord is parallel to the face-plate and the axis PO lies in the plane of symmetry of the model and passes through an arbitrary point G in the root chord. Fig.12 shows these elements and Fig.13 shows the initial setting when the plane of symmetry is parallel to the datum surface. When the model is in this position, the angular readings of the rotational and tilt scales are noted and become the zeros for the particular mounting.

It is now required to know the rotation and tilt necessary to bring any tangential plane RSC containing the generator RS (Fig.12) parallel to the datum surface.

Denoting by x the slope of the tangent to the aerofoil section at the point R it will be clear from Fig.12 that a rotation of x about the axis PO will bring the line CR (and all lines parallel to CR in the plane RSC) parallel to the datum surface.

To obtain the necessary angle of tilt we draw GH perpendicular to the tangent CRHU and as GH lies in the root chord plane it is also perpendicular to PO. After the rotation x, GH is perpendicular to the work-table or datum surface and consequently the plane containing the triangle GHF is also perpendicular to the datum plane. Hence to make HF (and therefore the tangent plane) parallel to the datum surface it is only necessary to tilt the model through the angle GFH. This angle ϕ (Fig.12) is equal to the angle TSU as TU is parallel to GH and triangles GHF, TUS are similar.

The required angle of tilt ϕ may therefore be calculated as follows

$$\tan \phi = TU/TS = TC \sin x/TS$$

$$= \frac{[LT - LN + NR \cot x] \sin x}{TS}$$

$$= \frac{[b - x + y \cot x] \sin x}{c}$$

where

b = base chord LT

c = span TS

(x,y) is the point R referred to L as origin.

x = slope of tangent at (x,y).

Finally/

Finally to obtain the height H (Fig.14) of this tangential plane above the datum surface we have

$$H = WP + PG \sin\phi + GH \cos\phi$$

$$= h + d \sin\phi + p \cos\phi$$

where h and d are constants obtained from the set up and from Fig.12.

$$p = GH = CG \sin x$$

$$= [LG - LN + NR \cot x] \sin x$$

$$= [a - x + y \cot x] \sin x$$ where a = LG is a constant of the set up.

Preparation and Mounting of Blank

In designing and preparing the blank for this model consideration was given to (a) providing a large precisely machined lug which would enable the blank to be rigidly clamped, while cutting, and also furnish precise datum surfaces for the final inspection of the aerofoil and (b) providing supporting metal for the flimsy trailing edge and vertex during manufacture. In consequence the blank, made from ½" thick Usaspeed steel, was made as shown in Fig.15. It should be noted that the model was not required to go to a point at the vertex but to a minimum chord of length 7/8".

After rough machining, the blank was heat treated to 750°C and allowed to cool slowly to promote secular stability. The upper and lower faces of the lug (dimensions 7" x 2½") were ground flat and parallel within 0.0001 in. and the edges finished straight and square within 0.0001 in.

The blank was then bolted to a robust angle bracket and position by dowels so that when the angle bracket was bolted to the face-plate AB and adjusted to position the following requirements were met:-

(a) edge JK (Fig.15) was parallel to face-plate AB: and TL, which was to be the base chord, was at a precise distance 7.1000" from the axis of tilt XY, i.e., d of Fig.14 equal to 7.1".

(b) the axis of rotation PO lay in the plane of symmetry of the clamping lug (Fig.15).

(c) the edge LK (Fig.15) was 3" plus 0.020" machining allowance from the axis PO thus fixing the constant a (GL of Fig.12) at 3.0000".

Finally, the S.G. dividing tilter was adjusted so that the surface JKLT of the supporting lug was parallel to the work-table and the 'zero' reading Z of the rotational scale noted.

Setting the Angle of Tilt

It was found that the 1 minute vernier reading tilt scale was insufficiently accurate to set the angles of tilt precisely enough in view of the large overhang of the blank. To remedy this a ½" ball, soldered to a robust stalk, was mounted on the face-plate and used as a sine bar (See Fig.13). To set a particular tilt, ϕ, the face-plate was rotated until the centre of the ball was in the plane defined by the axes PO and XY and the face-plate tilted until the top of the ½" ball was at the required distance from the datum surface. This distance was obtained from the formula

$$S = h + g \sin\phi + \tfrac{1}{2} \text{ diameter of ball}$$

in which $h = PW$ (Fig.14) and g is the perpendicular distance of the centre of the ball from the axis XY (Fig.13). By making g approximately equal to the distance of the vertex of the model from the axis XY and by setting the height of the ball to an accuracy of 0.0001 in. it ensured that the vertex was positioned to approximately this accuracy.

Computation

Before cuts were made on the mounted blank, it was necessary to decide the spacing and number of tangential planes to ensure a smoothly curving surface sufficiently close to nominal outline. Accordingly, basic data comprising a series of values of x, y and x were provided by the Aerodynamics computors based on the criterion that the excess metal at the intersection of any two tangential planes at the base chord should lie between 0.0004" and 0.0006".

This basic data was then used to compute the secondary data

$$\tan \phi = \frac{1}{c} [b - x + y \cot x] \sin x$$

and

$$p = [a - x + y \cot x] \sin x .$$

Finally, in conjunction with the constants of the set-up, the setting data for the cutting of each tangential plane was computed as follows.

Rotational setting $\theta_1 = Z + x$ (for a plane on top surface)

$\theta_2 = Z + 180^\circ - x$ (for a plane on bottom surface)

where Z is the zero reading of the rotational scale.

Tilt setting (by sine bar) $S = h + g \sin \phi + 0.2500$

Height of cutter $H = h + d \sin \phi + p \cos \phi$.

Roughing Out

Six tangential planes were chosen, one at the leading edge, one at the trailing edge and the others equally spaced between these extremes. Cuts were made, in turn, at these chosen positions (alternately on the top and bottom sides of the blank to minimize distortion) until each plane was within 0.008" of finished size. Planes intermediary to the first six were then chosen and these were machined to within 0.003" of finished size, the cuts being again made alternately from side to side of the blank to minimize distortion.

At this stage, with less than a dozen planes per side machined, the shape of the required model was well defined and generally within a few thousandths of an inch of size. It should be noted in particular that the thin trailing edge was still attached to the strengthening bar provided, by a series of 0.025" steps. Fig.16 shows a section through the model at this stage.

Finishing the Surface

With a freshly ground cutter finishing was started at the leading edge and machining continued plane by plane towards the trailing edge. Each plane was finished within -0.0002" to +0.0004" of nominal position. In all, 23 planes per side were cut, of which 7 per side were required to finish the high curvature within 1/8" of the leading edge.

Finishing/

Finishing the Trailing Edge

In the earlier work difficulty had been met when cutting thin trailing edges due to the thin unsupported metal bending away from the cutter. To obviate this the following technique was adopted.

Finishing cuts were first made on both sides of the trailing edge within 0.020" of the run out (see Fig.17). These cuts were easily made without deflection of the trailing edge as it was still adequately held by the strengthening bar. The cutter was then raised a few ten-thousandths of an inch clear of the finished portion and the section marked A (Fig.17) removed. Again the now very thin edge was sufficiently supported for this cut, 0.025" wide by about 0.0075" deep, to be made without the trailing edge deflecting or breaking clear of the support. Finally, with the cutter still raised slightly clear of the finished surface, the section marked B (Fig.17) was removed and the trailing edge was thus freed from the supporting bar. It was subsequently found that the trailing edge, although somewhat serrated, was razor sharp and no difficulty was experienced in finally grinding back this edge to achieve the 0.003" thickness required. It is believed that edges 0.001" thick could be made in this way if suitable material is used.

Inspection

Measurements perpendicular to the plane of symmetry were made on both surfaces of the model along the 3.5" chord immediately after machining. The measured departures from the nominal form are shown in Fig.18a. It will be seen that the form is generally within ±0.0005" of nominal and is therefore satisfactory.

The section is slightly thinner than was expected from the measurements made on each plane as it was cut. This may be due to small systematic errors in the settings required to cut each plane. On the other hand it may be due to the difficulty of locating a precise chord for measurement. A slight, but unknown, shift of the position of measurement towards the thinner metal of the apex results in a set of measurements which, when compared with nominal values calculated for a chord slightly further from the apex, gives the appearance of a section which is too thin.

