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MEASUREMENTS OF TRANSIENT PRESSURES ON A NARROW-DELTA WING DUE TO AN UPWARD GUST

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G. K. Hunt, D. R. Roberts

and

D. Walker

SUMMARY

With the aid of a new research facility, transient pressures have been measured on the upper surface of a narrow-delta wing when it entered a sharp-edged gust normal to the wing plane. This paper describes the facility and presents an analysis of the results of six runs through the gust by one model.

It is shown that the pressure distribution on any particular cross-section of the wing remains unaffected until that section enters the gust, and then begins immediately to change. The pressure change due to the gust develops at each section at a rate which is a function of the local span.

Replaces RAE Technical Note No. Aero 2781 - ARC 23,473.

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1 INTRODUCTION

A feature of the narrow-delta wing is the primary flow separation which occurs at the leading edges under lifting conditions. The resultant vortex sheets roll up along their free edges into two vortex cores above the upper surface of the wing, and the flow over the wing is otherwise irrotational and essentially three-dimensional. The narrow-delta wing has emerged[1] as a promising shape for efficient flight at supersonic Mach numbers, and this has aroused interest in a number of the special problems associated with the flow around it. One of these problems is the estimation of gust loads.

In a review of unsteady aerodynamic problems on wings with separated flow, Zbrozek[2] pointed out that nothing was known about the transient behaviour of the vortex flow over a narrow delta when it entered a gust. Not even the order of magnitude of the gust loads could be estimated, because the only existing methods of estimation were derived from two-dimensional potential-flow theory. More recently Hancock[3] has applied linear slender-wing theory to the gust entry problem, but the assumptions on which his argument is based are still the subject of some discussion. However, his paper has remained the only published theoretical work, known to the authors, relating in some detail to transient vortex flow on slender wings.

In order to cast some light on the problem an experimental investigation was undertaken at the R.A.E., in the course of which a new research facility was developed[4]. Measurements of transient pressures on the surface of a narrow-delta wing have been obtained, which indicate the development of the incremental lift on the wing as it enters a gust. This paper describes the new facility briefly and presents an analysis of the first results obtained from one model.

2 THE GUST RESEARCH FACILITY

The simplest analyses of gust response are based on the concept of an aircraft flying at constant speed through a sharp-edged gust. The new facility reproduces these conditions as nearly as possible by propelling a model along a prescribed path through still air, and creating artificially a sharp-edged gust across the path.

The model is carried along a straight railway track by a rocket-propelled sledge (Fig.1). The artificial gust is produced by the efflux from an open-jet wind tunnel blowing across the track (Fig.2).

The track is nearly 2000 feet long, and is situated at Farnborough, where it has been in use for several years for a variety of experimental purposes. There are three rails, built to ordinary railway standards, with the outer rails set to a gauge of three feet. There is a safety cage and a blast screen at one end of the track, and two complete installations of naval arresting gear near the other end (Fig.3).

The sledge runs on four shoes, two surrounding the upper flange of the centre rail in tandem, and the other two bearing on the outer rails. The model is mounted on the front of an aerodynamically stable dart, which is suspended from the frame of the sledge by a system of low-rate springs and a gimbal (Fig.4). This device was adopted to isolate the model, and the transducers inside it, from the vibrations induced in the structure of the sledge by irregularities in the track*. It has proved to be remarkably effective in practice.

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*K. J. Turner of R.A.E., Farnborough, made the suggestion which led to the design of this suspension system.

The wind tunnel was designed by the Low-Speed Tunnels Division of Aerodynamics Department[5] to produce a horizontal jet of air 15 feet wide and $4\frac{1}{2}$ feet deep. In order to minimise the time taken to complete the tunnel, its design was based on fixed-speed ventilating-fan units which were available commercially. The tunnel has a contraction ratio of only 2:1, but the velocity distribution across the jet is nearly uniform. In the plane of the track centreline the mean velocity is 46 ft/sec and the thickness of the mixing zone at the edge of the jet is about 10 inches.

3 INSTRUMENTATION

At present, experimental measurements are confined to pressures on the surface of the model, using transducers of a type developed by Owen[6]. This consists essentially of an electrical capacitance, with one plate fixed and the other formed by a diaphragm which is deflected by the pressure being measured. Over the diaphragm there is a cap with a small central hole, and the outer face of the cap is set flush with the surface on which pressure is to be measured. Variations in the capacitance of the transducer are used to frequency-modulate the output of an oscillator. The modulated signal is amplified and fed to a discriminator, which produces a d.c. voltage output proportional to the input frequency. This voltage is recorded by an oscillograph.

The transient response of one transducer and its associated equipment to a step change of pressure has been determined. The transducer was installed in the wall of a shock tube and connected to its associated oscillator, amplifier and discriminator. Four records of responses to pressure steps are reproduced in Fig.14. They show that the system is well damped and has a rise time of the order of 10^{-4} second. (The high-frequency oscillation visible on the records is due to vibration of the shock tube wall.) The rise time indicates that the pressure-measuring system should follow accurately an oscillatory pressure variation at any frequency up to 2 Kc/s.

The oscillators are carried on the sledge, with their own power supply, but the amplifiers and discriminators are on the ground. The frequencies to which the oscillators are tuned differ sufficiently to allow their modulated outputs to be mixed and fed to the amplifiers through a common connection. An earth connection is required in addition because, at high speeds, the sledge is not always in contact with the rails. The mixed signals are separated by the amplifiers, which are tuned to the same frequencies as the oscillators and are sufficiently selective to ensure that each amplifies the signal from only one oscillator. The two connections between the moving sledge and the equipment on the ground are made by means of knives attached to the sledge and strips of copper gauze secured in clamps parallel to the track (Fig.2). When the sledge passes the clamps each knife cuts a strip of gauze from end to end and, while it does so, a noise-free connection is established. The gauze strips are 30 feet long and are positioned so that signals are received during the last 15 feet of the approach of the model to the gust and throughout the length of the gust itself.

The discriminators are standard proprietary products with a limited bandwidth. At present only two pressure-measuring channels can be accommodated within this bandwidth because of the wide frequency separation necessary to avoid cross-talk. The bandwidth of the discriminators will be extended and the selectivity of the amplifiers will be increased, to allow more channels to be used in future tests.

The position of the sledge at any instant during its run, and hence its speed, is determined by means of coils fixed between the rails at regular intervals throughout the length of the track. A permanent magnet on the sledge induces an e.m.f. in each coil as the sledge passes over it and, since the coils are in series with an oscillograph, a sequence of pulses can be recorded while the sledge is moving. There is a special group of closely spaced coils near the tunnel, to indicate the approach of the model to the gust.

4 THE MODEL

The results presented in this paper were obtained from the somewhat arbitrary model that was used in the development of the experimental technique (Figs.5 and 6). It had a straight-edged delta planform with an aspect ratio of 1.2, and a length of 30 inches. The leading edges were sharp, but the trailing edge had a finite thickness. One side of the model was flat and the other was faired arbitrarily to provide sufficient volume to accommodate the transducers and their connecting pipes and cables. The included angle of the leading-edge profile, measured normal to the edge, was 45 degrees.

The model was mounted at zero incidence relative to the dart axis, with the plane of the wing perpendicular to the direction of the gust. The flat side of the model, on which pressures were measured, was the lee side relative to the gust, and thus represented the upper surface of a wing passing through an upward gust.

5 THEORETICAL BACKGROUND

A brief review of existing theoretical methods of estimating gust loads will provide a background against which to view the experimental results.

Two widely accepted theories relating to transient flow on conventional wings are those of Wagner and of Küssner. Both theories relate to subsonic flight, and are derived from the classical theory of potential flow past aerofoils in two dimensions. They are summarised in Ref.7, where they are adapted to apply to rectangular wings of finite aspect ratio. The two theories can be regarded as representing two extreme forms of gust entry conditions. Wagner's theory, which has been verified experimentally[8], predicts the flow around an aerofoil after a sudden change of incidence. Küssner's theory deals with the present problem, entry at flight speed into a simple, sharp-edged, upward gust.

The development of incremental lift on rectangular wings, as predicted by the two theories, is shown in Fig.7(a) and Fig.8(a). These figures have been adapted from Ref.7. They show that, even when the incidence of the whole wing changes instantaneously, the lift takes a finite time to build up, and that the lowest aspect ratios have the shortest build-up time. Local pressure changes on the wing surface probably follow generally similar curves.

Calculations for the narrow-delta wing are all based on slender-wing theory, applied to a hypothetical attached flow with infinite suction along the leading edges, which cannot be realised in practice. One of the essential assumptions on which this theory depends is that, provided the wing is thin, the flow in the y-z plane, perpendicular to the direction of motion of the wing, can be treated as two-dimensional and thus independent of x. Lomax et al[9] have considered the growth of lift on a narrow delta due to a sudden change of incidence without flow separation, and the result of one of their calculations is reproduced in Fig.7(b). This differs in two important respects from the results of Wagner's theory, Fig.7(a). The initial lift on the narrow delta is greater than the final steady lift, and the time taken to reach the steady lift is small. An analysis by Lehrian[10] of some experimental measurements tends to confirm the large initial lift.

The particular case of entry by a narrow-delta wing into a sharp-edged gust, again for the hypothetical flow without separation from the leading edges, has been studied by Miles[11]. He has specifically considered only supersonic flight speeds, in order to avoid trailing-edge and wake effects, but recent unpublished calculations by B. D. Dore, extending Miles' theory into the subsonic regime, suggest that these effects may not be very large. Miles calculated instantaneous lift as a function of the product of Mach number and aspect ratio, and gives in his book curves for three values of this parameter. When the aspect ratio is 1.2, as in the present experimental investigation, only one of these values corresponds to a supersonic Mach number, and this curve is reproduced as a full line in Fig.8(b). The other two curves have been included in this figure, as broken lines, to provide a qualitative guide to the development of incremental lift at subsonic speeds.

