CALIBRATION OF THE
MERRILL-G.A.L.C.I.T. WIND TUNNEL

AND

A SUGGESTION FOR A VARIABLE CROSS-SECTION ON A SMALL HIGH-SPEED WIND-TUNNEL

Thesis by

Jean Christophe Schwarzenbach

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SUMMARY

Speed, power and flow inclination calibration tests run in the Merrill-GALCIT wind-tunnel are described and results presented. A description of the new balance-system is included. Turbulence measurements with hot-wires were made in the tunnel at various speeds and with various screen configurations.

Tests run in a small scale model of the projected cooperative wind-tunnel at subsonic and sonic velocities are briefly described. A suggestion for introducing variable working-section walls in the new scale model undergoing construction is discussed and presented.

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A. CALIBRATION OF THE MERRILL--G.A.L.C.I.T. WIND TUNNEL.

I. GENERAL.

The purpose of the research forming the basis of this thesis was to investigate the new wind-tunnel built under the supervision of Mr. Albert Merrilland the G.A.L.C.I.T. at the Pasadena Junior College, and to present a complete calibration and description of the tunnel.

At the time of the assignment the tunnel had just been completed, but the power supply was not yet installed. Subsequently the tunnel cross-section was altered to accomodate models used in the investigation of the Tacoma bridge, thus causing a considerable delay in the tunnel's final completion.

Due to the expected increase in wind velocity it was felt that the balances used with the old, open jet, open return type tunnel would no longer be adequate and Mr. Merril undertook to design a new balance system, in which work the author attempted to give some assistance. A description of the new balances is included.

All the tests described in this paper were run with the glass sidewalls of the working section in place, since higher wind velocities as well as a more undisturbed flow of air through the working section are obtainable by this configuration, as compared to tests run with these sidewalls removed.

During the month of May the author was requested to give some assistance to Mr. Richard Shevell in his research regarding the new cooperative wind-tunnel, and a description and summary of this work is included at the end of this manuscript.

II. DESCRIPTION OF THE TUNNEL.

The Merrill-GALCIT tunnel is located in the steam-house of the Pasadena Junior College, in Pasadena, California. It has a closed working section and a closed return, and is capable of developing wind-velocities up to 70 miles per hour. A section through the tunnel appears in figure 1.

The working section is rectangular, two feet by four feet, and the balance system is placed directly beneath it. Down-wind from the working section a diffusor leads to a screen, the purpose of which is to prevent loose objects from striking the airscrew. This latter is of four-bladed, wooden construction and is fitted with a small spinner. It is driven through a belt from an induction motor placed immediately below it, the belt system being encased in a manner to prevent pressure from escaping from the tunnel. The motor was built by General Electric, andhas the following specifications:

1150 RPM at full load
60 cycle, 3 phase
30 H.P.

Following the propeller the crossection of the tunnel is further expanded as it follows around the four corners. These are fitted with bent sheet-metal vanes to guide the air-flow around them, and to prevent losses in the corners.

The maximum crossectional area of the tunnel is found immediately preceding the working section, and measures

48 square feet. The minimum area is 8 square feet and there fore the contraction ratio of the tunnel is 6 : 1 .

In the lower west corner, at the maximum crosssectional area, two small pressure-leads on each side of the tunnel record the momentary static pressure, and, as is shown later thereby give a means of determining the dynamic pressure in the working section. These leads are attached to an alcohol manometer, with a slanting glass tube, calibrated in centimeters. The fluid level in the tube is a measure of the pressure and has been denoted throughout these tests as the length l.

Thus the pressure at the lead-orifices, denoted by p_w in inches of water is found as follows:

let γ = specific gravity of the alcohol
l = length in centimeters of the alcohol column
α = angle of the glass tube,

then

$$p_w = \frac{l}{2.54} \sin\alpha \cdot \gamma$$

α was measured with a vernier-protractor and was found to be: $8^\circ\ 10'$.

By a spring loaded rotary valve the static pressure manometer may be cut off from the pressure in the tunnel, so that it is not necessary to read this manometer at any particular moment, since by a simple pull of a string the valve is suddenly closed, and the immobilzed length of fluid l indicates the pressure which existed at that moment. This device makes the operation of the tunnel by a single person possible.

III. THE BALANCE SYSTEM.

Since the author spent a considerable amount of time on preparing drawings and discussing details of the projected new balance system with Mr. Merril ,it seems logical to include a description of the system.

The old balances were built into a steel tubular framework on wheels,and were primarily capable of reading three components, lift ,drag and pitching moment. Yaw-moment could be measured by modifying the pitching moment balance.

All the balances are beam balances,rough adjustments made by moving weights from one calibrated notch to another. Then by turning a calibrated screw the final adjustment could be made and the force read to within .001 lbs. This accuracy was not equaled in the application or in the transmitting of the forces, and the last figure of these readings was not signifigant. All the balances are damped in dashpots containing oil and equilibrium with no forces acting was achieved by adding or removing lead washers from receptacles attached to the balances.

Disadvantages of this old system were:

1.) the framework was too small to house conveniently all the equipment.

2.) there was no possibility of measuring a side-force;

3.) the model-support neck was too small,particularly for the high speeds arrived at in the new tunnel,allowing excessive model vibration.

A host of smaller difficulties have also been noticed and the attempt has been made to eliminate them as far as possible from the new system.

This new system was therefore built in the form of a steel -tube cube, of larger dimensions than the old frame. (Fig. 2.) Inside of this tube framework is hung a smaller cage, also cubic in shape. It is supended at the four corners by thin steel rods machined down at both ends to allow unrestrained motion of the inner cage in all horizontal directions. This arrangement allows all horizontal force components and moments to be measured. The inside of the frame is very spacious and leaves ample room for the installation of all the balances, and the sensitivity of the inner cage to applied forces is very high, due to the length and fineness of the supporting rods.

The balances have been designed with a view to possible future changes. The first project is one in which side-force, drag and yaw-moment alone were to be recorded, and consequently the model support has been built into the inner cage such that the model can be rotated through 360°, and all three aforementioned components measured. This is done with 2 side-force balances and a drag balance. The side-force balances are placed on each side of the drag-balance and give between them both side-force and yawing moment. It is to be remembered that since the drag-balance is off center a correction to the yaw-moment must be included from this source.

The new balances differ from the old ones mainly in their type of suspension, since as is shown in figure 3, short , steel flexing members are used, machined to a very small diameter at their focal point. These members are in compression, which is possible since they are flexing members at one point only, and all the motion is about this one point. This lends rigidity to the whole system, increases the accuracy and saves space. At present, for lack of time, the two side-force balances have been installed with roller-bearings instead of flexing members. As long as these bearings are new the frictional losses will presumably be negligible, and it is proposed to replace them eventually by the fixtures described above.

Another innovation is the installation of small chains, hanging from the ends of the beam balances. The end of such a chain passes over a pulley fastened to the balance-supporting structure, and the length of such a chain end is a measure for the amount of chain weight applied to the balance. Thus the final adjustments are made without touching the balances, by merely pulling the chains. This is a decided advantage when unskilled operators are at the balances.

Lift and pitch-moment balances will be designed and installed as soon as needed, and if required a rolling-moment balance may also be added, thus enabling all six components to be measured simultaneously.

IV. THE VELOCITY CALIBRATION.

The primary objective of the calibration of this tunnel was to determine the velocity profile in the working section, so that the mean dynamic pressure over any model could be determined. Furthermore a means must be provided to establish the dynamic pressure acting on a model without having to insert a pitot-static tube into the wind-stream, since this would frequently interfere with the tests.

In the Merril- GALCIT tunnel the static pressure at the maximum crosssection of the tunnel located immediately before the working-section is taken as a measure of the velocity at the model. Denoting the dynamic pressure in the working-section by q and the static pressure at the maximum cross-section by h, then the desired relation is the ratio q/h as a function of position and engine spped. This ratio has been determined experimentally, by inserting a calibrated pitot-static tube of the Prandtl type furnished be the GALCIT into the working section, and measuring the static pressure simultaneously as described in section II. The pitot tube was movable in a fore and aft direction along the center-line of the tunnel, and could be placed anywhere in a section located such that the static orifice of the tube was 17.25 inches from the beginning of the working-section.

As will be seen in the subsequent pages, this ratio q/h at full speed was found to be approximately 1.7 The assumption is usually made that the wind-stream in the working-section is at the normal atmospheric pressure. Calculating the value q/h that should result from this assumption it is seen:

Bernoulli : $p_1 + \frac{\rho}{2} V_1^2 = p_2 + \frac{\rho}{2} V_2^2$

Continuity : $A_1 V_1 = A_2 V_2$

then: $h = p_1 - p_2 = \frac{\rho}{2} V_2^2 \left[1 - \frac{A_2}{A_1} \right]^2$

where : p is the pressure
v is the velocity
ρ is the density
A is the cross-sectional area,

and the subscript one denotes conditions at the maximum cross-section and two the conditions in the working-section.

Since the ratio A_2/A_1 is the contraction, and is equal to 1/6 , we find that

$$q/h = 1.03 \quad \text{(theoretical.)}$$

This value shows a large disagreement with experiment. Mr. Merrill has calibrated the tunnel with the side-walls removed from the working-section and found values of q/h which agree closely with the theoretical value. Whereas he found approximately the same dynamic pressure as found in these tests, the static pressure h was roughly one third higher than that arrived at by the author. With the side-walls removed the condition of atmospheric pressure in the working-section is certainly fulfilled. Consequently, since conditions through the contraction must be similar in both cases, we must assume that the static pressure in the working-section with the side-walls in place must be below atmospheric. As discussed in the chapter on turbulence , the working-section is vented to the atmosphere at its end. However this vent is not very large, and the only explanation that can be given for the low pressure is that the flow resistance through this vent is too high to allow the inflow to compensate for the losses of air escaping through the leaks in the circuit, unless a large pressure difference exists between the working-section and the atmosphere. A rough idea of the magnitude of this difference may be arrived at by assuming that the same pressure-drop through the contraction occurs in the case of the tunnel with side-walls in or out. Then with $q \doteq 12$ lbs/ft^2 and $q/h = 1.7$ we find $h \doteq 7$ lbs/ft^2 . The pressure difference between working-section and atmosphere is one third of this and therefore about 2.3 lbs/ft^2.