The surfaces of the model were then hand finished: graded emery cloth moistened with paraffin was used to remove the excess metal at the intersections of the tangential planes and final polishing was done with a paste of SIRA powder and paraffin.

The edges of the model were finished to size by grinding and the necessary holding lug formed by milling.

Due to the fact that much hard work had to be done to remove the milling cutter marks from the surface, thus making the model undersize, final inspection was made with respect to a set of axes shifted slightly into the thicker metal. This shift of axes was designed to maintain the correct maximum thickness at the expense of making the trailing edge appear thicker than nominal and the leading edge neighbourhood thinner. The results of final inspection along one of the chords is shown in Fig.18b. It will be seen that the surfaces are within ±0.001" of the nominal form.

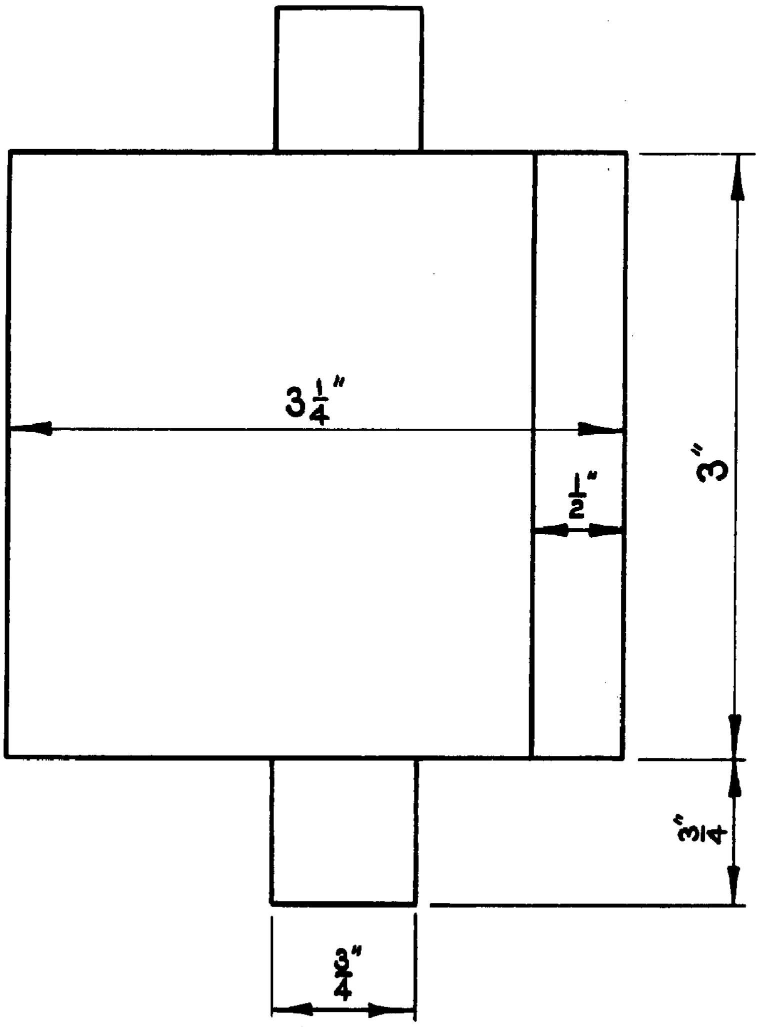
Conclusions

(1) The accuracy achieved in this trial manufacture of a half-delta wing model was generally just within ±0.001 in. allowed. It is now obvious that greater accuracy could be achieved if models are machined slightly oversize to allow of the removal of more metal when hand finishing.

(2) The geometrical ideas and formulae developed in this paper are for a particular type of aerofoil model. General formulae for all types of models envisaged by the aerodynamicists cannot be laid down at this stage, but the general ideas of rotating and tilting a blank under a cutter can be applied to other types and has, in fact, already been successfully used to produce an elliptic cone well within ±0.001" of nominal form.

JDS.

FIG. 1.


3¼"
½"
3"
¾"
¾"

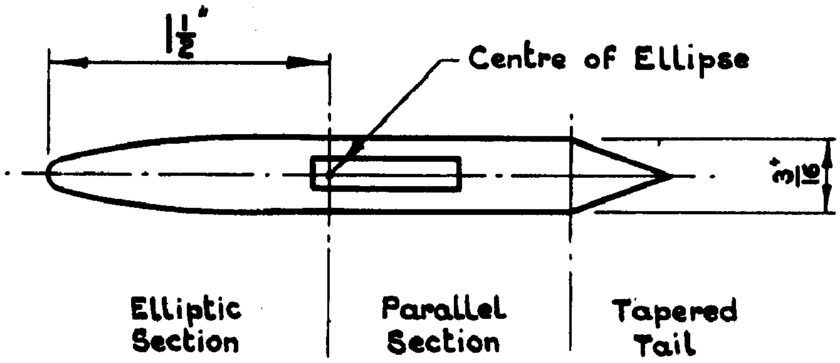

1½"
Centre of Ellipse
3/16"
Elliptic Section
Parallel Section
Tapered Tail

FIG. 1.

FIGS. 2 & 3.

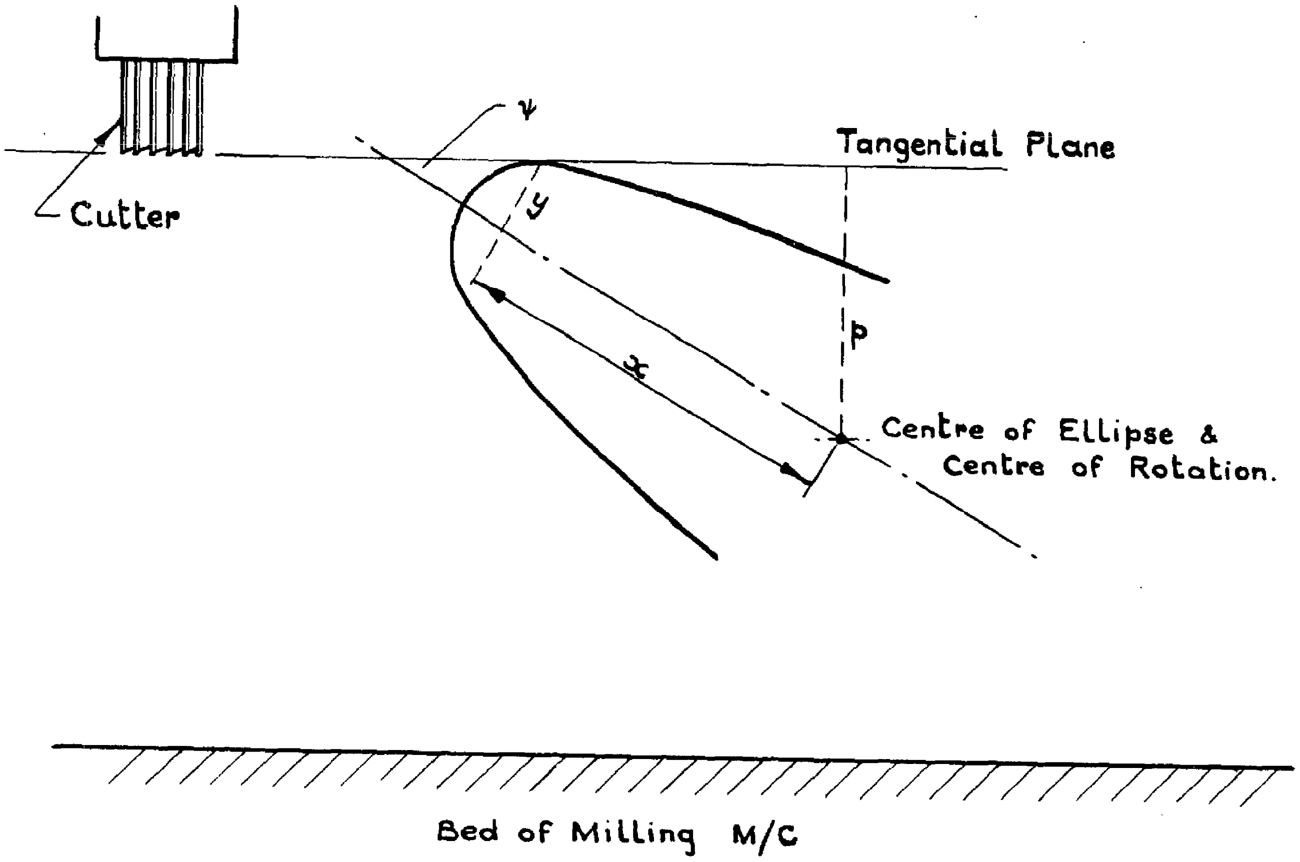

Cutter
ψ
Tangential Plane
y
p
x
Centre of Ellipse & Centre of Rotation.
Bed of Milling M/C

FIG. 2.