The transient vortex flow on a narrow-delta wing, when it enters a sharp-edged gust, was considered by Zbrozek[2] and by Hancock[3]. The argument developed by Hancock is more detailed than that of Zbrozek, but they are fundamentally similar and lead to the same conclusion. Based on the concepts of slender-wing theory, it has been argued that the rate at which vorticity is shed from the leading edges at a particular longitudinal station is a function of the local angle of incidence at that station only. When the gust front reaches each x-station, the flow in the y-z plane at that station changes instantaneously from the steady flow associated with the original incidence to that associated with the new incidence due to the gust. If the wing is thin, the vorticity is convected along the wing at flight speed, and there is thus a discontinuity in the strength of the wing vortices across the gust front (Fig.9(a)).

Zbrozek[2] also postulated an alternative form of transient vortex flow, in which there is a delay in the formation of the leading-edge vortices. The flow over the complete wing cannot then reach its steady state until some time after the gust front has passed the trailing edge (Fig.9(b)). Obviously the dynamic loads imposed on the structure of a full-scale aircraft by this kind of transient flow could be considerably less than those imposed by the transient flow predicted by slender-wing theory.

No attempt has been made to calculate transient pressures at points on the wing surface for the model tested. However, in order to relate the transient-vortex-flow theories to the present experimental results, the forms of pressure change at the transducer positions, indicated by the two theories, are shown qualitatively in Fig.9.

6 EXPERIMENTAL RESULTS

Preliminary runs showed that rapid local fluctuations of pressure occurred inside the gust, probably caused by tunnel turbulence. The fluctuations were large enough to obscure the steady pressure changes induced on the wing surface by the gust, except in the region of the leading-edge vortices. The initial experiments were, therefore, confined to measurements under the vortices, and attempts to measure pressures elsewhere on the wing were postponed. The two pressure transducers were installed on a three-quarter-span ray from the apex of the wing, spaced half the length of the model apart.

The data obtained from the model were recorded by a multi-channel oscillograph. A typical record is shown in Fig.10. The upper trace shows the pulses from the postion-indicator coils, and the other two traces show the pressure variations indicated by the transducers. Timing marks appear on the bottom edge of the record every 0.004 sec. Inspection of the record shows two principal features. First, there is a time-lag between the responses of the two transducers to the gust which corresponds closely to the chordwise distance between them. Second, the form of the response of each transducer to the gust is essentially the same. There is an approximately exponential approach to the steady conditions inside the gust; this is usually, but not always, preceded by an initial peak.

All the records were obtained after the rocket motors had finished burning, when the sledge was decelerating at about 9 ft/sec^2. At the forward speed of 190 ft/sec, at which these experiments were done, the time taken by the model to enter the gust and reach steady conditions inside it was about 0.05 sec. Therefore, for the purpose of analysing the transient flow during that period, the speed of the model was regarded as constant. The spacing of the pulses from the group of six coils then became a convenient scale of length.

Instantaneous positions of the model, relative to the gust, were calculated from the corresponding positions of the sledge indicated by the coils, taking account of the forward shift of the dart on its suspension due to the deceleration of the sledge. The dart was always free to oscillate in a fore-and-aft direction, though it was not observed to do so appreciably, so the calculated positions of the model may include errors of up to an inch.

An analysis of the records of six runs has been made, and the results are presented with this paper. As measurements of this kind have not been published before, the method of analysis, though straightforward, is described. The essential notation is set out in Fig.11.

Each trace was treated in the same way. The mean initial and final levels, between which the pressure change occurred when the model entered the gust, were determined by inspection. The irregularities in the recorded pressure change were eliminated by fitting an exponential curve to the record, with the final pressure level as its asymptote. If there was an initial peak it was ignored. The co-ordinates of this smoothed curve were then read directly in terms of pressure and of distance penetrated into the gust, by reference to the transducer calibration and the scale of length provided by the pulses from the coils. The smoothed curves so obtained were difficult to compare directly, because the initial and final pressure levels measured by a particular transducer varied somewhat from run to run. Subsequent analysis was, therefore, based on the quantity $\Delta p/\Delta p_0$ (Fig.11). When values of this quantity obtained from the forward transducer were plotted against x_0/c_1, and the values from the aft transducer were plotted against x_0/c_2, reasonably similar curves were obtained. However, it is inconsistent with the concepts of slender-wing theory that the flow development at any section should depend on the length of wing ahead of that section. Distances penetrated into the gust by each section were, therefore, treated as multiples of the local span at that section. This has no effect on the similarity of the results from the present experiment, but would be important in the case of a wing with curved leading edges.

The results of the analysis are presented in Fig.12 and 13 in the form of curves of $\Delta p/\Delta p_0$, plotted against x_1/b_1 for the forward transducer and against x_2/b_2 for the aft transducer. In spite of some variation between individual curves, an obvious trend is revealed. At a particular cross-section of the wing, 90 per cent of the pressure change due to the gust is completed only when the section itself has penetrated into the gust a distance equal to about five times the local span at that section.

7 DISCUSSION

The results obtained from this investigation indicate for the first time the development of incremental lift on a narrow-delta wing when it enters a gust. The slightly unusual shape of the model is probably unimportant as it possessed the essential characteristic of a sharp, highly-swept, leading edge.

One of the most important facts established by these measurements is that the pressure distribution at any given cross-section of the wing remains unaffected until that particular section enters the gust. In this respect the experiment supports the concepts of slender-wing theory (c.f. Fig.9(a)) but the step change of pressure indicated by Hancock's theory has not occurred. The observed pressure change is much more gradual and is roughly exponential in form. The rate of development of the gust-induced flow at a particular cross-section is shown to be a function of the local span at that section.

In this experiment the model approached the gust at zero incidence and vortex flow was not established before the gust was encountered. It may be argued that vortex flow would be established above the wing of an aircraft in flight and that these tests are unrepresentative of real conditions. However, if the cross-flow remains two-dimensional during the transient conditions following gust entry, in accordance with slender-wing theory, the development of the gust-induced flow must be the same whether vortex flow is established before entering the gust or not. This point will be investigated, by making further tests in which the model will approach the gust at an angle of incidence large enough to establish vortex flow.

A feature of the experimental results is the initial peak which frequently occurred in the responses of the transducers to the gust. The shock-tube calibration of the pressure-measuring system shows that the peak is not an acoustic or electronic transient and must be an aerodynamic effect of some kind. The calculations of Lomax[9] and Miles[11] indicate an initial peak in the transient development of lift in potential flow (Figs.7 and 8); this suggests that the experimental peaks may be associated with the momentary development of a local attached flow before the leading-edge separations begin to dominate the flow pattern. However, the peaks may be associated with the mixing zone at the edge of the gust. The duration of the peaks corresponds closely to the time taken by a point on the model to traverse the mixing zone. The flow in the mixing zone is unsteady, and the amplitudes of the peaks are scarcely different from the maximum amplitude of the pressure fluctuations caused by turbulence inside the gust. The unsteady nature of the flow in the mixing zone may account for the variety of peak shapes that have been recorded, and for the different peak shapes that have frequently been indicated by the two transducers on the same run. (See, for example, Fig.10.) The present results are not sufficient to explain the mechanism of the peaks. A more detailed study of the development of the gust-induced flow will be necessary with, perhaps, an investigation of the effects of varying the mixing zone thickness.

The transducers were installed under the expected final position of one of the vortex cores. Therefore they have probably shown quite accurately the times taken by the gust-induced vortex flow to develop locally. At the angle of incidence induced by the gust, under steady conditions, roughly half the nett load on a spanwise element of the wing is associated with the vortices. The transducers have, therefore, shown the times taken to develop about half the nett loads induced by the gust on local spanwise elements. The potential flow is unlikely to change appreciably after the vortex cores have reached their final strengths and positions. Thus, in fact, the transducers have probably indicated the times taken to develop the total loads on local spanwise elements. The transient variation of the load on such an element cannot be inferred from the transient pressure variation at one point. Simultaneous measurements of transient pressures at a number of points across the span, on the upper and lower surfaces, will be necessary to enable the transient load on a spanwise element to be determined.

8 CONCLUSIONS

A new research facility has been developed which enables transient aerodynamic effects on lifting surfaces to be investigated. It has been used to obtain measurements of transient pressures on the upper surface of a narrow-delta wing as it enters a gust normal to the wing plane.

The pressure distribution over any cross-section of the wing remains unaffected until that particular section enters the gust. Then the pressure distribution immediately begins to change. This supports the general concepts of slender-wing theory.

The form of the pressure change due to the gust is the same at all cross-sections, but is less severe than the step change predicted by Hancock's theory. There is an approximately exponential approach to the steady conditions inside the gust; this is usually, but not always, preceded by an initial peak. At any cross-section, 90 per cent of the total pressure change due to the gust is accomplished only when the section itself has penetrated into the gust a distance equal to about five times the local span at that section.