The values of q/h were found as follows:

If: γ = spec. gravity of alcohol in pitot-static manometer

p_w = static pressure in inches of water,

Then: $\frac{q}{h} = \frac{p\gamma}{p_w}$ where h is the pressure difference between max. cross-section and atmosphere instead of working section, as used in the theory.

The actual velocity calibration consisted of three parts:

1) q/h calibration throughout the cross-section approximately in the model plane.
2) a survey lengthwise through the working-section at the centerline.
3) a determination of q/h at the various engine settings.

1.) Velocity distribution in model plane.

Simultaneous measurements of dynamic pressure and static pressure were taken at 3 inch intervals in a horizontal plane and 4 inch intervals in a vertical plane, excepting that near the walls in the vertical direction another series of points were measured at two inches from the wall, to discover any possible drop in speed along the walls.

The results of this survey have been plotted both in the form of profiles showing the deviation from the average value of q/h along the horizontal lines in percent, (Fig. 4) and in the form of a contour diagram, giving lines of constant q/h, or for a given static pressure at any instant, giving lines of constant dynamic pressure.

It is apparent that the largest deviation from the average value q/h=1.703 is approximately 6 % . However it will be noted that the profiles in the region of the model position are much nearer the mean value. Furthermore the value 1.703 is the average of the whole cross-section. Thus if the average values of q/h tabulated below are used, this will cause the average deviation to be within 2.9% of the value used on a span of 36 inches, for instance, and correspondingly less on smaller spans. Since upon repeat measurements at the same position during one test a maximum q/h deviation of 1.4% was found, it appears that the use of the tabulated values will be accurate within these limits.

The contour-line diagram shows that the fluctuations in dynamic pressure are not local in character, but extend over large areas of the working section. It is probable, therefore, that by reforming the guiding vanes in the corners, which at present have been arbitrarily adjusted by hand, the magnitude of these areas could be reduced. However, as these results show, their effect is not excessive and other factors in the tunnel such as power fluctuations, balance readings etc. introduce errors of at least the same order of magnitude, so that the correction was not deemed urgent.

The values tabulated below are average values over an area extending from 4 inches above to 4 inches below, and a half-span north and south of the respective center-line. They are valid for flow conditions at approximately full speed.

Model Span in inches	0	6	12	18	24	30	36	42
q/h	1.688	1.712	1.713	1.717	1.722	1.725	1.725	1.724

2.) Axial Calibration

The dynamic and static pressures were further determined, on the center line of the tunnel, extending from 1" to 28" from the beginning of the working section. The same equipment was used as for the section calibration. The results are plotted in figure 6. The accuracy of the test points is not high, although they are within the limits that have been experienced in other tests. This test was run on two consecutive days, since the author was unable to find sufficient time in which to run the tests in one stretch, due to the very marked power-drop effect if the tunnel was run over a prolonged period at full speed. (See flow-inclination) test.) Nevertheless the value of q/h = 1.675 at section 17.25 compares reasonably well with 1.688 found in the section calibration and somewhat less well with 1.718 for the speed calibration described below. However this only shows a variation from the mean at that particular point of 1.3%. Over the approximate model location q/h is within 1.5% of the axial q/h, and is thus also within tunnel accuracy, although an unsignificant increase from front to rear can be observed, probably due to the proximity of the contracting nozzle. Thus the q/h determined at section 17.25 can be considered valid at all stations in that region.

3.) Calibration For Different Speeds

Having determined the full speed characteristics, it was now important to find values of q/h at lower speeds, and check the theoritical hypothesis that it is constant with the speed.

The motor as installed at present has only ten different speeds, spotted somewhat at random within the speed range. Two runs from full speed through all settings were made, and the average values of both runs used as the basis of the resulting curves and values. The pitot-static tube was again placed on the tunnel center-line, and the result can be compared to those found under 1.) and 2.) above. The agreement is reasonable.

Thus the primary objective of this test was to furnish the data for figure 7 in which q/h is plotted as a function of the static pressure.

It is immediately apparent that whereas this represents a linear function, it is not a constant. This is dissappointing, and must be accounted for at slower speeds. The procedure to find the average span q/h at a slower speed would be then as follows:

Find $(q/h)_{CL}$ for the h in question.

Multiply the $(q/h)_{\text{span average}}$ found on the tabulation page 14 by the ratio: $\frac{(q/h)_{CL}}{1.688}$

since 1.688 is the average q/h at the center line at full speed, found from the section calibration.

It is in this manner that the values of dynamic pressure and velocity were found for the power calibrations.

4.) Since the wind-stream of the tunnel appears to be quite rough as indicated by model vibrations and the fluctuation of the fluid level in all manometers, a fine screen was inserted in the wind-stream, to reduce the unevenness.

The screen was placed right at the beginning of the working section. It consisted of a fine precision wire mesh, 30 wires per inch. The pitot-static tube was placed as usual at the center-line at station 17.25.

Values of q/h versus h have been plotted as they were for the case with no screen. (Figure 7.)

Also values of dynamic pressure versus h, together, with the values found in the absence of the screen have been plotted. (Figure 8.) The loss in dynamic pressure due to the screen is high, amounting to about 2/3 of the screenless case. However the readings were extremely consistent, indicating a very smooth flow. No fluctuations were observed in either of the manometers, and wind velocities of 45.5 feet per second were obtained, despite only proceeding as far as engine step 5, since the screen was not very rugged. Therefore it would seem desirable to run tests with the screen in, when this speed is adequate for the purpose, since the ease with which scale and manometer readings are made will greatly increase the accuracy of all results.

V. THE POWER CALIBRATION

It was desired to find the power actually delivered to the tunnel, to determine the dependence of dynamic pressure on the revolutions per minute and to find the RPM for the various engine settings. It was not known whether the engine was actually delivering the rated 30 horsepower or not, and the possibility of a speed increase from this source was considered.

With the help of Mr. Holtzklaw of the Electrical Engineering Department, runs were made determining voltage, amperes and kilowatt input, into the primary and secondary windings of the induction motor, by using an analyser. Simultaneously RPM and static pressure readings were taken for each engine setting. An efficiency was assumed and the engine output determined. Apparently there is no procedure other than this to determine the output of the induction motor, unless a dynamometer is used, a procudure too complicated to warrant consideration.

The power was computed as :

$$HP = \eta \frac{(K_p - K_s)E}{.75}$$

where $K_p =$ primary kilowatts
$K_s =$ secondary kilowatts
$E =$ voltage
$\eta =$ efficiency.

The power of step 10, or maximum output, was found to be 31.2 HP. This was for
$I = 75$ Amps.
$E = 331$ Volts
$RPM = 1156$

Since the engine is rated at 30HP for $E = 220$, $I = 72$, $RPM = 1150$, this result is reasonable.

To find the dynamic pressure at the center line and the average dynamic pressure for the whole tunnel the method outlined in section IV, 3, was used.

The average value of q/h for the whole tunnel was found to be 1.703. Accordingly for full speed condition the dynamic pressure in this test was found to be:

$$q = 12.7 \quad lbs/ft^2$$

The kinetic energy thus passing through the working section per second is found:

$$\frac{K.E.}{sec.} = \frac{m}{sec.} \frac{1 v^2}{2}$$

where $\frac{m}{sec.} = \rho \frac{volume}{sec.} = \rho \; A \; v$

accordingly $\frac{K.E.}{sec.} = q\,A\,v\,\frac{ft.lbs.}{sec.} = \frac{q\,A\,v}{550} = 19.1$ HP

Thus the energy ratio of the tunnel at full speed is:

$$\frac{19.1}{31.2} = .612$$

This extremely low value of the energy ratio is difficult to explain. By including the belt-efficiency it might be raised some 20 % at best, and the ratio is still very poor. The many air-leaks through access doors are certainly sources of energy losses, as is the heavy screen inserted in the diffusor. It is made of heavy flattened wire and certainly has a high resistance. Finally a large part of the loss must be attributed to the propeller, which due to lack of time was not specifically designed for the tunnel, but merely taken over from the old installation. This energy loss is probably also directly connected with the separation phenomena described in the section on turbulence.

The results obtained at different engine speeds have been plotted on figure 9, where the velocity and q are measured at the tunnel center-line. By comparing the test-points, corresponding to different motor settings giving q, of this figure to those of figure 7, it will be noticed that a certain engine setting does not correspond to a definite dynamic pressure. Thus it is impossible to run the tunnel at an exact, predetermined speed. Theoretically this would not be too serious, since force coefficients and other dimensionless values are supposedly independent of the velocity. Needless to say this is however not strictly true, as may be seen from the fact that the value of q/h decreases with decreasing wind-speed. Therefore accurate test results can only be arrived at if constant dynamic pressure can be maintained.

To correct this limitation, the installation of a sensitive speed control is necessary. This is being considered at the present time. Such a device would also eliminate to some extent the serious difficulty encountered during many of the tests described herein, namely the marked fluctuation of power.

From these tests and also others it was apparent that after the motor had been run for an extended period at full speed, the RPM dropped markedly, and if it was allowed to rest and cool it would recover its former velocity. This is probably due to overheating in the engine windings, since furthermore the motor is installed on a badly ventilated basement floor, and closely hemmed in by the tunnel walls. Therefore if prolonged tests at full speed are desired, an improved method of ventilation should be devised, possibly in the form of a fan.

The method of finding the dynamic pressures and velocities corresponding to these tests has been discussed before.

VI. DETERMINATION OF THE FLOW INCLINATION:

It is important to determine the flow-inclination with respect to the horizontal through the working section.

The method chosen consisted of determining the polar of a model wing, first in a normal position and subsequently inverted. Thus, if a flow inclination existed, the components C_D and C_L at any particular given true angle of attack would have a different ratio if the wing is normal or inverted. The angle between the resultant forces is twice the flow inclination angle.

The wing used had a 24" span and a wing area of .613 $ft.^2$ It was mounted in a heavy block, and could be rotated through 360° and inverted. The mounting block was adjustable and calibrated, so that the angle of attack could be read from any arbitrary horizontal setting. The whole model was mounted on an arm of approximately ½" diameter.