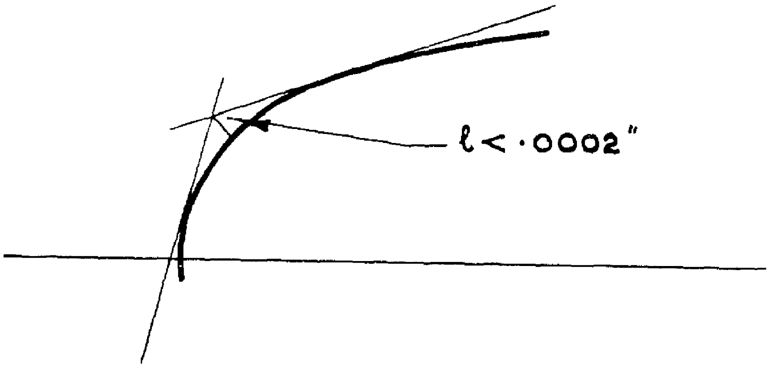


FIG. 3.

FIGS 4 & 5.

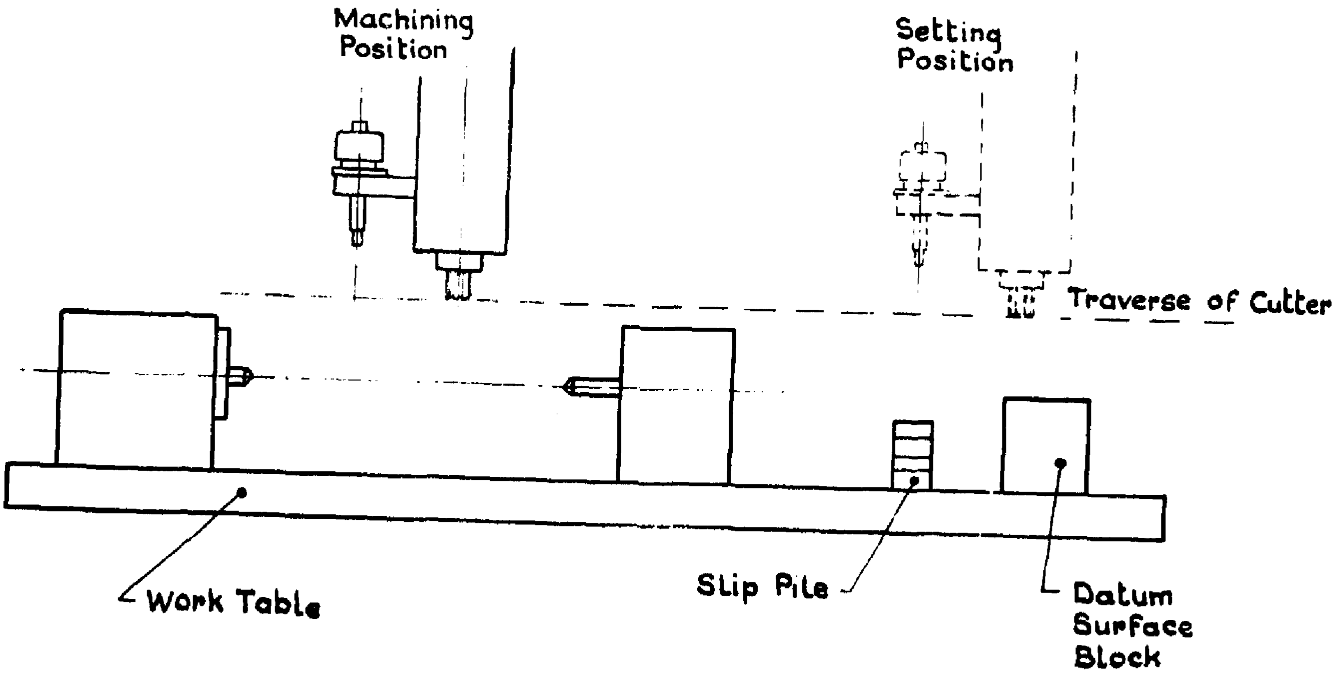

Machining Position
Setting Position
Traverse of Cutter
Work Table
Slip Pile
Datum Surface Block

FIG. 4.

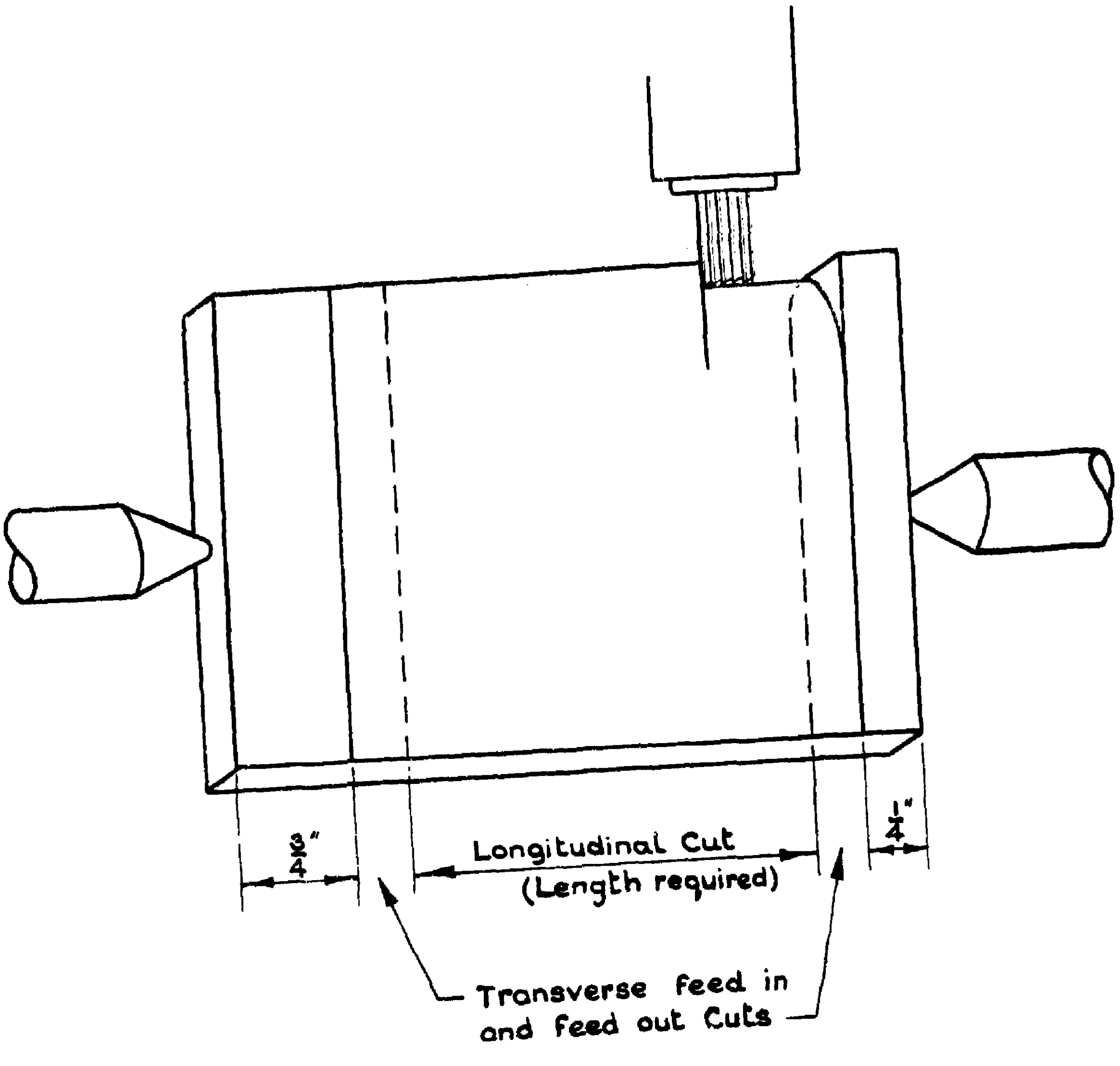

$\frac{3}{4}$"
Longitudinal Cut (Length required)
$\frac{1}{4}$"
Transverse feed in and feed out Cuts

FIG. 5.