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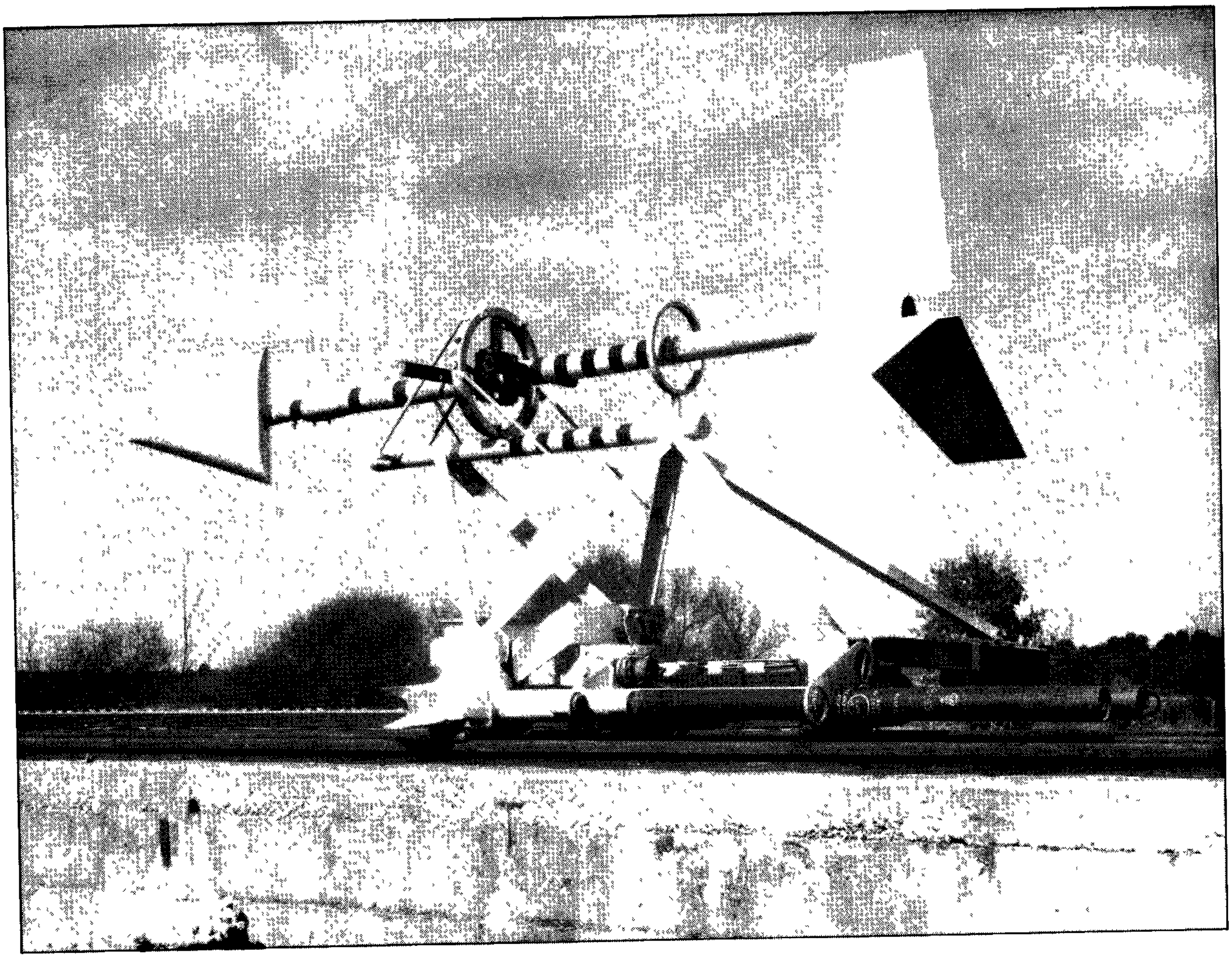


FIG.1. THE SLEDGE

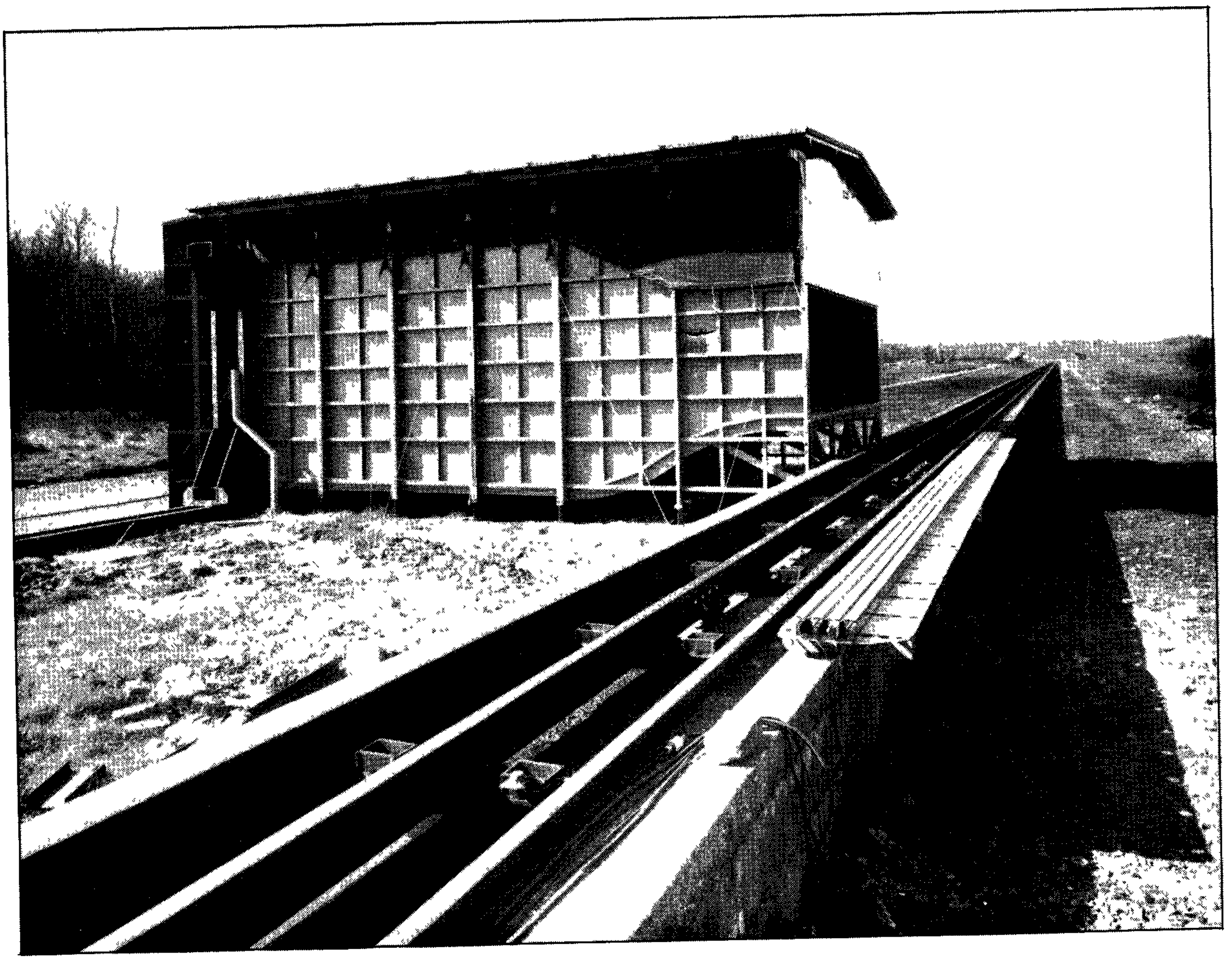


FIG.2. THE TRACK AND THE TUNNEL

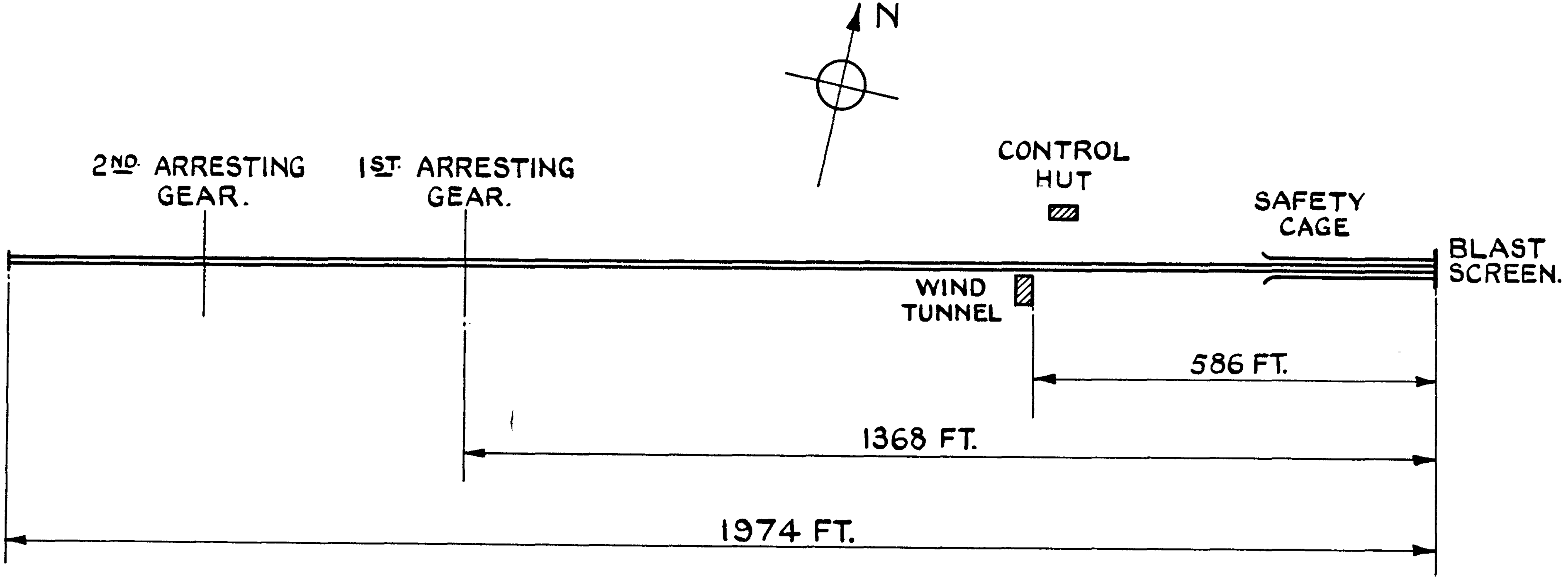


FIG. 3. PLAN OF THE GUST RESEARCH FACILITY.