The test was run twice, the results of the first test appearing to be unsatisfactory, since power fluctuations amounting to 17% velocity difference were observed. These fluctuations were of a slow nature, but prohibited accurate determination of both lift and drag since, due to the excessive model vibration explained below, equilibrium could only be established by observing the light-flashes of the balance over a period of many seconds, attempting to achieve an equal flash distribution. Since this could not be done on both lift and drag balance simultaneously it was essential to have a constant dynamic pressure over the period of balance-adjusting.

On the date of this first test, April 6, 1942, power fluctuations were observed throughout all Pasadena, and therefore the author decided to repeat the experiment.

Unfortunately on the second test completely constant dynamic pressure was still not achieved. However points were rechecked in instances where an excessive difference appeared, and the results are believed to be as accurate as the equipment permits. A glance at these results will show that this accuracy is very low, since despite all precautions, it would be senseless to attempt to establish any value for the flow inclination other than that it is within 20' of arc. The reasons for the insensitivity of this test are briefly.

1.) Assymetry and high tare drag of the model support system.

2.) Weakness of the model support.

3.) Speed fluctuations of the induction motor giving varying dynamic pressure.

The assymetry of the support system can be the only explanation for the fact that the polars of the two wing systems differ as they do. A free wing whose force components are measured by two different coordinate systems must determine two polars. Each point of the one polar must correspond to a point on the other, both corresponding to a certain absolute angle of attack. Then the angle between the two corresponding force components is the angle between the coordinate systems, and must be constant for all points of the polar. It is immediately apparent from Figure 10 that, whereas the experimental points of the different wing orientations fit quite readily into a smooth polar, these polars cross each other at two places other than at zero lift. This is a contradiction of the theory indicated above, and points to a difference in aerodynamic conditions between normal and inverted attitudes.

The effect of the high tare drag, amounting to 96.5% of the total drag at minimum drag position is obviously to destroy the significance of the measurements. Thus the low drag position of the polar is very approximate in character.

The socket for supporting the model was mounted on a rod of approximately ½" diameter, and this rod was too light for the forces experienced in the present tunnel. Thus excessive model fluctuation was possible, amounting to amplitudes at the wing tips of 2 inches or more. This often took the form of a constant flutter, and made a reading of the balances an exceedingly difficult and tedious task. In the new balance system this support will be more rigid and this difficulty will be largely eliminated.

Finally during the course of this test the power-input was found to drop off as the motor became overheated. This drop was peculiar in character and amounted to a definite drop in dynamic pressure of approximately 8.5%. If the motor was allowed to cool the former higher pressure niveau could be attained. The test was run in this manner, but this requirement introduced the necessity of making the balance adjustments rapidly to prevent overheating, giving rise to the errors discussed in the description of test number one.

In consideration of the foregoing it would seem unwise to draw any further conclusion from these tests than that there is no flow inclination which would affect the results of measurements obtained with the balances used herein and the power supply in the described condition. The flow inclination is less than 20' of arc, appearing to be as an average 15' above the horizontal and downstream directions.

Computations:

Measured L, D, ℓ

$$L = C_L S q$$

$$D - d = \frac{C_D S q}{1.274}$$

where: $L =$ Lift measured in lbs. on scales

D = Drag

d = tare-drag = .03054 q, from previous model calibrations

S = wing Area = .613 $ft.^2$

q = dynamic pressure in $lbs./ft.^2$

1 = static pressure in centimeters

$$1\ \ell\cdot\gamma\cdot\frac{.14205}{2.54} = h'' \qquad .14205 = \sin.\ 8^{\circ}\ 10'$$

$$q = q''\ \frac{62.4}{12}$$

γ = specific gravity of fluid = .814, (measured)

$\frac{q''}{h''}$ for 24" span = 1.722 (see page 14)

VII. TURBULENCE MEASUREMENTS

The fact that there are no honey combs or screens inserted into the wind before the contraction, and the fact that the tunnel walls are in many instances quite rough, led to the questions whether the turbulence level of the tunnel was not quite high. Furthermore models and manometer readings oscillated excessively, and it was thought that considerable light could be shed on the cause of these phenomena by turbulence measurements.

The method that was adopted is the usual hot-wire resistance measurements. Only a brief description is included since the method has been extensively described in other publications. (ref. No.3). It consists of placing a very fine wire, (.00025 inches in diameter in this case) and very short, (2mm.) at right anlges to the velocity which is to be determined. The resistance of the wire is a function of its temperature, and thus, in turn, is a function of the wind-velocity component at right-angles to the wire-axis. Therefore by measuring the change in resistance in the wire, we can calculate the velocity fluctuation. A very slight current is maintained in the wire, and the resulting voltage fluctuations are amplified, compensated for time-lag and recorded.

The turbulence has been defined as a percentage of the mean stream velocity U, and has been presented by measuring and tabulating the quantities:

$$\frac{\sqrt{u'^2}}{U}\,100 \quad \text{and} \quad \frac{\sqrt{v'^2}}{U}\,100$$

where u' is the difference between the mean-stream velocity U and the instantaneous velocity at any point, and v' is the velocity at right angles to the tunnel axis.

Mr. Stanley Corrsin and Dr. Hans Liepmann, both of the aeronautics department of the GALCIT, made the measurements described in this chapter possible. They had been making extensive hot-wire measurements at the GALCIT and furnished the equipment and supervised the tests run in the Merrill-GALCIT tunnel.

In addition to the usual hot-wire equipment an oscilloscope was used to show the nature of certain flow irregularities, which had been noticed by violent fluctuations of the galvanometer indicator.

The hot-wires were mounted on the center-line of the tunnel, approximately in the position at which the velocity calibrations were made, namely 17.25 inches aft of the beginning of the working-section.

Runs were made at different speeds, with the glass sidewalls in place and the tunnel clear. Subsequently measurements were taken with a 30-mesh precision copper-wire screen, the same as was used in the velocity calibration, as well as with a cheese-cloth screen. The screens were inserted into the wind-stream at the entrance of the working-section. Their wooden one inch by one inch frames presented definite obstacles to the wind-stream since they were not recessed into the tunnel wall. However due to the large distance from these disturbances to the hot-wires, the errors introduced from this source are considered negligible.

During the course of measuring the u' component it became immediately apparent that there was not only the normal turbulence of more or less constant amplitude with respect to time, which is present in most tunnel wind-streams, but that superimposed on this oscillation was another of much larger amplitude, and extremely aperiodic in character. These bursts of turbulence were observed in the oscilloscope and appeared to be similar in nature to the smaller scale turbulence, although having a many times larger amplitude. These bursts would last approximately from ¼ to ½ seconds and appear at intervals of less than five seconds. The cause of these bursts of severe turbulence is not as yet apparent. The investigators placed light threads on the walls of the contraction and of the working section and also inserted them on the ends of rods into the free stream. These threads behaved in marked accord with the oscilloscope observations, lying quietly in the wind stream for the majority of the time, and occasionally flapping quite violently and changing their direction, so that in such instances of turbulence they actually no longer were parallel to the walls or tunnel axis, as the flow characteristics would lead to expect, but were at an angle of perhaps some 10 or 15 degrees to their normal positions. Furthermore all threads under observation seemed to change direction simultaneously and in the same direction, and these shifts were accompanied by a burst of turbulence observed in the oscilloscope.

The v' measurements also showed a large-scale turbulence superimposed on the basic, but instead of appearing in isolated bursts, the intense turbulence lasted for more prolonged periods of time. Since the flow was seen to change direction,by observing the threads, a v-component of velocity would thus be introduced, and this would naturally be recorded by the hot-wire. Thus the excessively high v' components of velocity found in these measurements is a result of the flow-direction changes, which in turn appears to coincide with the u' bursts of turbulence.

No more than some speculative suggestions can be offered as explanation.

As has been described before, the static pressure at the maximum cross section is measured at all times, and certain oscillations spaced at similar time intervals as the turbulence bursts described above, may be observed at higher speeds. However no correlation can be noted, since of course the manometer system has a considerable time-lag. It is improbable that the motor could give cause to pulsations of such short duration. No reason can be given to expect the propeller to cause such irregular propulsive forces, although it is doubtless also a source of turbulence. It might appear however that certain unstable separation phenomena could give rise to these occurrences. The thread investigation showed a definite separation at the end of the working section, where an air-slot of one inch width is located. The diffusor level is approximately 1/8" below the working section floor, thus presenting in addition to the air slot a marked discontinuity and the air entering the tunnel at this point causes a large vortex which actually occasionally blew the threads upstream. That this separation could carry all the way around the tunnel and cause the flow-irregularities described above is probably not likely. In any case however such a disturbance is detrimental to the diffusor flow and thus to the energy ratio, which, as we have seen, is extremely low. Due to the insufficiency of the present air-slot it would seem extremely desirable to design a new one, of larger dimensions. This slot should be built to allow the air to enter the tunnel tangentially to the diffusor wall, thus reducing the probability of causing separation at this point. Furthermore by carefully sealing all air leaks the necessity of a large vent could be reduced. Possibly by cutting some small holes in the end of the diffusor and allowing the air to be drawn into the tunnel at this point by the propeller, the static pressure in the working-section could be raised to atmospheric without necessitating the presence of a large slot.

When this large separation vortex was noticed the slot was taped over, in the hope of eliminating the disturbance and reducing the turbulence. However, although the separation point seemed to vanish, as indicated by the threads held into the wind-stream, no change was noteiceable in the turbulence characteristics.

The most violent thread oscillations were observed in the contraction and since it is a short but high-ratio contraction, one might suppose that this leads to separation at opposite walls at different moments. In this manner changes in flow direction would be caused, as well as high turbulence. This would be substantiated by the fact that there is no honeycomb to smooth the flow in the tunnel, and the vanes inserted in the corners are rough and irregular. Thus improvement would presumably be obtained by making a gentler contraction or introducing a honey-comb after the last corner before the working section. There is no room for both contraction-change and honey-comb, since an effective comb should be followed by a straight portion of tunnel, to allow decay of the eddies introduced by it. The Merrill-GALCIT tunnel cannot be lengthened, since, for one reason, the building accomodating it will not permit it. It might therefore be best to first introduce a honey-comb in the tunnel as it now stands, and if this improvement is not satisfactory, to subsequently lengthen the contraction section.