REPORT ON THE MANUFACTURE OF AN AEROFOIL

DEPARTURES OF SURFACES FROM BASIC FORM

(Measured in direction perpendicular to plane of symmetry)

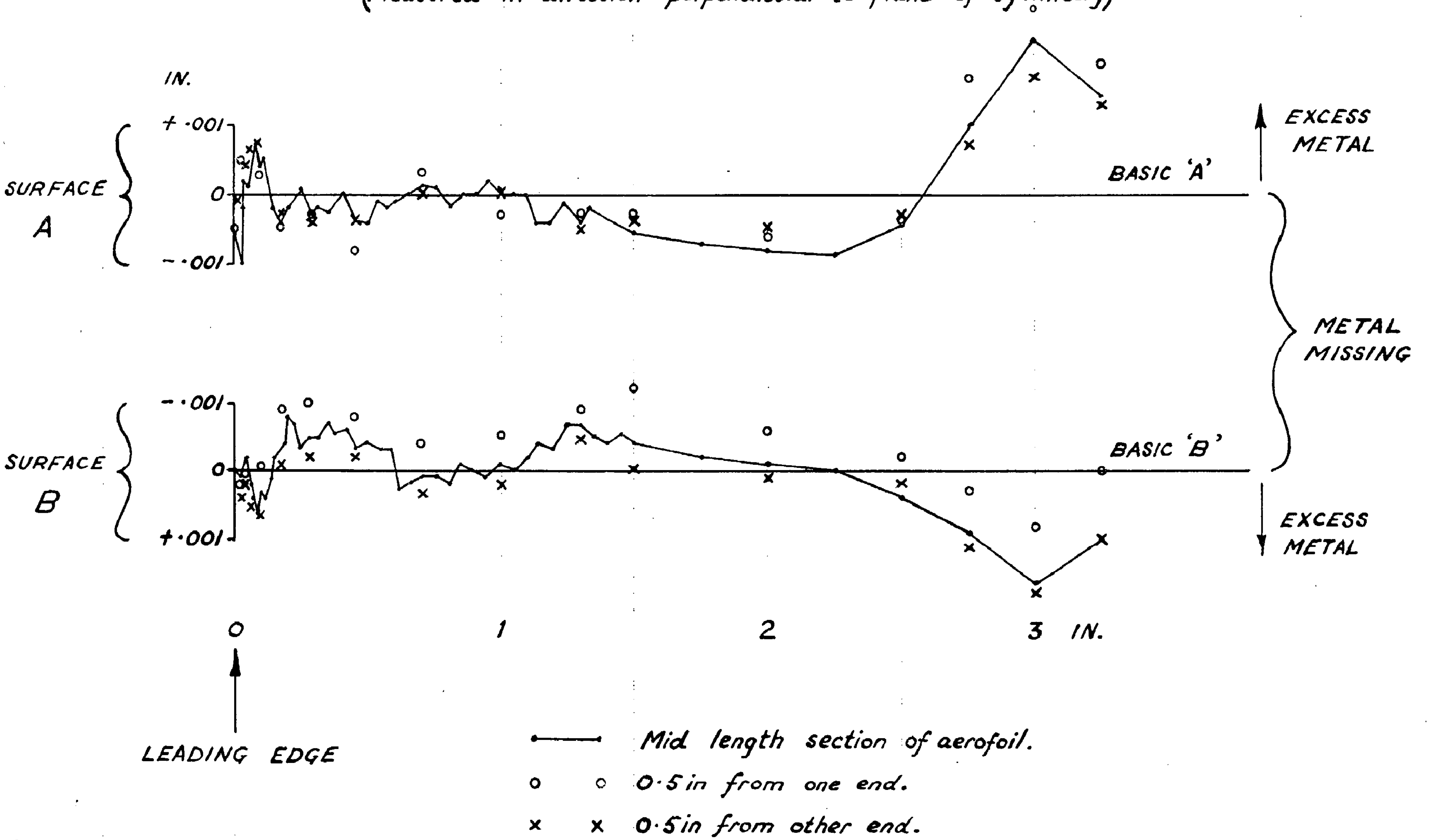


FIG. 6.