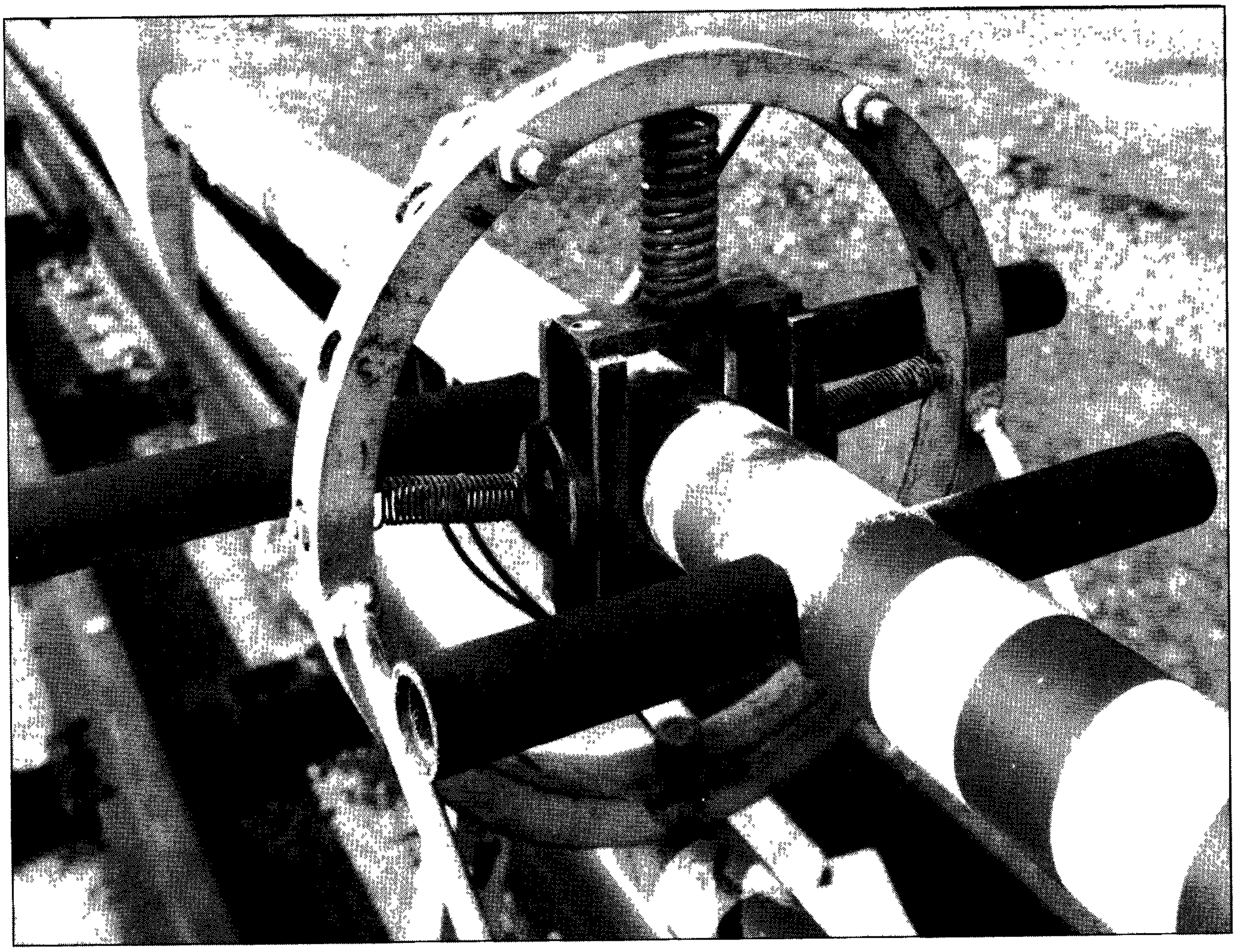


FIG.4. THE SUSPENSION SYSTEM FOR THE DART

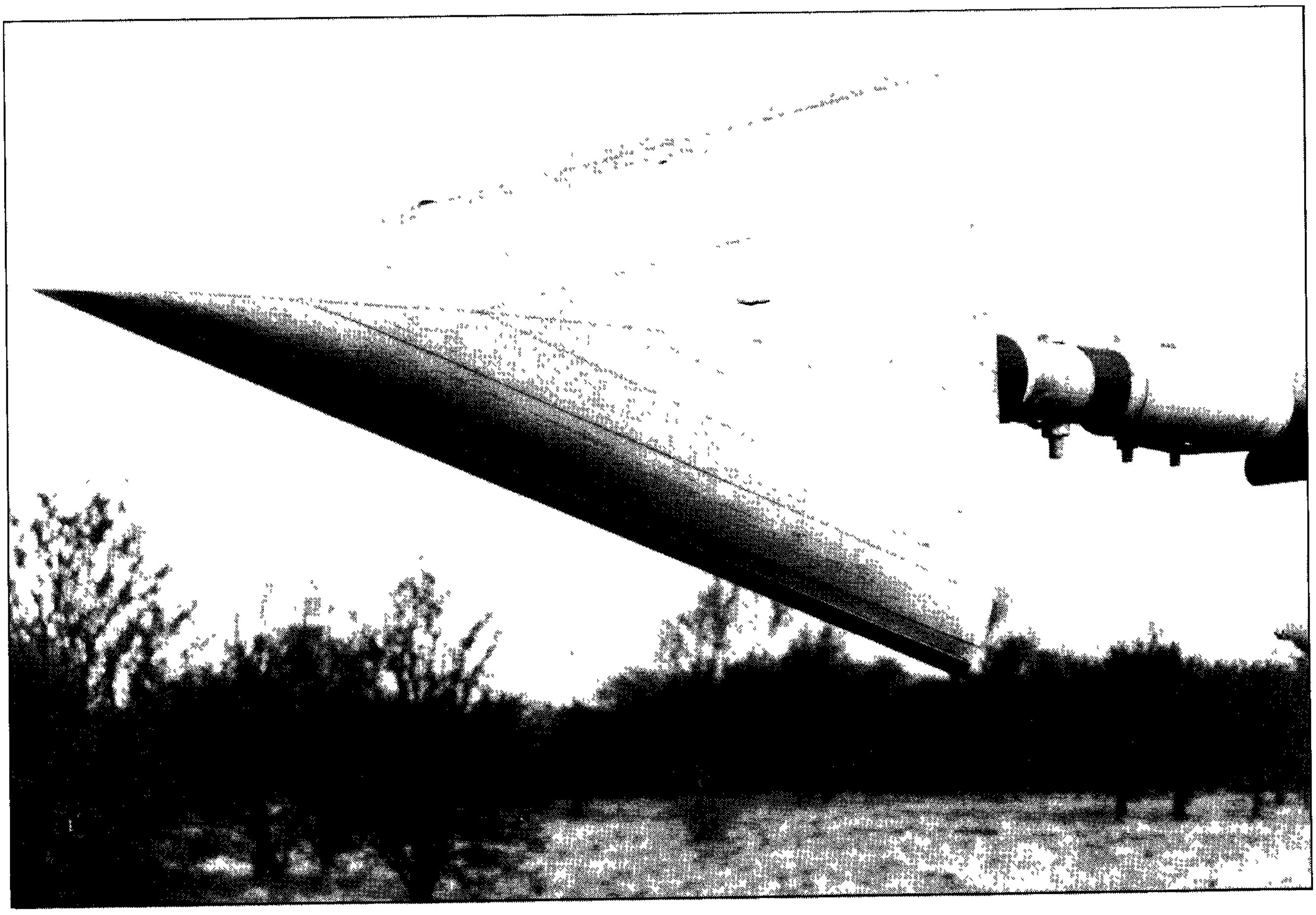


FIG.5. THE MODEL

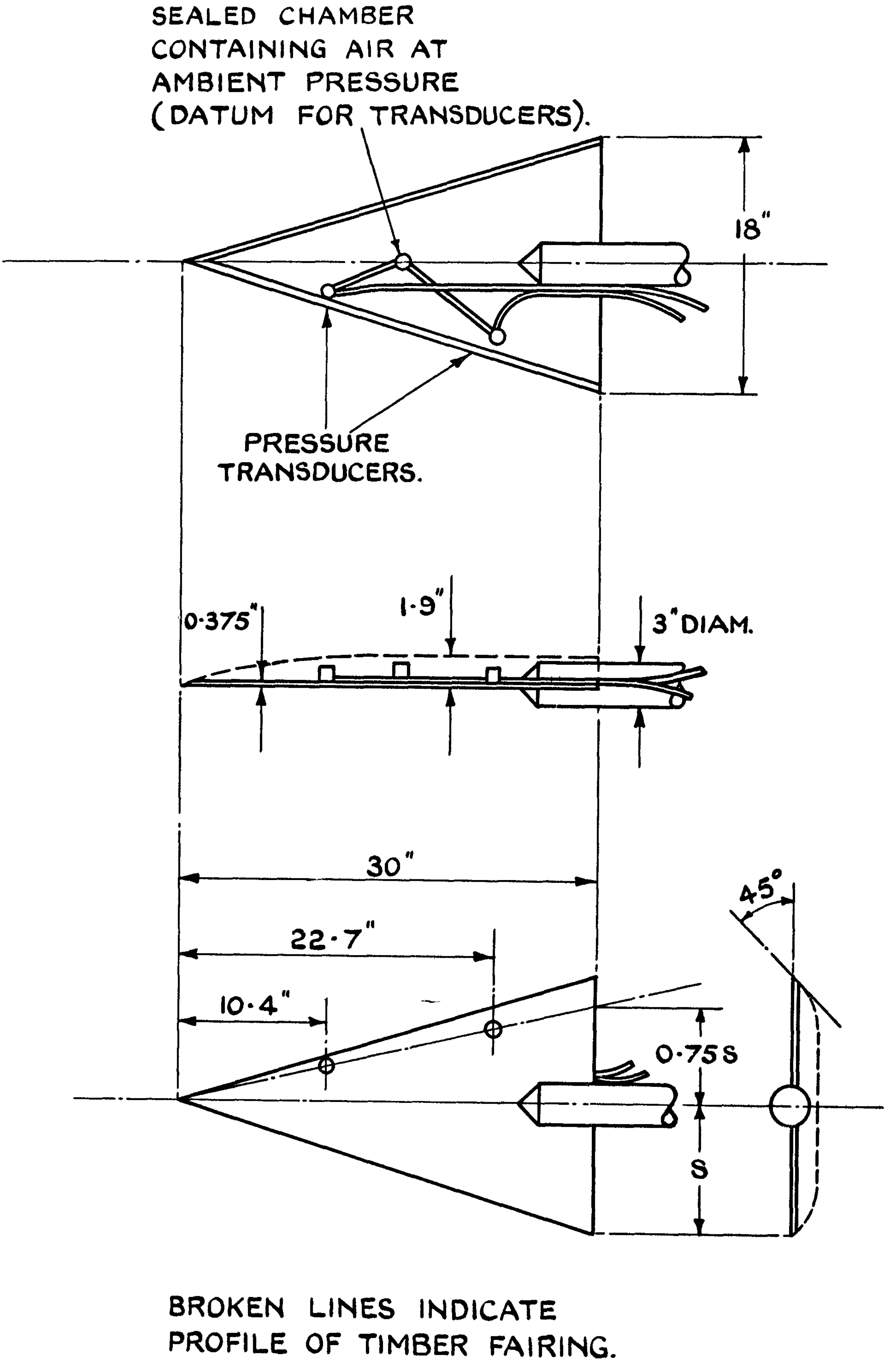