It is interesting to note that the best flow conditions were found with the 30-mesh precision screen. Both turbulence coefficients were reduced approximately to half their previous values, and the violent bursts were largely eliminated. Thus for slower speed tests the use of the screen is strongly advised. By inserting a similar screen in the tunnel immediately before the contraction the turbulence might be reduced with much less resulting loss in dynamic pressure.

The insertion of the cheese-cloth screens proved to increase the turbulence as compared to the wire-mesh, although an improvement over the free tunnel condition was still apparent. This increase of turbulence over the wire mesh may be explained by the fact that the cloth-mesh is probably extremely irregular in character, allowing large-scale velocity differences over the whole screen, and introducing irregularity from this source. Furthermore due to the highly flexible character of the cloth, small oscillating motions such as flapping and stretching will presumably occur constantly, giving rise to small pressure changes. These disturbing effects would not be present in the wire-mesh screen.

The percentage turbulence found for the different conditions is listed below. That the resulting values are reasonably precise is indicated by the fact that the free-tunnel results at different speed check very well with one-another.

CONDITION	U f.p.s.	$\% \frac{\sqrt{u'^2}}{U}$	$\% \frac{\sqrt{v'^2}}{U}$
No screen	32.2	.57	
No screen	51.6	.55	2.8
No screen	77.7	.60	
30-mesh precision	33.8	.37	1.4
30-mesh precision	45.5	.31	
cheese-cloth	5.2	1.0	1.7

B. TESTS RUN IN A SMALL MODEL OF THE COOPERATIVE WIND-TUNNEL AND A SUGGESTION FOR A VARIABLE WORKING-SECTION WALL.

I. DESCRIPTION OF TESTS

During the month of May the author was called upon to give some assistance to Mr. Richard Shevell in his research problem concerning the new cooperative wind-tunnel, the design of which is being studied by the GALCIT at present.

The tunnel is to be a high speed tunnel, with a working section of approximately 8 feet by 12 feet.

The effects of compressibility are of extreme importance since the velocities considered approach that of sound. Because little data is available on tests in this region it was decided to build a small model of the contraction, working-section and diffusor, and to endeavor to gather information on certain problems. (Figure 11) These were briefly to find the effect of the high speeds on the energy ratio, on the diffusor efficiency, and to find a diffusor form which eliminated or reduced separation at the high speeds. Furthermore there should of course be no pressure gradient in the working-section.

Mr. Shevell's report on the subject is complete and accurate, and an attempt at duplication by the author of this paper would be useless. Therefore merely a brief outline is included. Eighteen small orifices spaced approximately 2 inches apart along the walls of the plaster-cast tunnel model were the means of finding the local static pressures. Plugs in the entrance and working sections were provided to permit the introduction of pitot-static tubes and total-head manometers, and a glass window was provided at the working section to permit observation of the proceedings. The power was supplied from a large pressure tank, and the model made small enough, so that sonic velocities could be attained by the volume of air pumped into the tank by the compressor. Thus the model working section was built 3.096 by 2.193 inches.

II. SUMMARY OF TESTS

A brief summary of the results obtained follows:

1.) A Mach number of 1.05 was obtained at the end of the working section. The Mach number M is defined as:

$$M = \frac{v}{a}$$

v = wind velocity
a = velocity of sound

For the airstream to return to the high pressure and corresponding low velocities of the exit within the expanding diffusor, it must create shock-waves with their attendant pressure jump. These, the observers believe, were made visible by the oil droplets present in the wind, which flowed in small, slow streams along the tunnel walls. At high speeds these streams stopped abruptly in a transverse line behind a pitot-static tube, supposedly due to the pressure-gradient of the shock wave caused by the disturbance. Furthermore an arch believed to be condensed water-vapor was seen to encircle the pitot-static tube at Mach numbers in the vicinity of one, possibly resulting from pressure and density gradients in shock-waves.

2.) Separation was found to exist near the end of the diffusor.

3.) The curves of pressure against tunnel position found in these tests show a constant pressure existing up to Mach numbers around .82 and thence an increasingly steep and

and negative pressure gradient through the working section. This is attributable to the increasing effect of the boundary layer, since with increasing M larger changes in pressure are caused by small changes in crossectional area, as is seen from the following equation:

$$\frac{dp}{p} = \frac{M^2}{1-M^2} \cdot \frac{kdf}{f}$$

p = pressure

f = crossectional area

k = heat constant , 1.4 for air

The curves found are extremely similar to those found by Dr. Ackeret of the E.T.H. in Zurich, Switzerland, (Ref. 1.) and thus give a good check to the measurements made with his tunnel.

Due to this increasing sensitivity to changes in crossectional area it follows that it is not possible to build a working section with fixed walls, such that there will be no pressure gradient through it, for all Mach numbers up to one. This difficulty is further aggravated if disturbances such as models or pitot-static tubes are inserted into the tunnel. Therefore if it is nevertheless wished to run significant tests at these velocities, there is no alternative but to adjust the tunnel crossection to the particular velocity, and, which is still more difficult, to the particular model.

The tests run with the small model described before having shed such a wealth of information in such a simple arrangement, it has been decided to construct another, wooden model, constructed more carefully and including various improvements over the old arrangement. Among these the problem of affording a variable wall for the test section is receiving considerable attention, and the author has been asked to include a workable suggestion on this subject.

III. THE VARIABLE CROSSECTION.

It has been explained above why good results could not be obtained without a variation in crossection. What then are the problems involved in affording this variable area? In the case of the full scale tunnel these problems are obviously primarily the enormous size of this varying wall, and the fact that the tunnel must be accessible through the walls that are to be varied. Thus the wall would have to be split in parts, and furthermore be flexible to avoid discontinuities. It would have to be rigid enough to withstand the relatively large negative pressures inside the tunnel, amounting to about ½ an atmosphere, unless the space outside of the wall were also held at this low pressure, a scheme involving a multitude of new design problems. The crossection being somewhat octagonal in shape, a discontinuity must arise at the joining of wall and corner fillet, unless the fillet is attached to the wall, in which case it would have to be flexible too. These and other obstacles could probably only be overcome at the price of tremendous cost increase and delay. An easier scheme might prove to be the introduction of preformed walls, fitting within the normal, fixed ones, in which case a different wall would possibly be needed for each speed considered as well as for each model. The author knows too little about the problem to go into further detail. However he will attempt to outline a possibility for the model tunnel.

The problems here are virtually the same but in a much smaller scale. First the question arises as to what is to be achieved by the variable wall. The primary objective is to maintain an even pressure throughout the section. This is relatively easily obtained for any Mach number less than one, for the empty tunnel. However when a model is introduced, there will again appear a gradient, and this could only be removed by practically continous position control along the wall. This is of course not practical. There would not be a great value in achieving a constant pressure for an empty tunnel only, but it is the authors opinion that any correction to the tunnel wall will certainly cause the critical Mach number, at which a gradient appears, to be raised, particularly if the adjustment can be made in the presence of the disturbing element. Whereas a cure for the problems is not contemplated, the variable wall will certainly provide good test conditions at higher Mach numbers. This improvement will be the better, and the value of the small scale results the greater, if the sensitivity of the wall-control is high. Therefore fixed wall corrections, as have also been suggested, would merely prove the variable correction and not the tunnel wall. The results would furthermore not be conclusive, since differences in fit and in surface roughness might well cause variations comparable to the corrections contemplated. On the other hand if a flexible wall is inserted, the smallest effects of position change can be observed. Finally, by such a device the airflow may first be chosen, and subsequently the walls adjusted as desired, whereas if an insert must be made, the wind-speed must be adjusted to the wall configuration, a cumbersome procedure in the case of the model in question.

For these reasons the author suggests a tunnel with a thin flexible metal wall, adjustable by thumb-screws. To afford the possibility of not only adjusting the minimum crossection, but of also making some allowance for the presence of a disturbance in the tunnel, two thumb-screws are suggested. This will also permit test-material to be gathered on the desirable shape of a corrected wall. Figure 12 shows the projected wall.

Since many other tests are to be made with the tunnel, it is extremely desirable to be able to remove this whole apparatus and replace it by either glass windows for Schlieren photographs, by plugs for pitot-static tubes and so forth. It is suggested that a standard fitting be constructed in which all these devices will be interchangeable, possibly among all four walls.

The problem of the corner fillets, the author believes can not be completely solved. There will of necessity be a discontinuity when the wall is projected beyond the normal wall. In this suggestion small sheet-metal covers are extended to the point of maximum wall-deflection, to prevent an air gap at a sharp metal edge, connecting to a cavity, in the working section. Some such seal is almost certainly essential. The secondary fillets on this small seal, (refer to figure 12), can be removed, and tests can show whether their presence or the presence of a free sheet edge is more detrimental to the flow.

Due to the low pressure in the tunnel, it is desirable that the chamber behind the flexible wall be vented to the tunnel, to prevent pressure loads from affecting the wall. However the author believes that there will be sufficient leakage around the top of the wall to fulfill this condition.

By calibrating the thumb-screws the exact wall position can be known at any instant.

In an article by Dr. Gasperi, (ref. 2) the possibility is indicated of making a workable supersonic tunnel, with only one of the four walls adjustable. Although it is realized that an inclination will be given to the airstream, nevertheless the desirability of leaving as many walls clear for other equipment as possible calls for the first experiments to be made with only one adjustable wall. Should this prove unsatisfactory it would be an easy matter to duplicate the arrangement on the opposite wall, if the fittings have been made identically.

To find the necessary wall travel the following rough calculations were made:

Assume $M = .9$, which represents the region under consideration. Assume the changes in pressure and area are small compared to the original values:

$$\frac{\nabla p}{p} = \frac{kM^2}{1-M^2} \cdot \frac{\nabla F}{F}$$

F = crossectional area = 6.45 in^2.

$k = 1.4$ for air

∇p, the pressure drop through the working section was found to be 4.3 cm of mercury on the three high speed runs.