Ref:- M 146 - 168
D.O. Ref:- 2656

FIG. 6

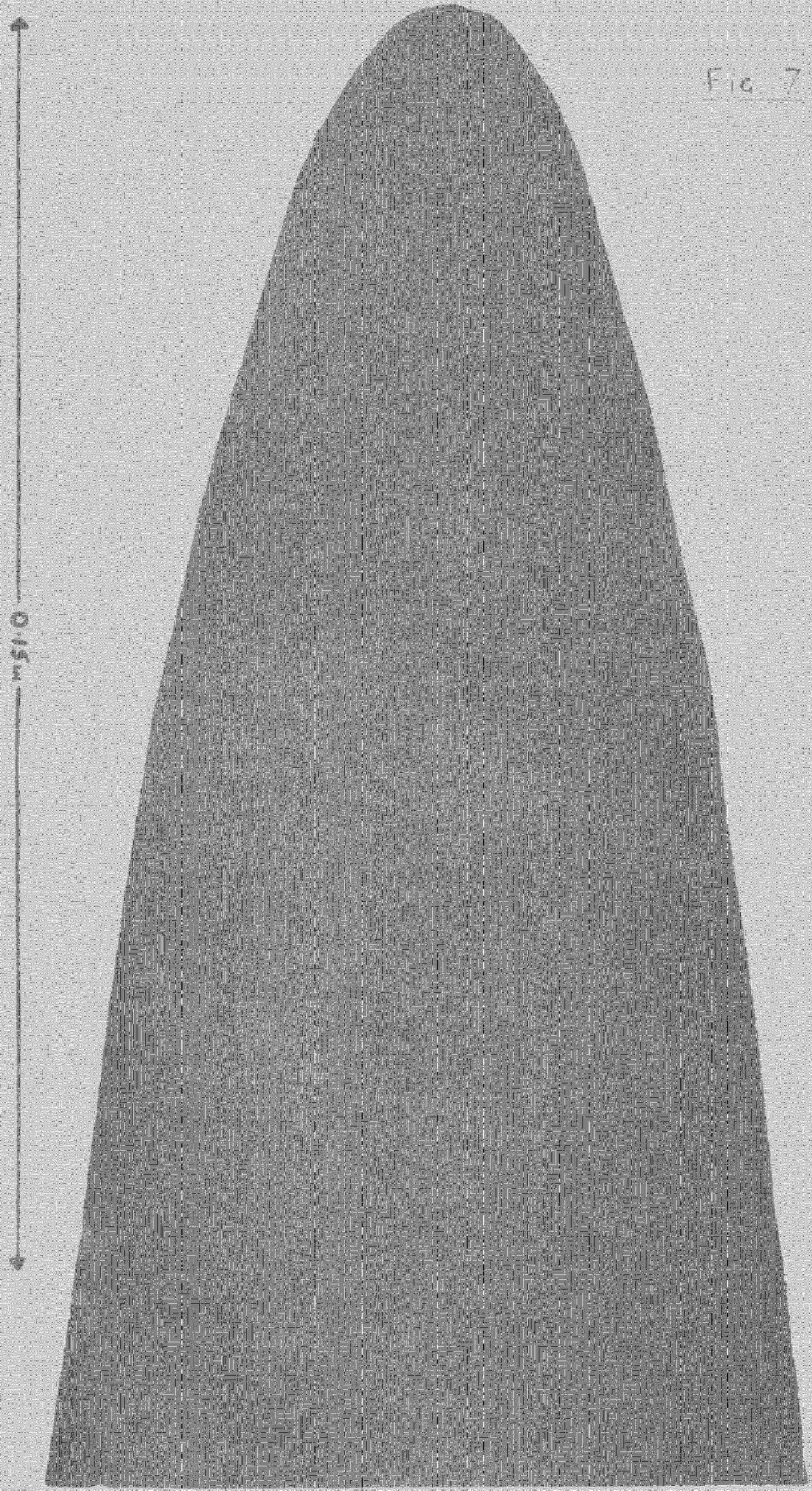


Fig 7

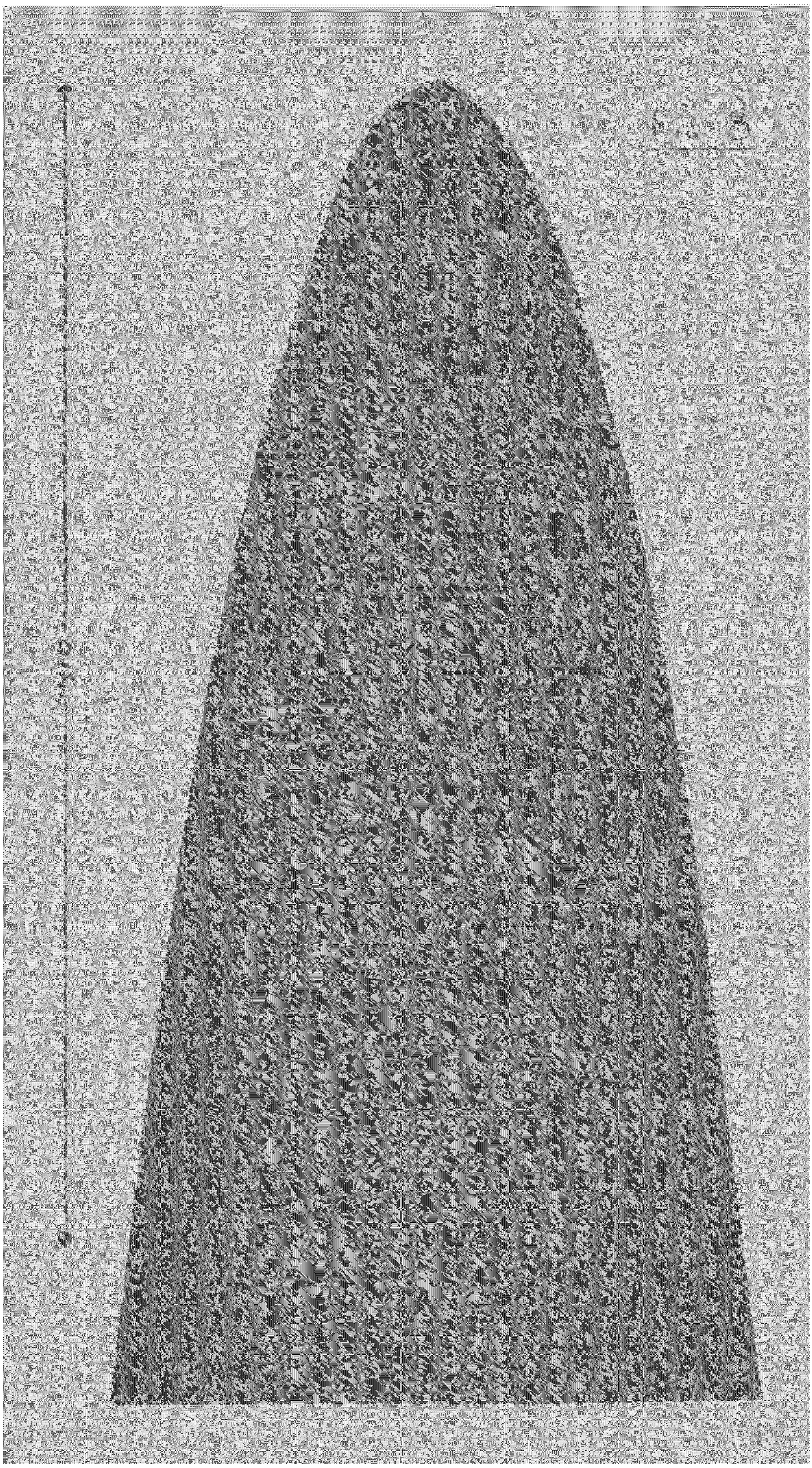


Fig 8

FIGS. 9 – 11.

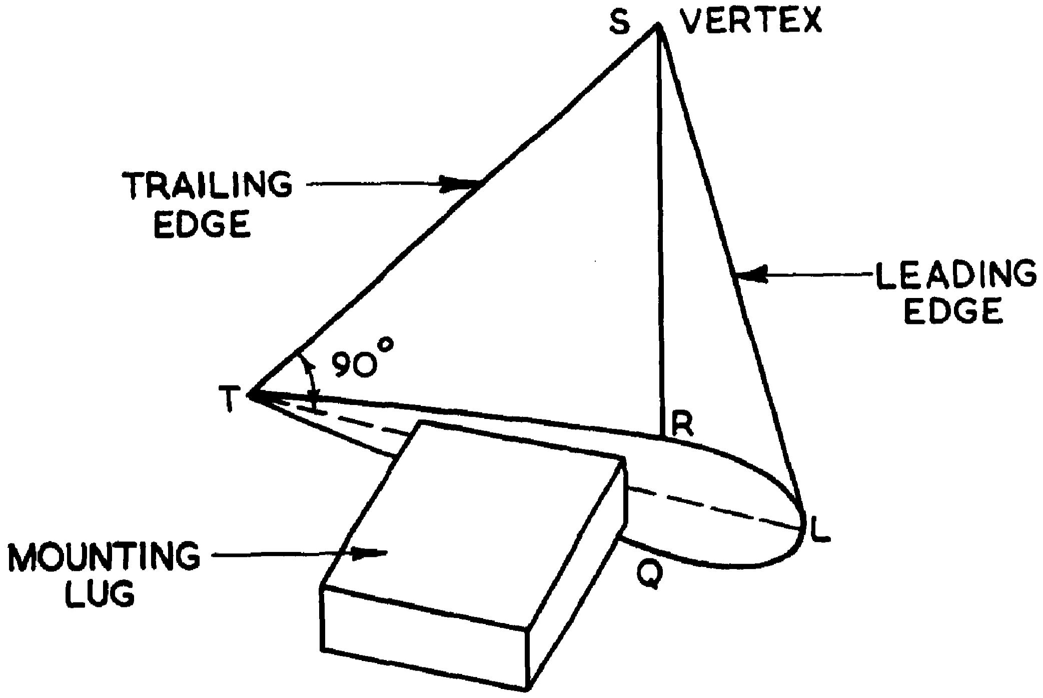

S
VERTEX
TRAILING EDGE
LEADING EDGE
90°
T
R
L
Q
MOUNTING LUG

FIG. 9.