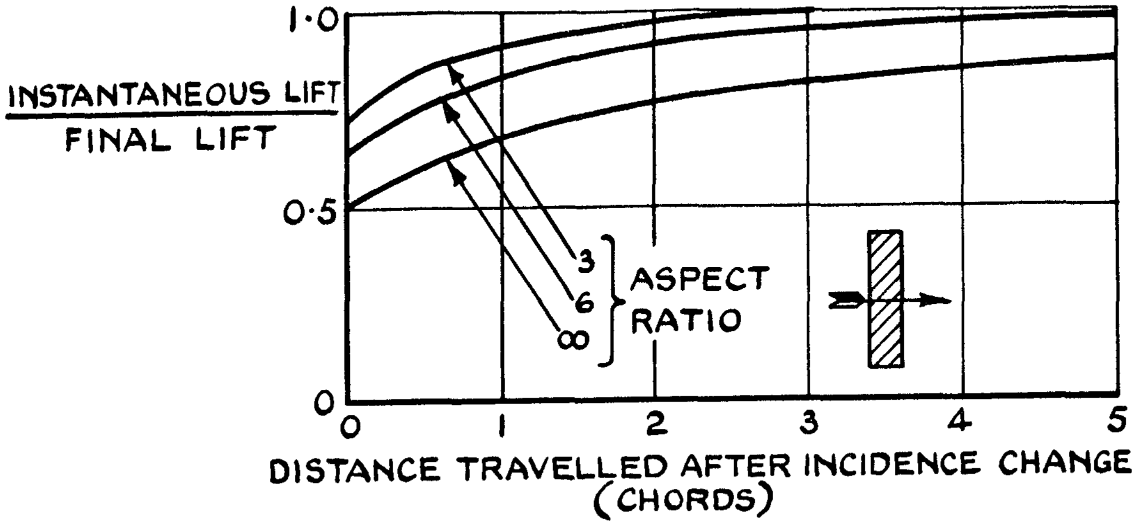
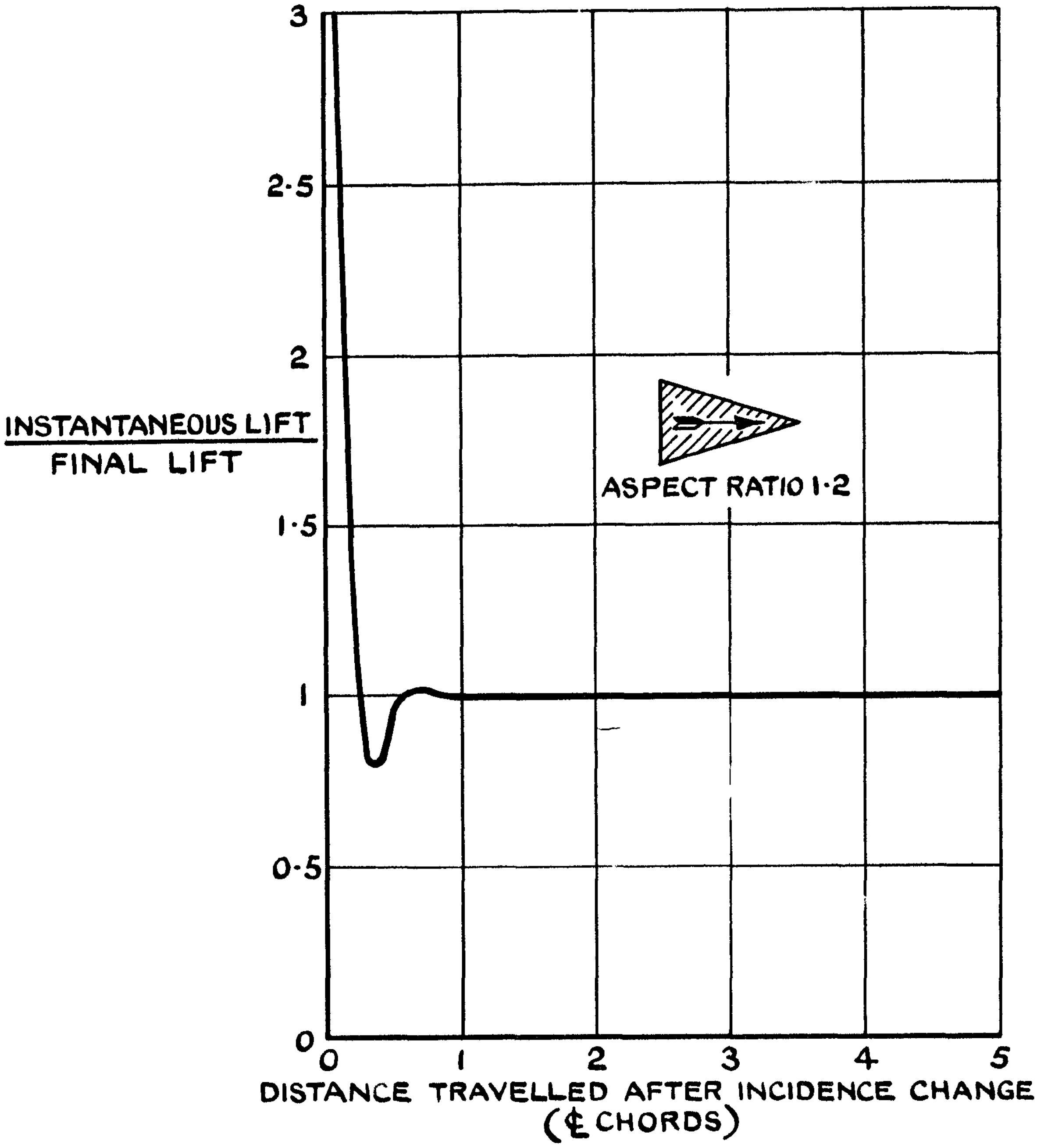


FIG. 6. GENERAL ARRANGEMENT OF THE MODEL.

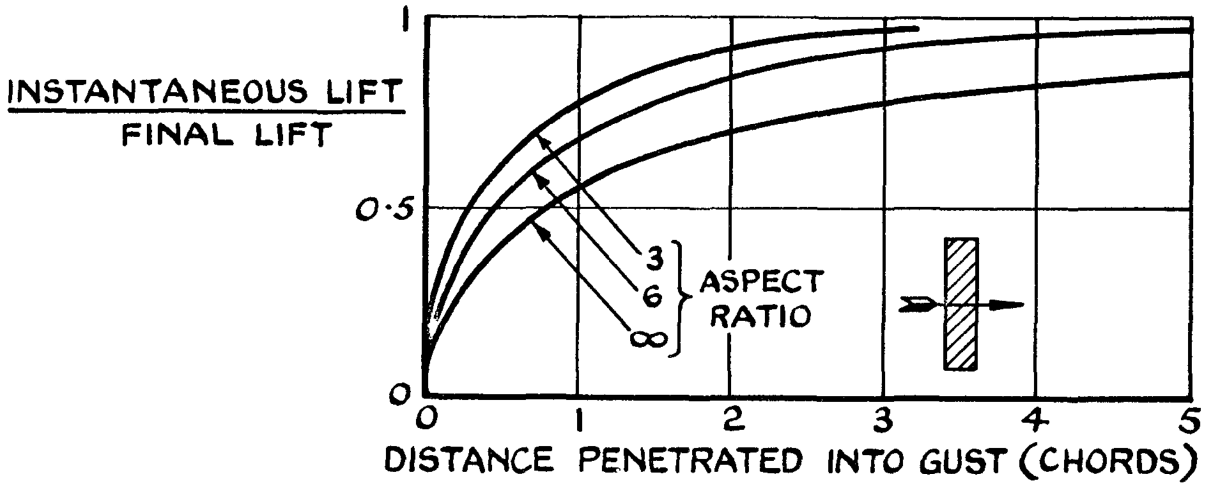


(a) RECTANGULAR WINGS, $M \simeq 0$. (WAGNER)