$p = 51$ cm of mercury = average pressure in working section at the high-speed runs.

$\nabla F = .033$ in^2.

$\delta = \frac{\nabla F}{1.301} \approx .0407"$ necessary wall travel.

Thus .1" wall travel will be ample. The author suggests using

.01" sheet steel, for the flexible wall.

Since in the model in which the experiments were made Mach numbers larger than one were achieved downstream from the working section, the device suggested in these pages will presumably afford the possibility of attaining supersonic velocities in the working section itself. Undoubtedly the corner-fillet disturbances will be more noticeable if operation of the model tunnel is contemplated in this regime, but at the same time very interesting data could be collected on the effect of sonic velocities and shock-waves on the velocity-distribution, the boundary layer and the diffusor flow. In short a host of problems await the experimenter, and whether or not this device proves successful, the variable wall for a high speed tunnel will ultimately become essential, and every venture in this field will shed added light on the nature of the problem.

REFERENCES

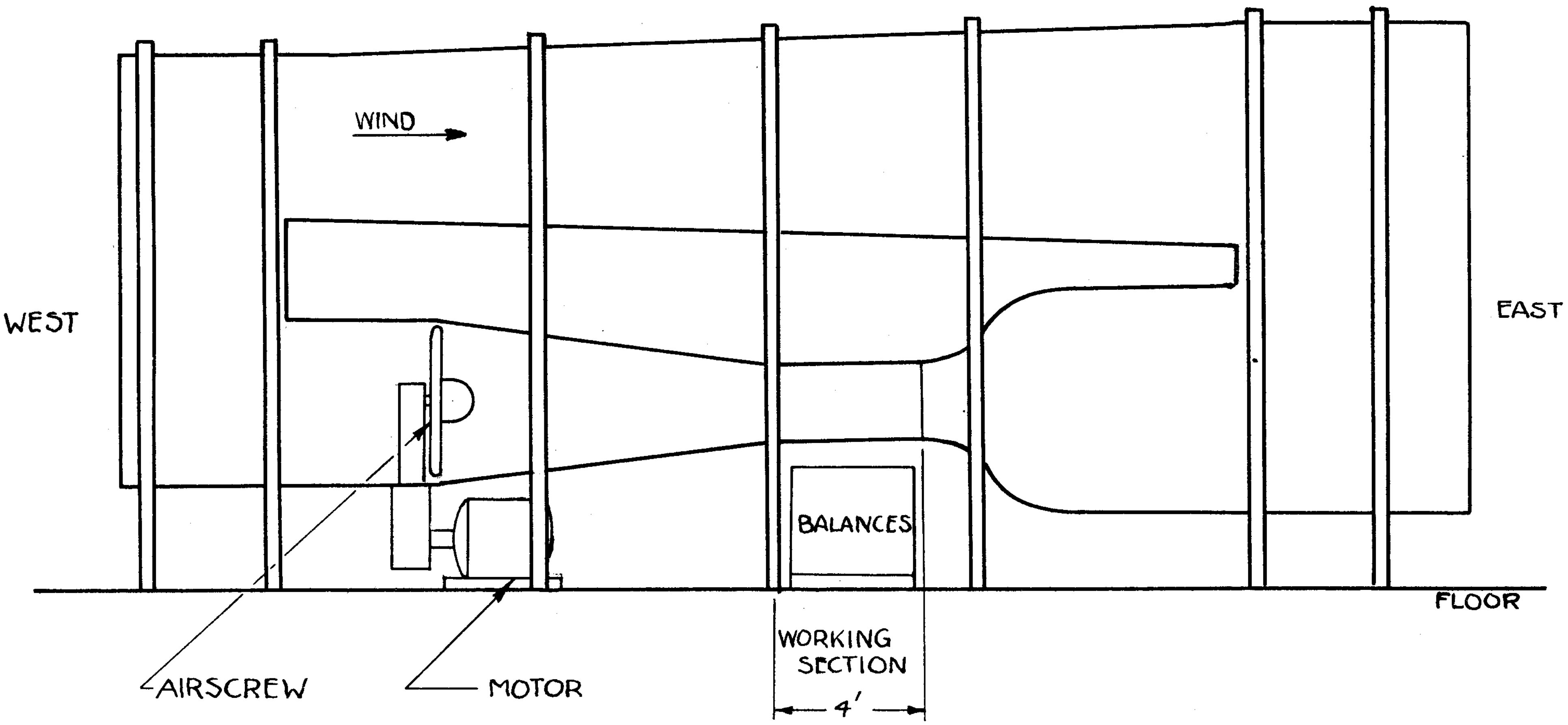
Ref. 1
J. Ackeret : Windkanaele fuer hohe Geschwindigkeiten.
(Convegno di scienze fisiche, Roma, 1936.)

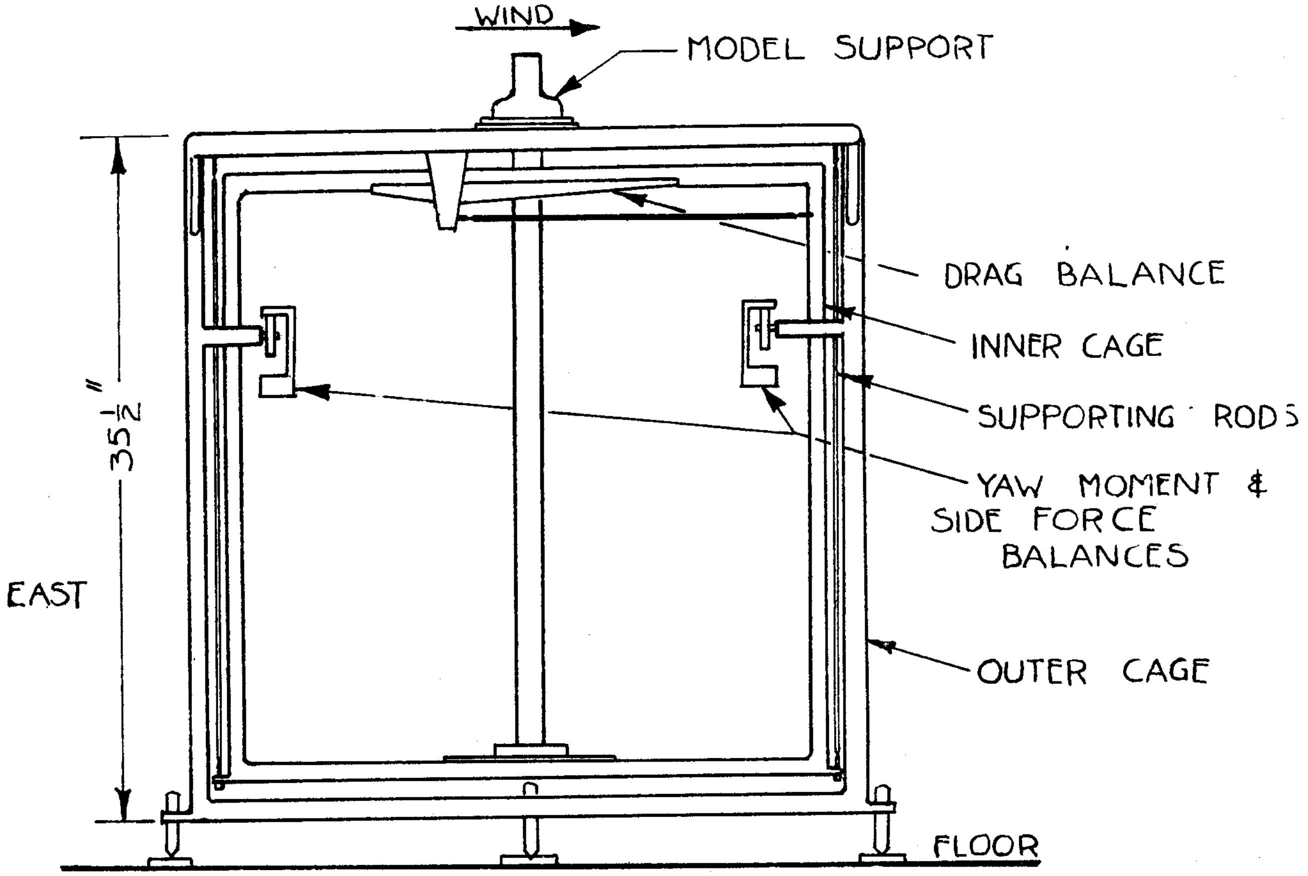
Ref. 2.
M. Gasperi : (Convegno di scienze fisiche, Roma, 1936.)

Ref. 3. : NACA Technical Report 320.

MERRIL - GALCIT WIND TUNNEL

SCALE 1" = 4'
FIGURE 1.