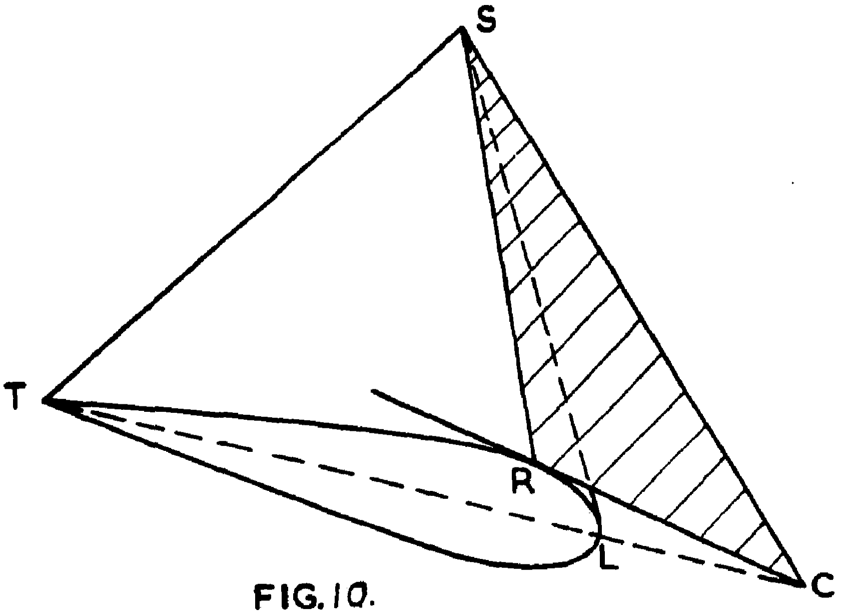


FIG. 10.

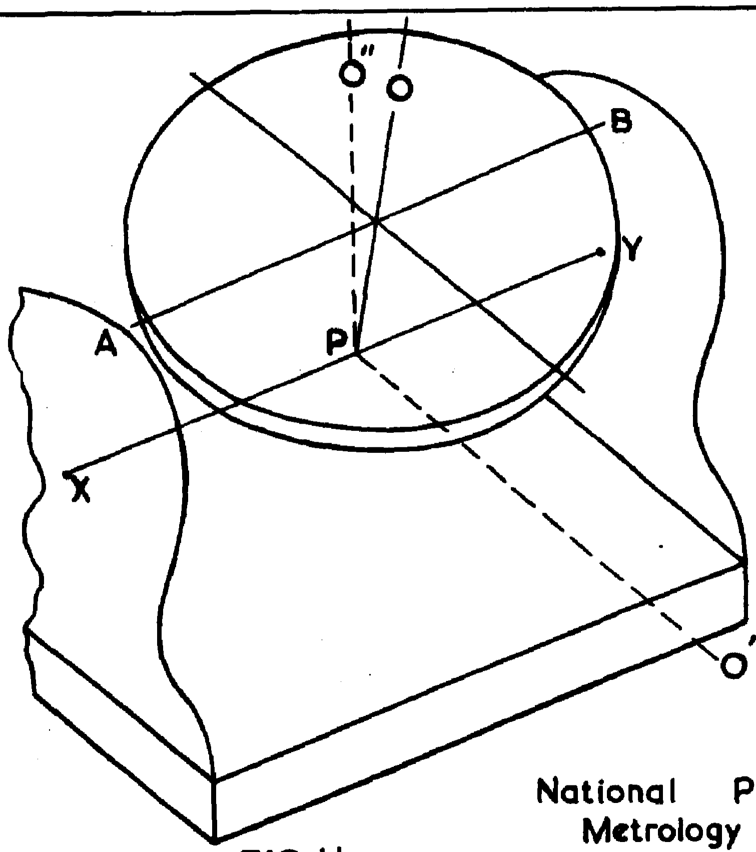


FIG. 11.

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Metrology Division,
Teddington, Middx.

SS288

15,941.
Figs. 12-14.

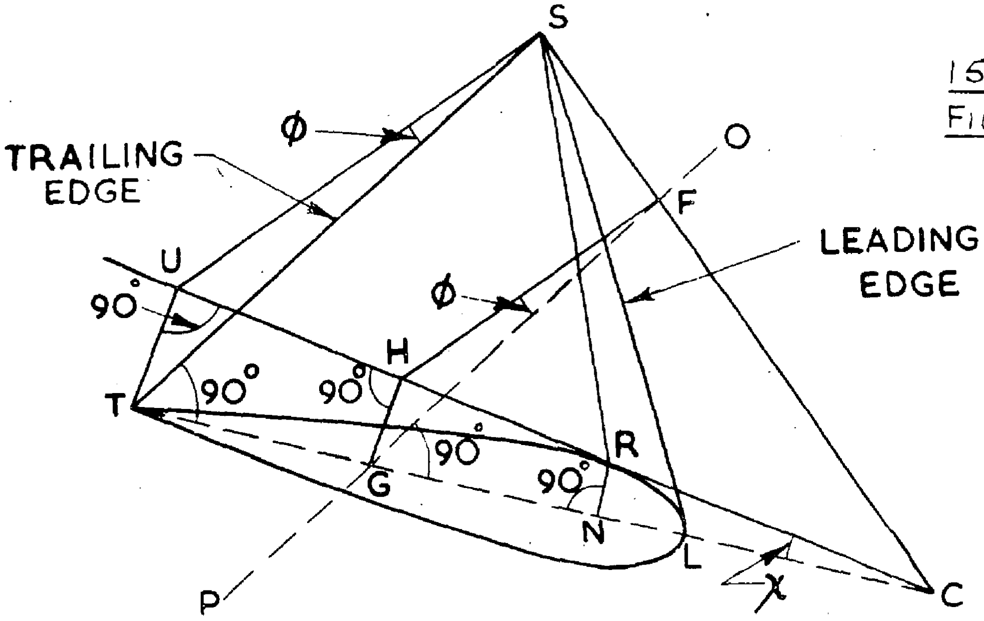
S
Ø
TRAILING EDGE
O
F
LEADING EDGE
U
90°
Ø
H
T
90°
90°
90°
R
G
90°
N
L
χ
C
P

FIG. 12.

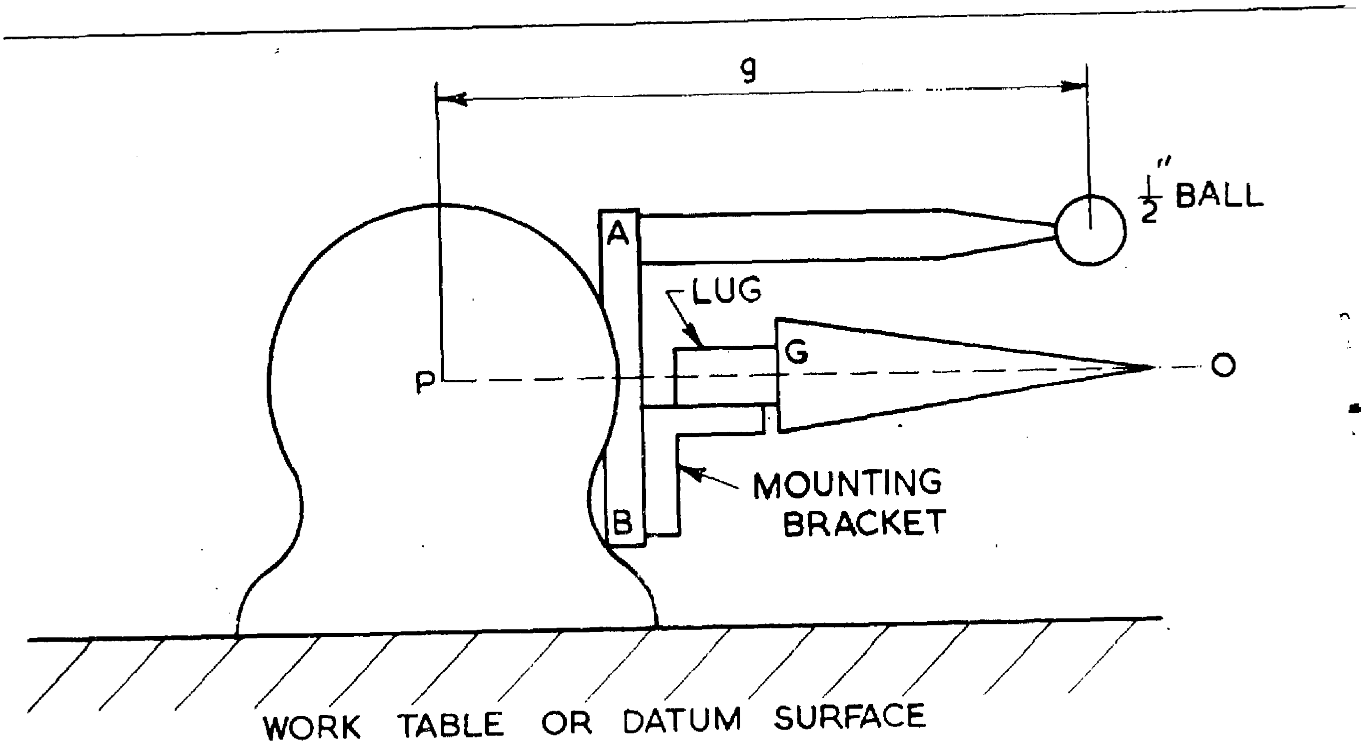
g
1/2" BALL
A
LUG
G
P
O
MOUNTING BRACKET
B
WORK TABLE OR DATUM SURFACE

FIG. 13.