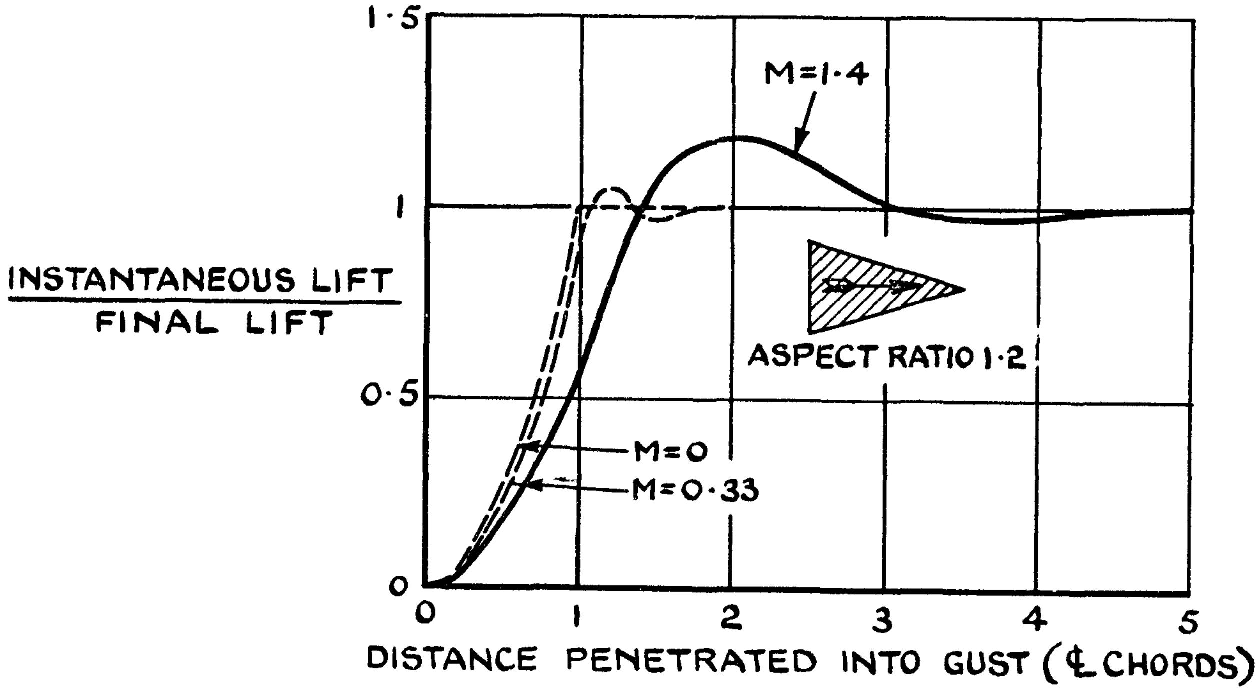


(b) NARROW DELTA WING, $M = 0{\cdot}42$ (LOMAX, HEASLET, FULLER & SLUDER) (HYPOTHETICAL ATTACHED FLOW)

FIG. 7. THEORETICAL GROWTH OF LIFT IN POTENTIAL FLOW DUE TO A SUDDEN CHANGE OF INCIDENCE.

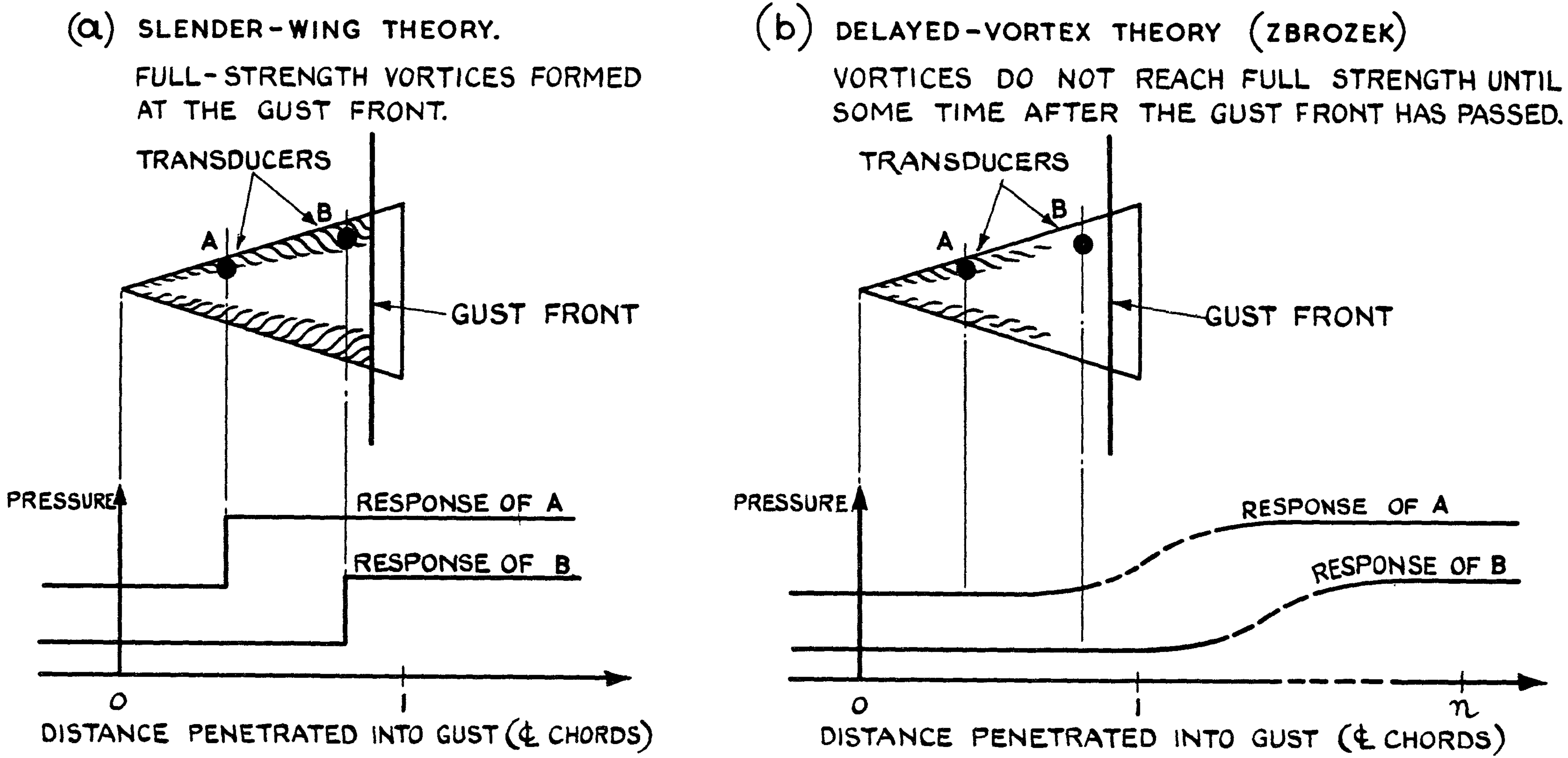


(a) RECTANGULAR WINGS, $M \simeq 0$. (KÜSSNER)



(b) NARROW DELTA WING. (MILES)
(HYPOTHETICAL ATTACHED FLOW)

FIG. 8. THEORETICAL GROWTH OF LIFT IN POTENTIAL FLOW DUE TO A SHARP-EDGED GUST.



(a) SLENDER-WING THEORY.
FULL-STRENGTH VORTICES FORMED AT THE GUST FRONT.

(b) DELAYED-VORTEX THEORY (ZBROZEK)
VORTICES DO NOT REACH FULL STRENGTH UNTIL SOME TIME AFTER THE GUST FRONT HAS PASSED.

FIG. 9. TRANSDUCER RESPONSES TO BE EXPECTED FROM THEORETICAL FORMS OF TRANSIENT VORTEX FLOW.