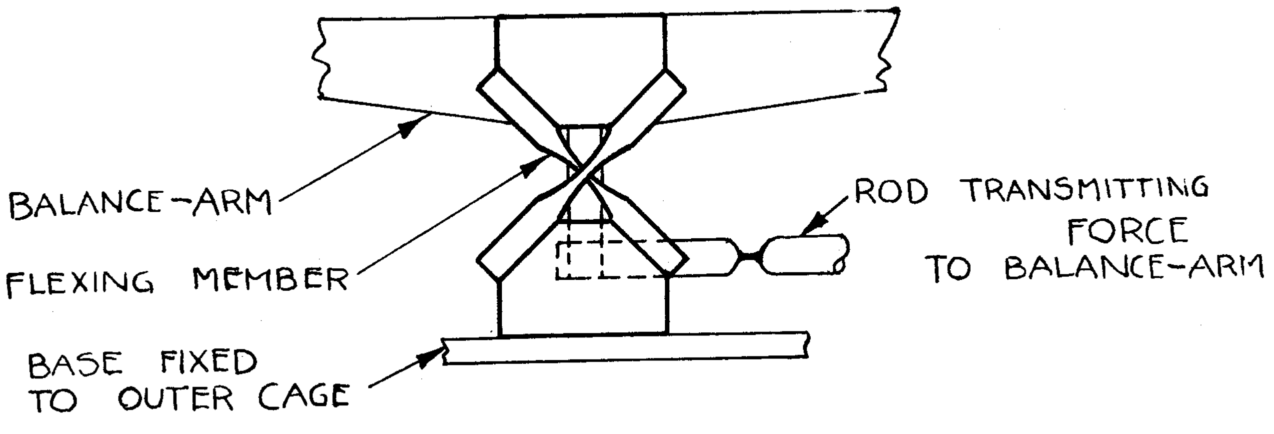




NEW BALANCE SYSTEM

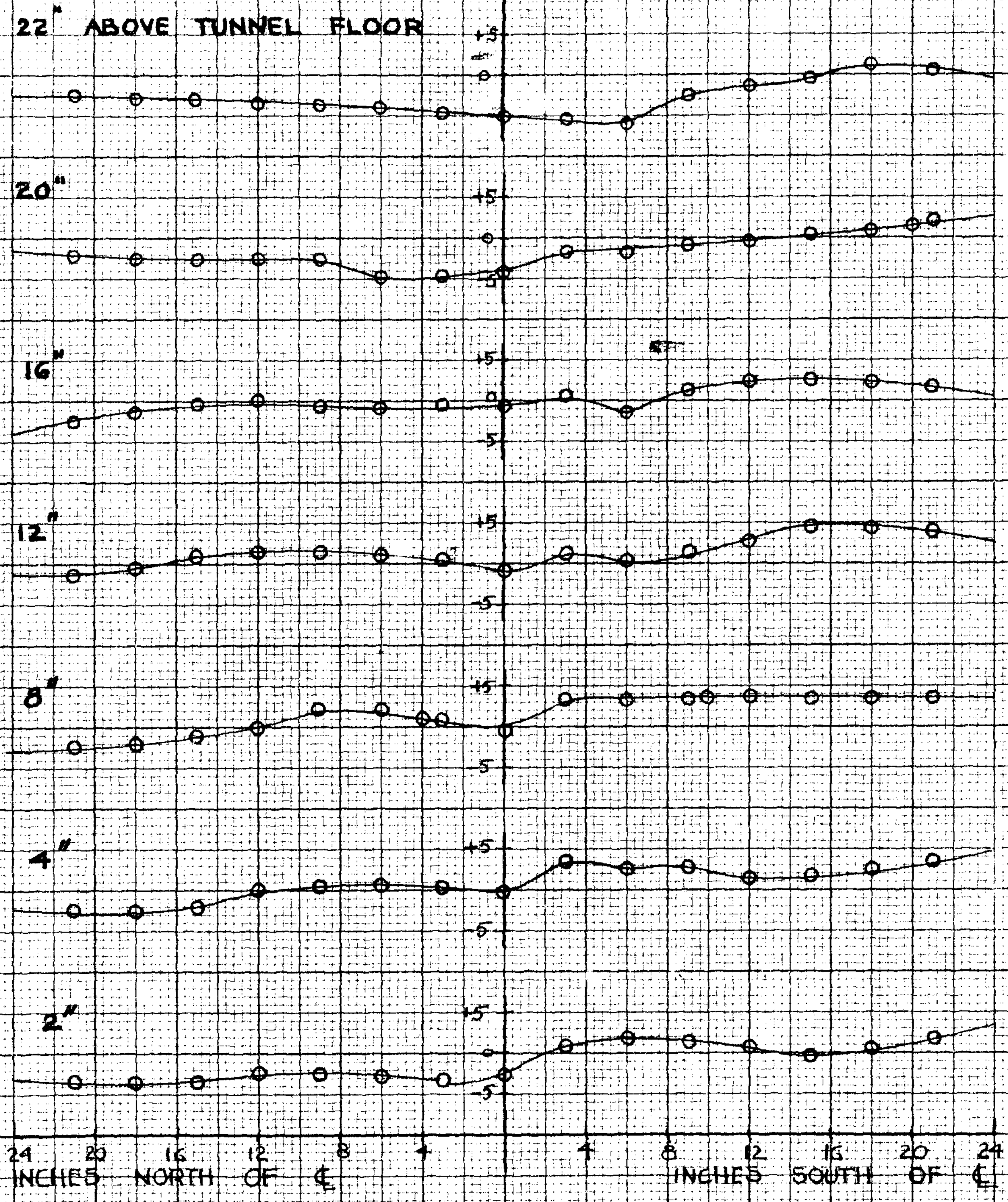
(SCALE $\frac{1}{10}$) FIG. 2 (SCHEMATIC)

NOTE: LIFT & ROLLING MOMENT BALANCES NOT DRAWN, CORRESPONDING TO DEVELOPEMENT TO THIS DATE



DRAG-BALANCE DETAIL (FULL SCALE)