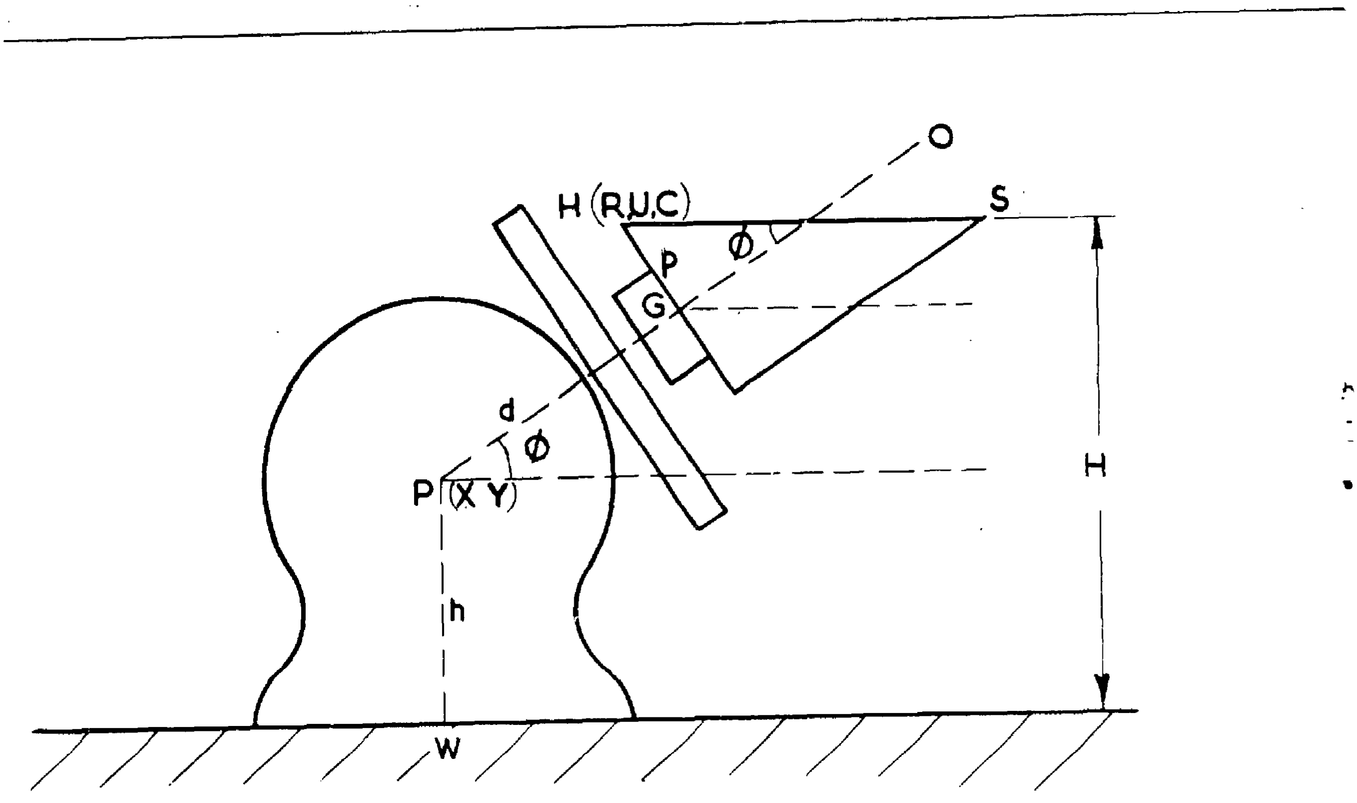
O
H (R,U,C)
S
Ø
P
G
d
Ø
P (X Y)
H
h
W

FIG. 14.

FIGS. 15-17

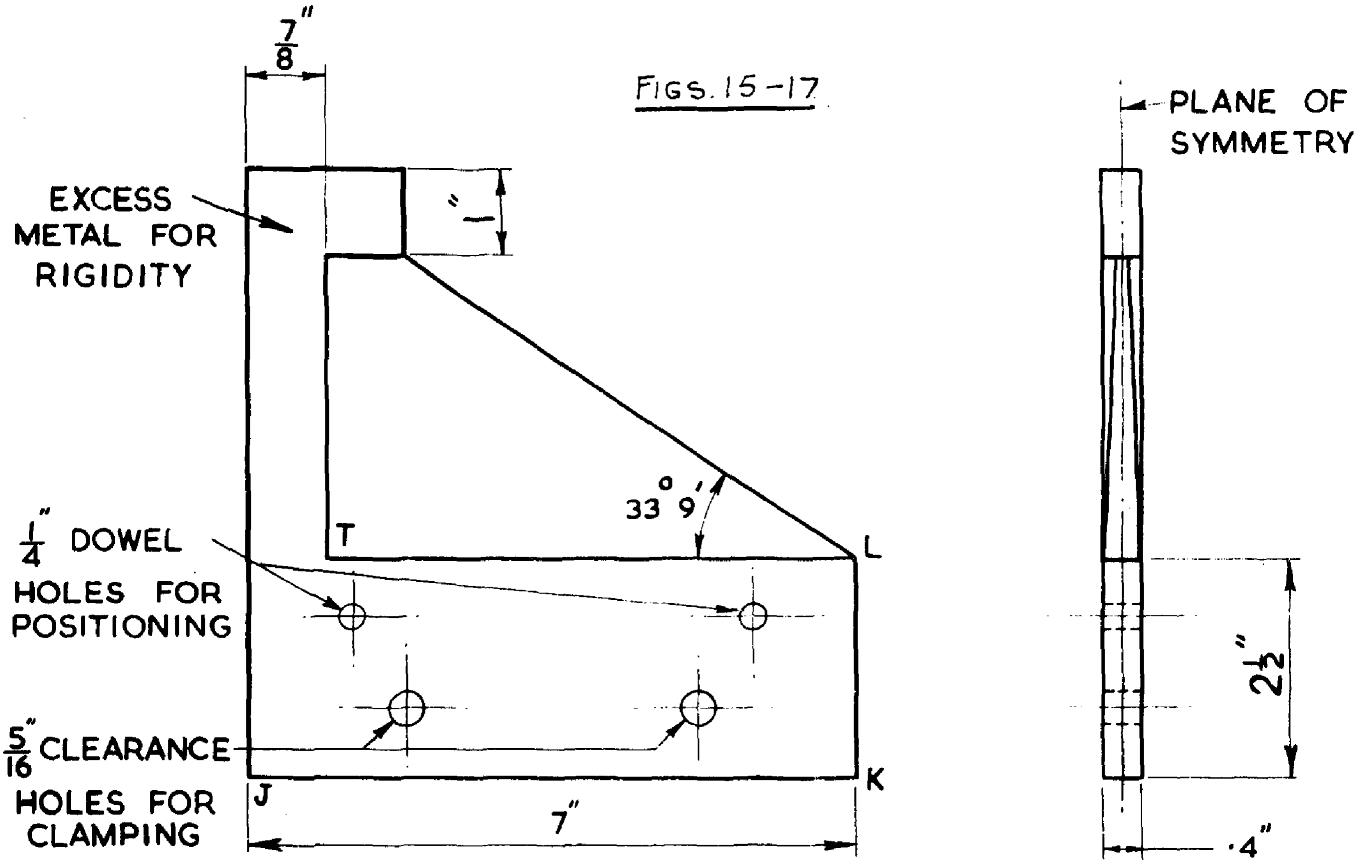
7/8"
EXCESS METAL FOR RIGIDITY
1"
T
33° 9'
L
1/4" DOWEL HOLES FOR POSITIONING
5/16" CLEARANCE HOLES FOR CLAMPING
J
K
7"
PLANE OF SYMMETRY
2½"
·4"

FIG. 15.