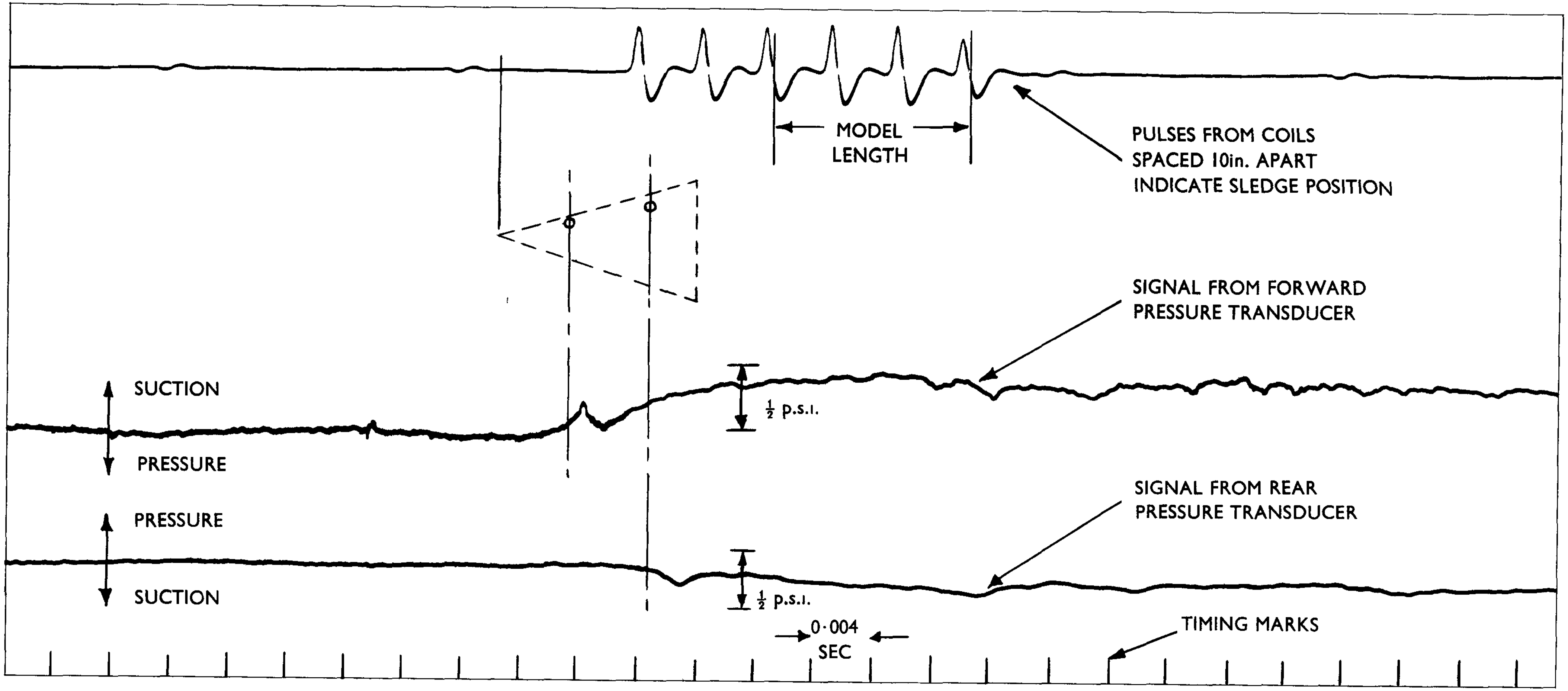
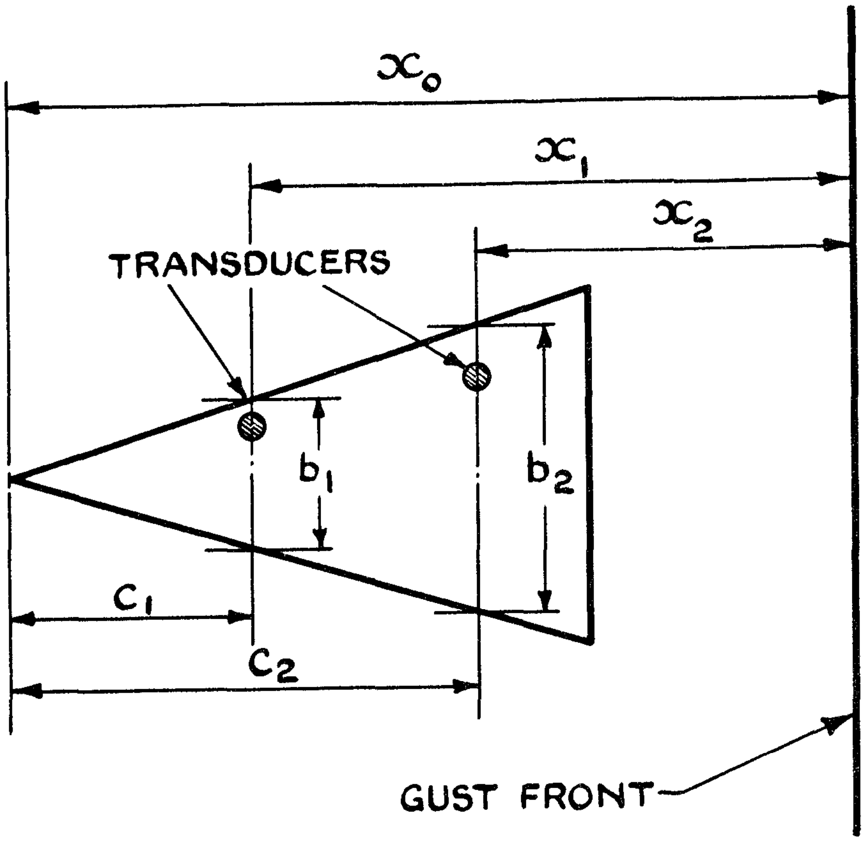
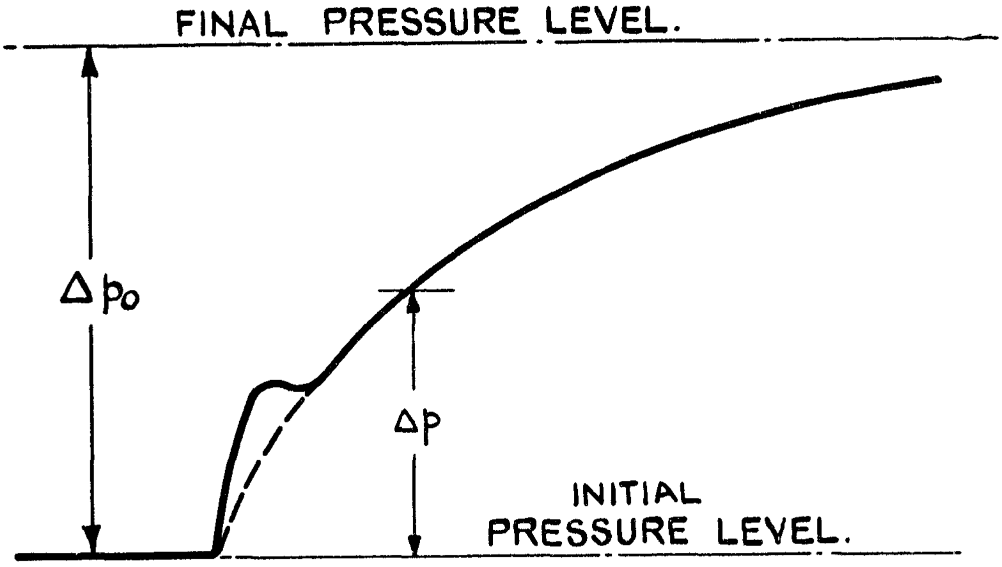


FIG. 10. TYPICAL RECORD OF TRANSIENT PRESSURES ON THE UPPER SURFACE OF A NARROW DELTA WING

(FORWARD SPEED 190ft/sec; GUST SPEED 46ft/sec; INITIAL INCIDENCE ZERO)

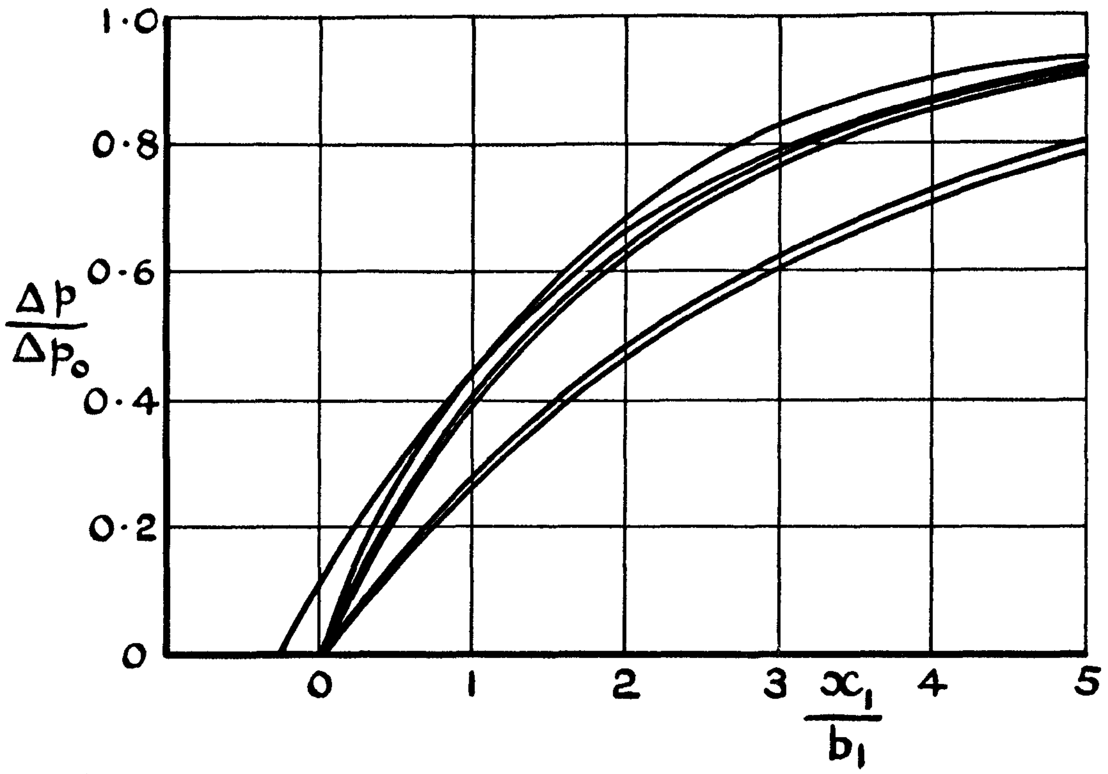


(a) MEASUREMENTS OF LENGTH

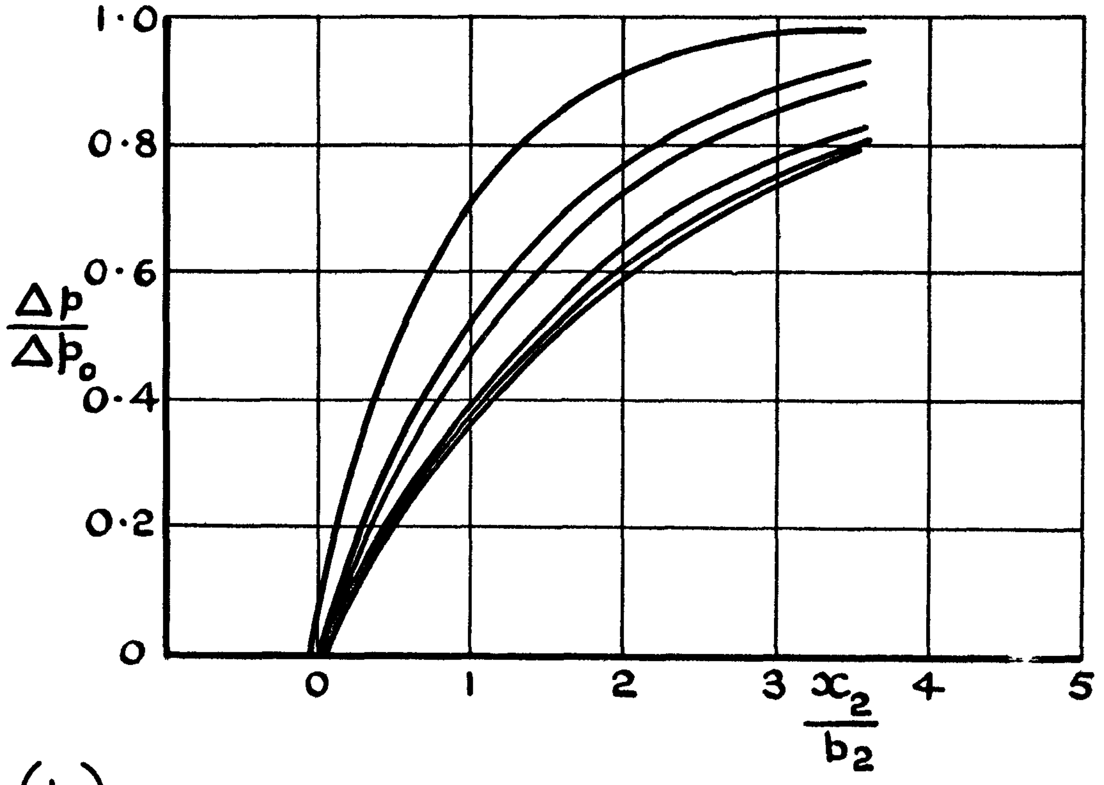


(b) MEASUREMENTS OF PRESSURE

FIG. 11. NOTATION USED IN PRESENTATION OF RESULTS.