FIG. 3

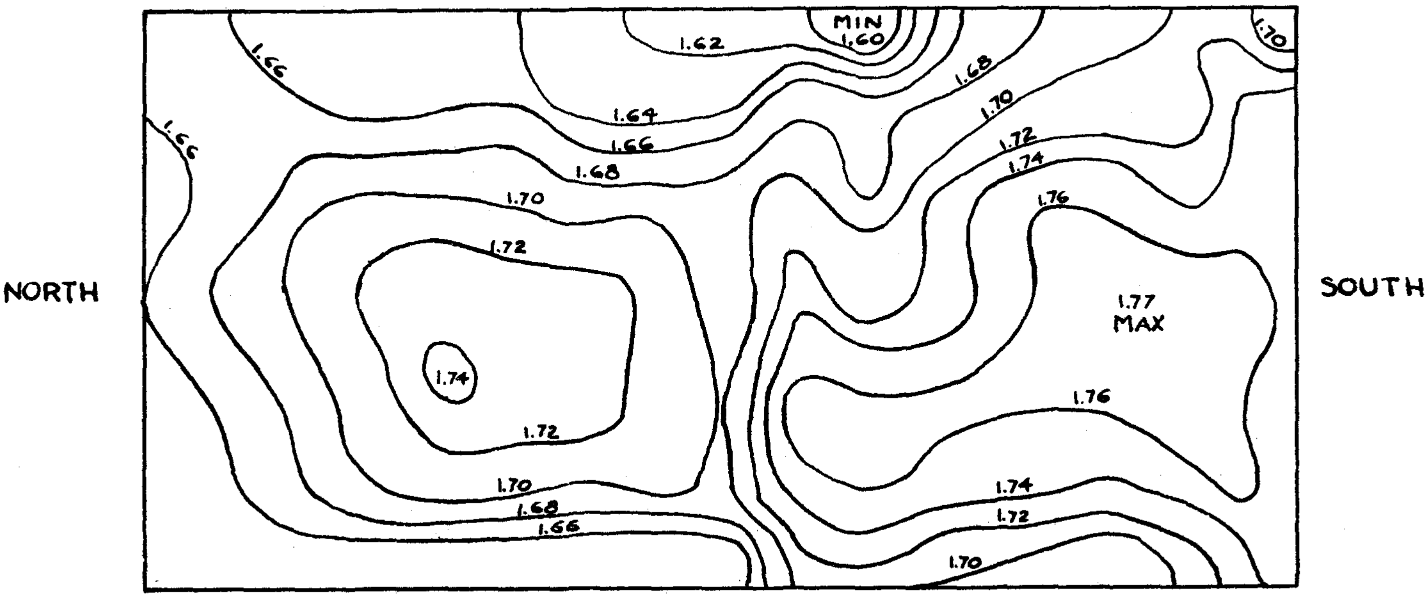


DYNAMIC PRESSURE PROFILES

CROSSECTION THROUGH WORKING SECTION

ORDINATES ARE PERCENT VARIATION OF q/h FROM q/h_{MEAN}

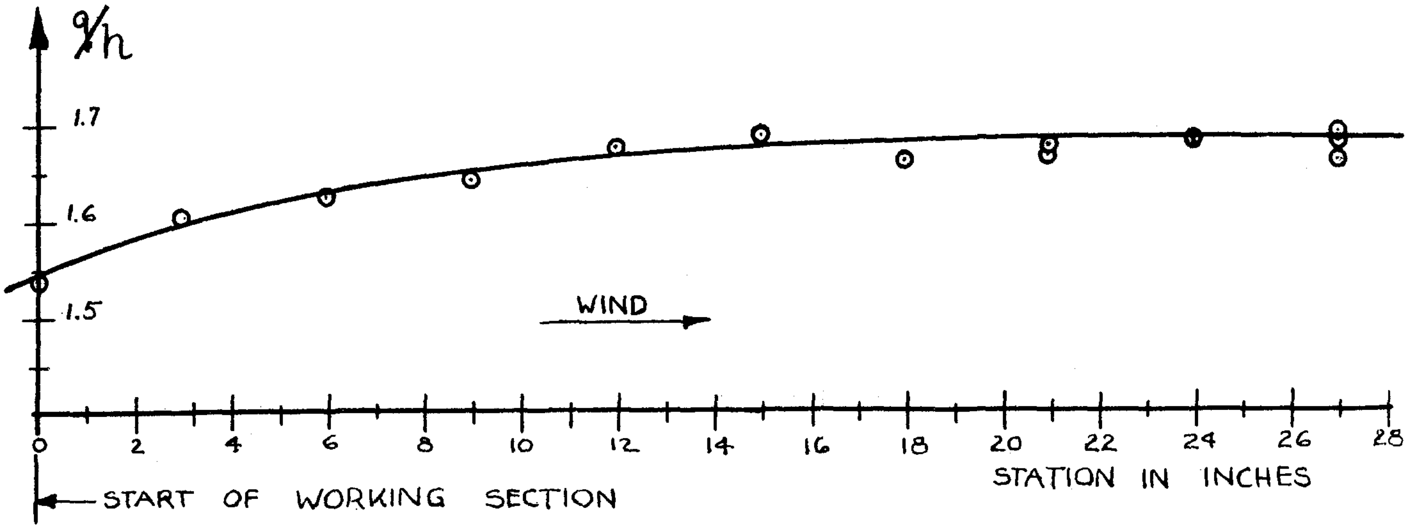
FIGURE 4



DYNAMIC PRESSURE DISTRIBUTION
SECTION 17.25

NUMBERS REFER TO LINES OF CONSTANT q/h

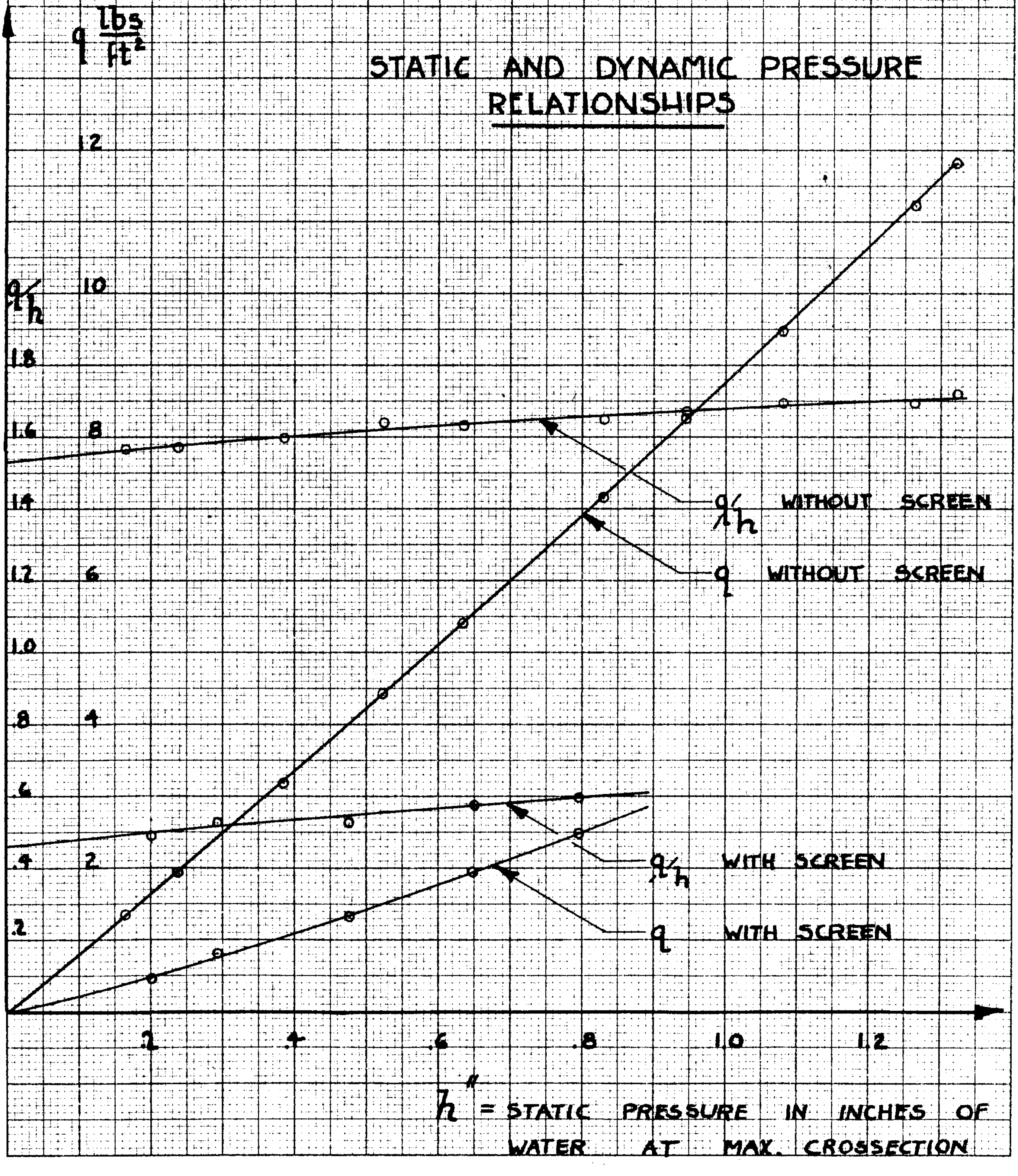
FIG. 5



AXIAL CALIBRATION

FIG. 6

FIGS. 7 & 8



STATIC AND DYNAMIC PRESSURE RELATIONSHIPS

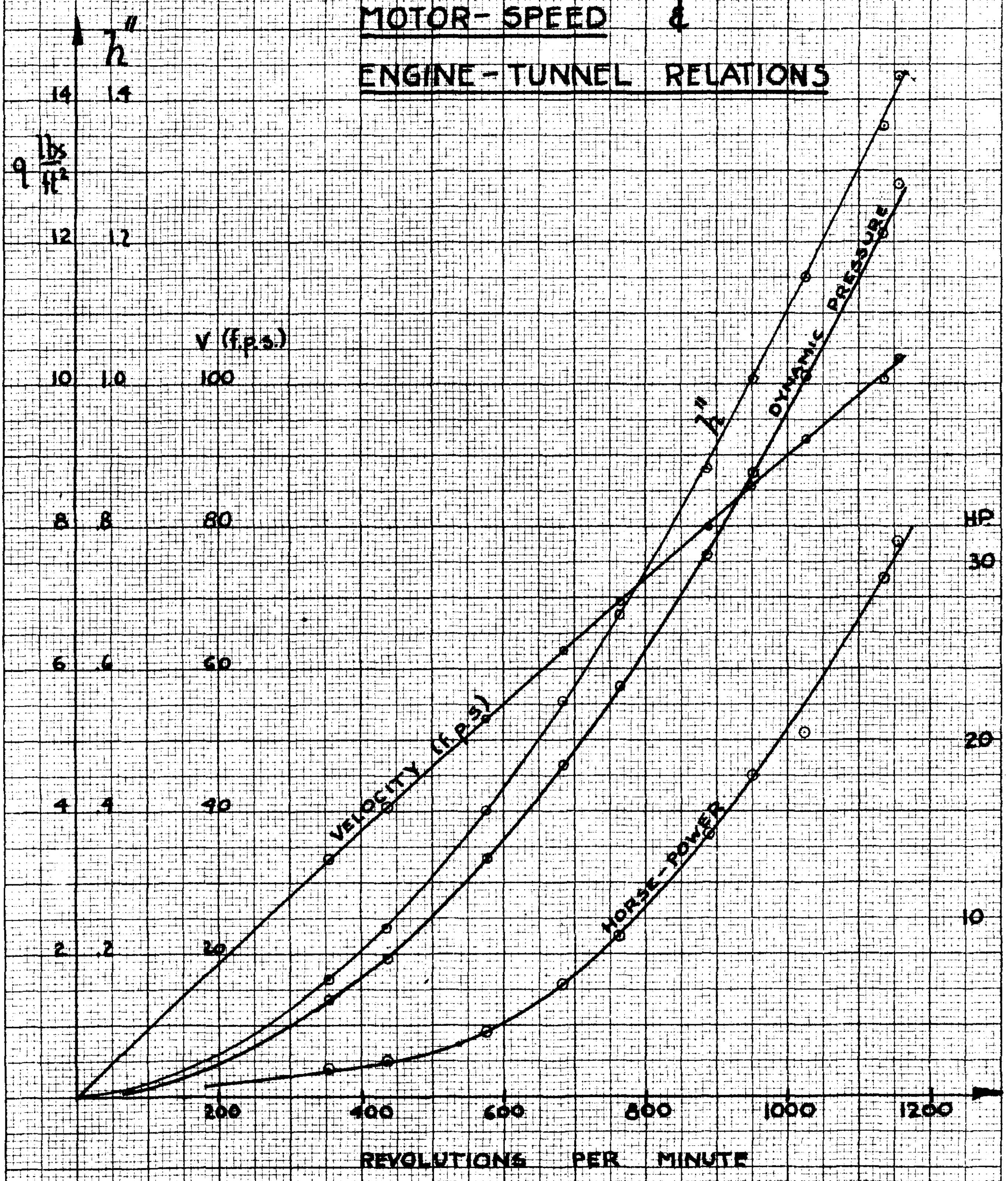

MOTOR-SPEED &
ENGINE-TUNNEL RELATIONS
h"
q lbs/ft²
14
1.4
12
1.2
V (f.p.s.)
10
1.0
100
8
.8
80
6
.6
60
4
.4
40
2
.2
20
HP
30
20
10
h"
DYNAMIC PRESSURE
VELOCITY (f.p.s.)
HORSE-POWER
200
400
600
800
1000
1200
REVOLUTIONS PER MINUTE