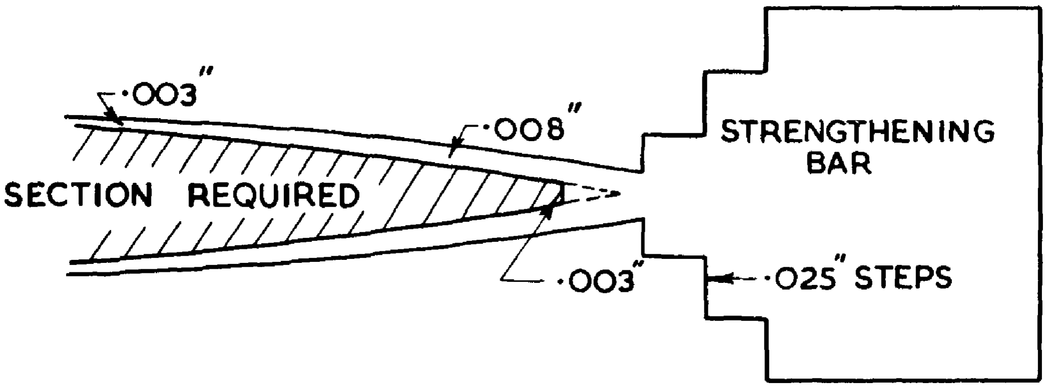
·003"
·008"
SECTION REQUIRED
STRENGTHENING BAR
·003"
·025" STEPS

FIG. 16.

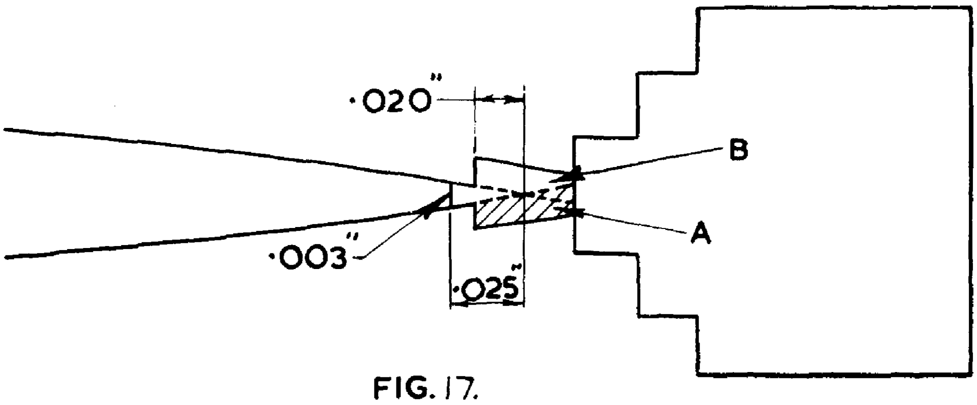
·020"
B
A
·003"
·025"

FIG. 17.

FIG. 18.

MEASURED ERRORS OF 3·5 IN. CHORD

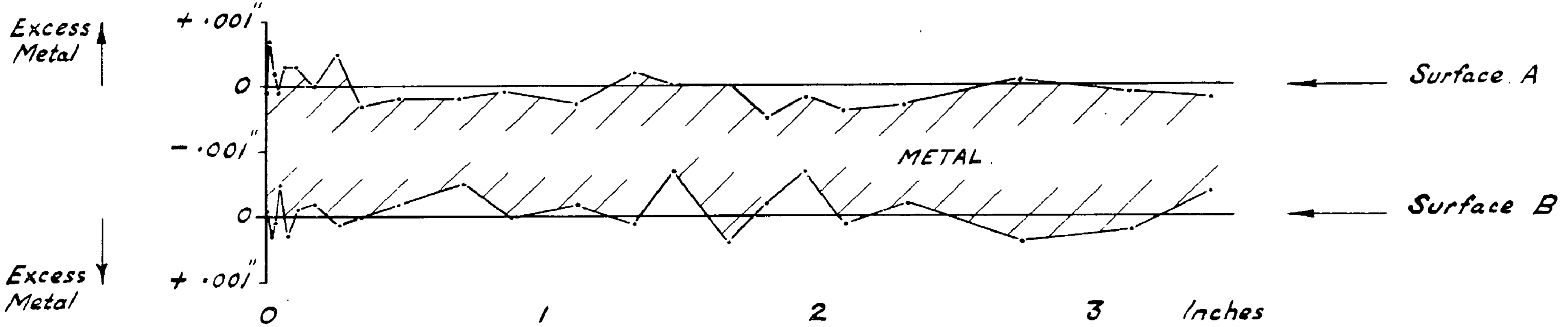

FIG. 18A

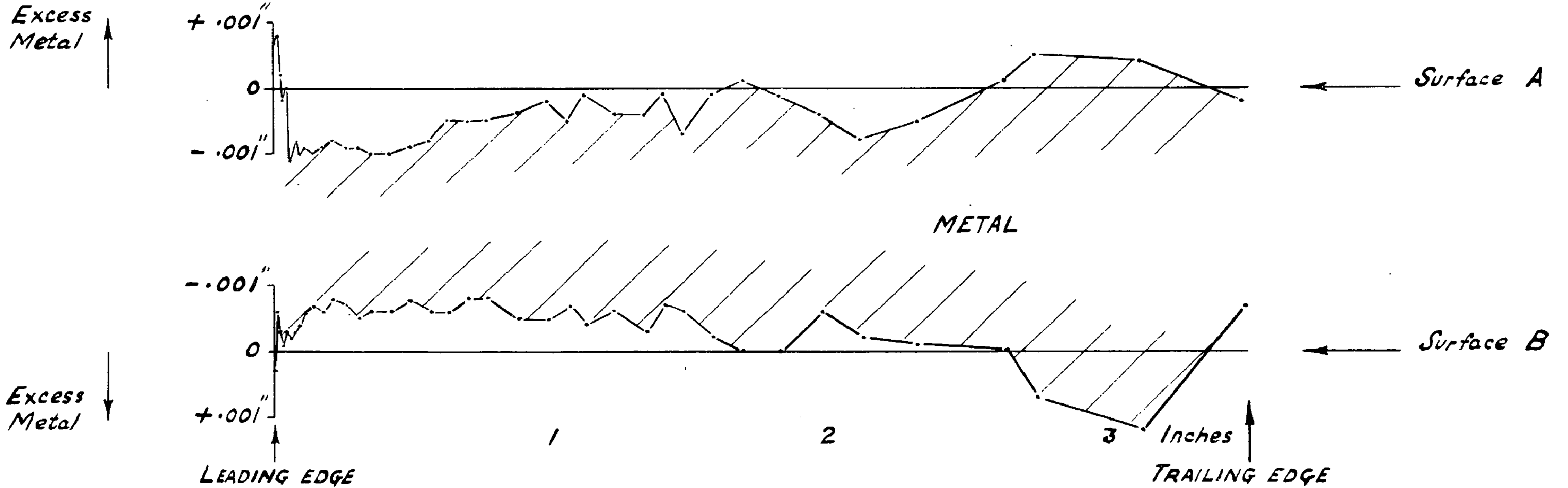

FIG. 18B.

C.P. No. 166
(15,941)
A.R.C. Technical Report

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