(a) FORWARD TRANSDUCER



(b) AFT TRANSDUCER.

FIG. 12. SUMMARY OF RESULTS FROM EACH TRANSDUCER

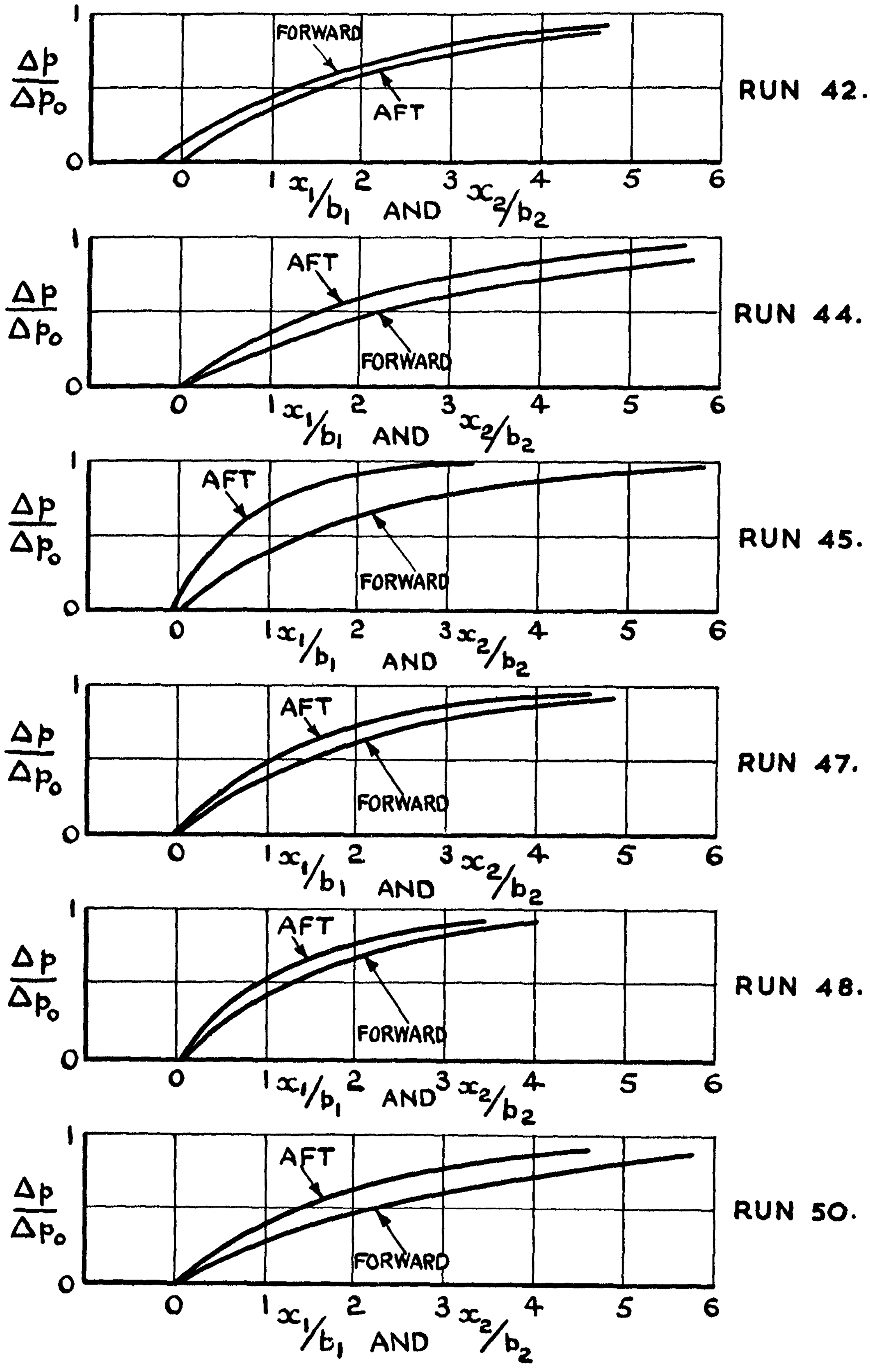


FIG. 13. SUMMARY OF RESULTS FROM EACH RUN THROUGH THE GUST.

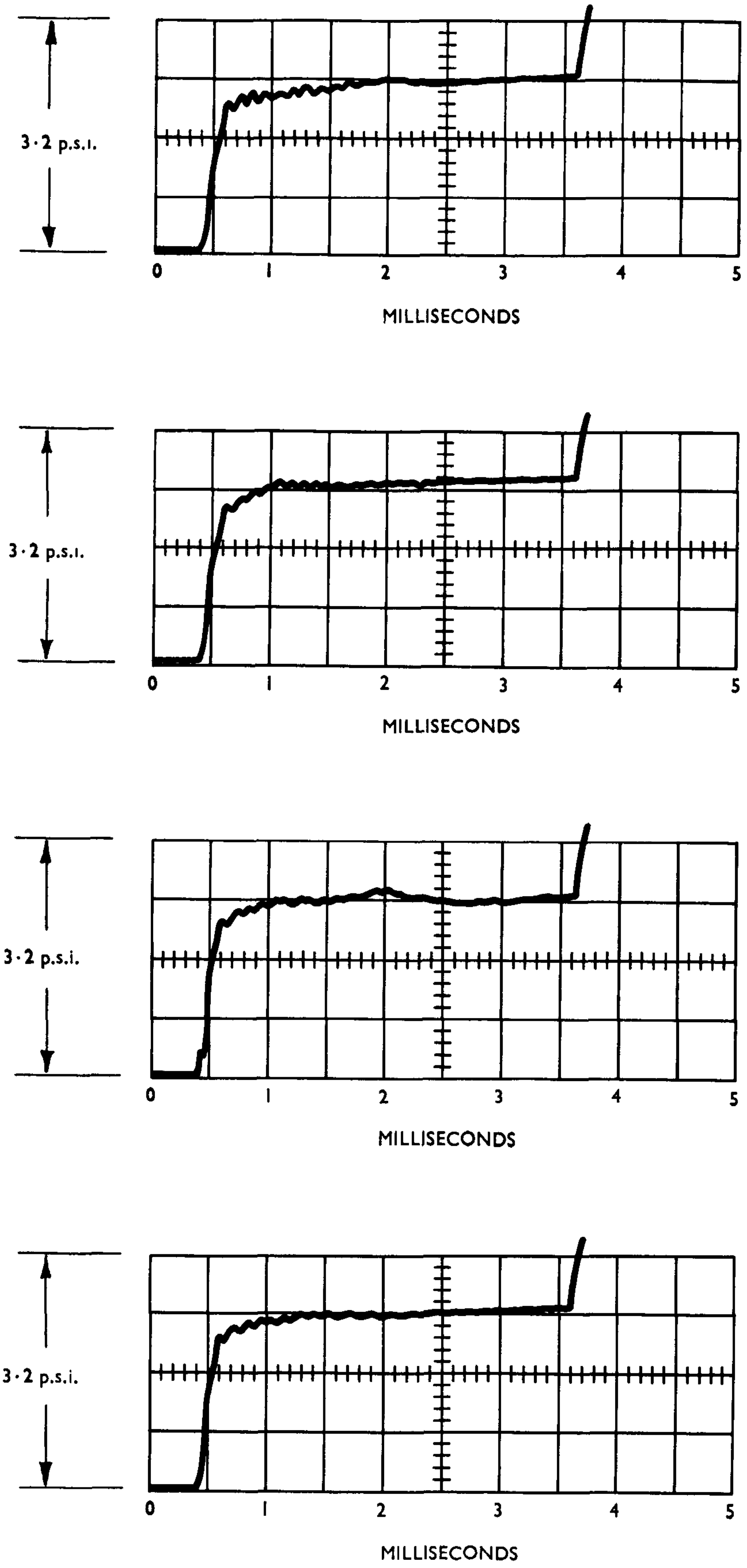


FIG.14. RESPONSE OF THE PRESSURE-MEASURING SYSTEM TO A PRESSURE STEP

(TRACED FROM ORIGINAL OSCILLOGRAPH RECORDS)

A.R.C. C.P. No.624

533.693.3:
533.6.048.5:
533.6.048.2:
533.6.078

MEASUREMENTS OF TRANSIENT PRESSURES ON A NARROW-DELTA WING DUE TO AN UPWARD GUST. Hunt, G.K., Roberts, D.R. and Walker, D. September, 1961.

With the aid of a new research facility, transient pressures have been measured on the upper surface of a narrow-delta wing when it entered a sharp-edged gust normal to the wing plane. This paper describes the facility and presents an analysis of the results of six runs through the gust by one model.

It is shown that the pressure distribution on any particular cross-section of the wing remains unaffected until that section enters the gust, and then begins immediately to change. The pressure change due to the gust develops at each section at a rate which is a function of the local span.

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