FIGURE 9

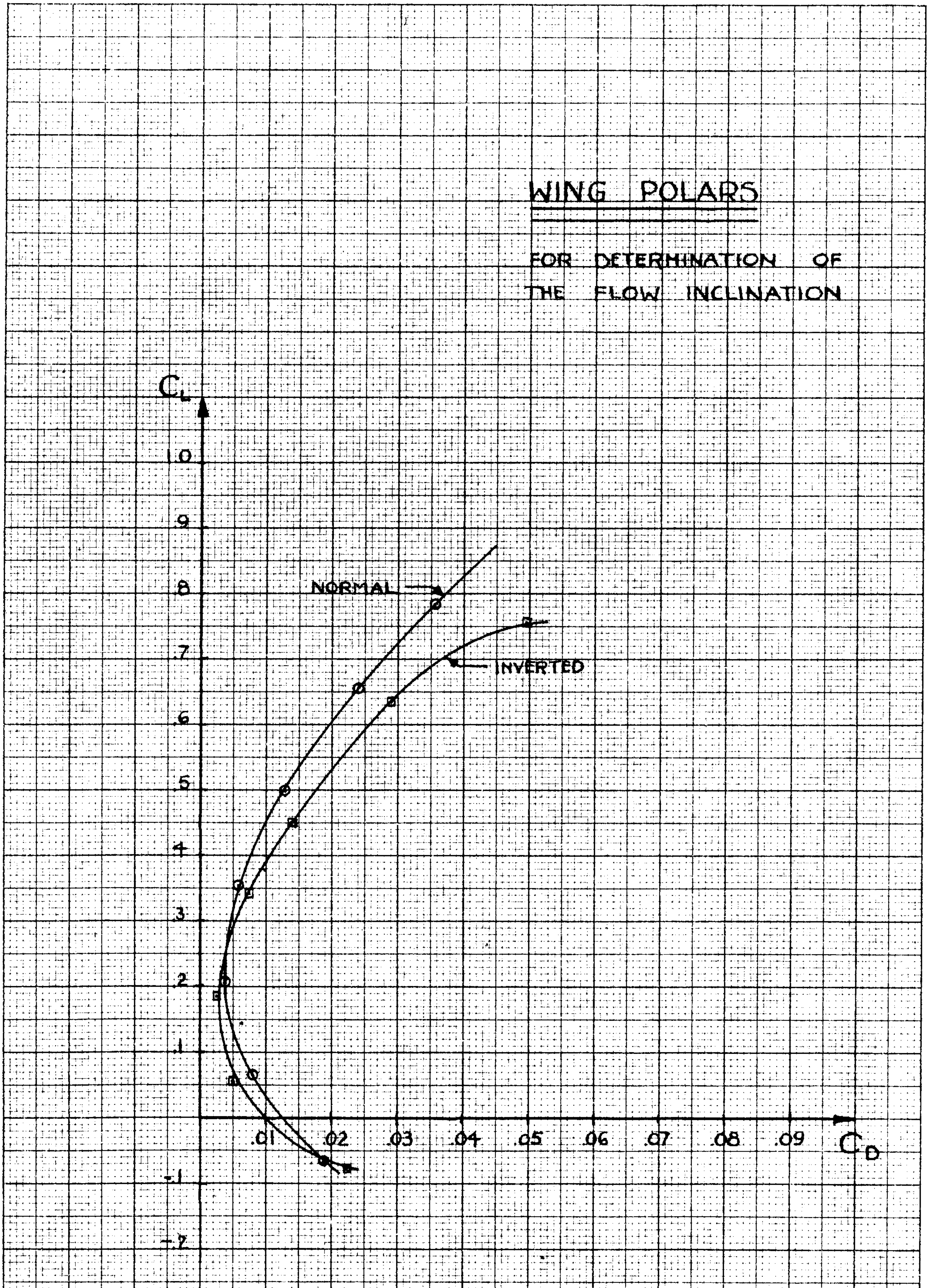
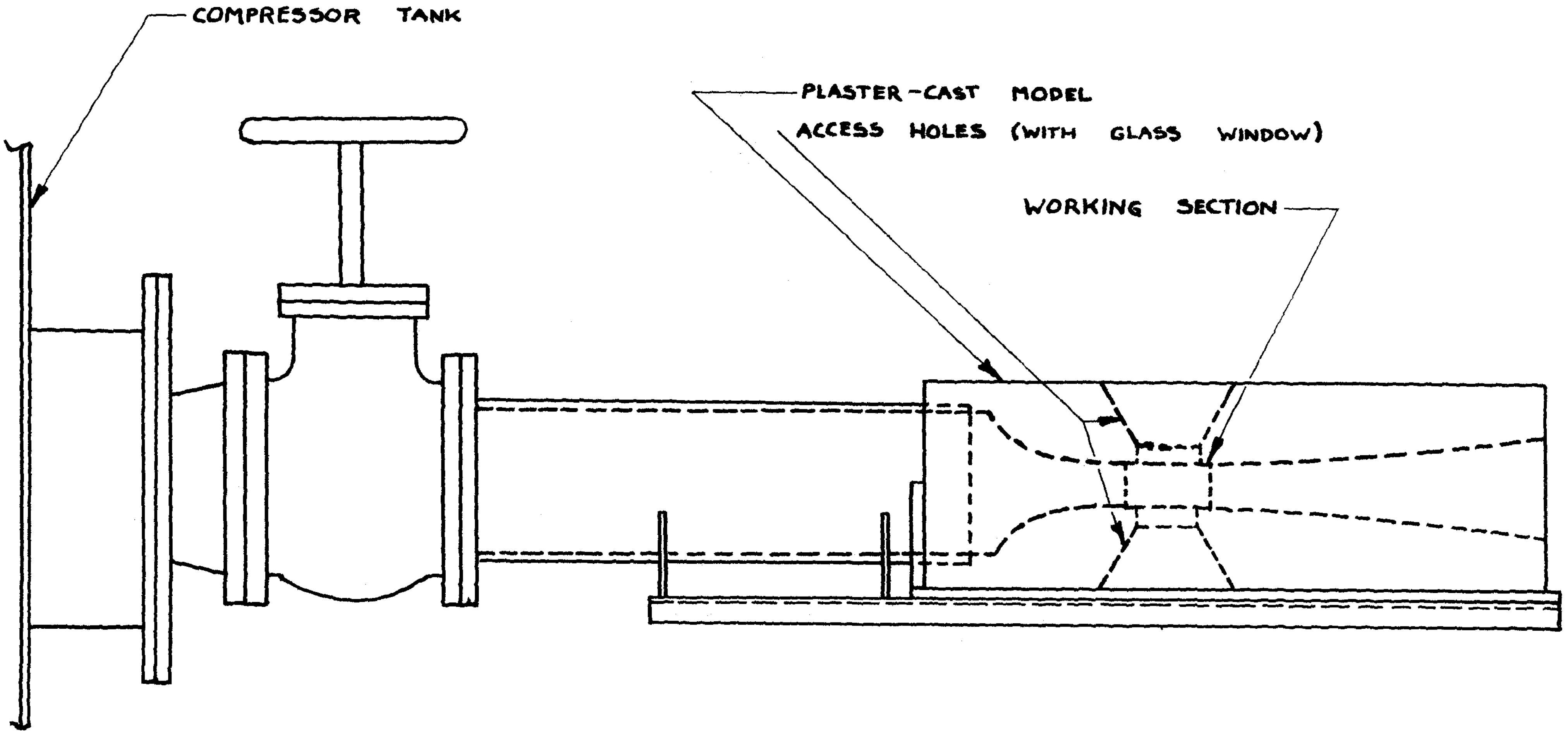

WING POLARS
FOR DETERMINATION OF THE FLOW INCLINATION
C_L
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
-.1
-.2
.01
.02
.03
.04
.05
.06
.07
.08
.09
C_D
NORMAL
INVERTED

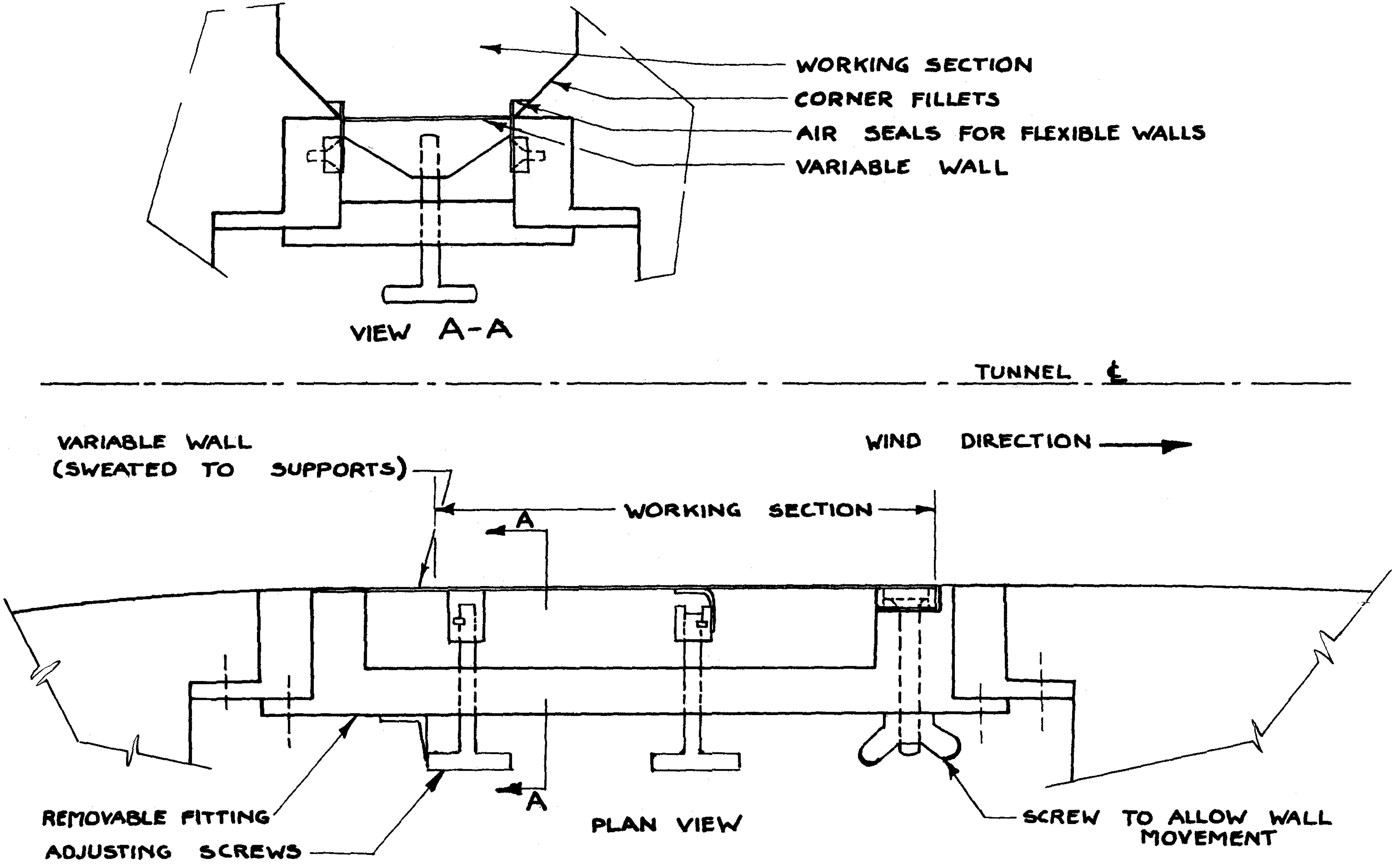
FIGURE 10



MODEL OF COOPERATIVE WIND-TUNNEL

SCALE: $1\frac{1}{2}'' = 1'$

FIGURE 11



VARIABLE WALL

FULL SCALE

COOPERATIVE WIND-TUNNEL MODEL

FIGURE 12