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Of course there is a similar group of formulæ corresponding to (1·7); but it seems hardly necessary to write them out, as the formulæ (7·4) correspond most closely to the problems of physical importance.

The formulæ (7·4) given above agree with Macdonald's on writing

$$\psi = \frac{\partial U}{\partial z},$$

but it should be observed that his J is the reciprocal of ours.

Attention may be directed to the fact that in the formulæ (7·4), the vanishing of Z and γ does *not* involve the vanishing of the other components of force, in contrast to what was proved in § 2 for the case of spherical polar coordinates.

XI. *The Resonance Theory of Audition subjected to Experiments.* By E. H. Barton, *F.R.S.*, *and* H. M. Browning, *M.Sc.**

[Plates II. & III.]

THEORIES of audition have been recently under considerable discussion†: indeed this controversial subject appears to be of perennial interest. Helmholtz long ago advanced his hypothesis of sympathetic resonance, and supposed at first that the rôle of resonator was played by each of the arches of Corti. This latter detail was afterwards modified, the basilar membrane being then considered to act somewhat like a set of resonators or harp strings. It was shown that this was possible owing to its fibrous nature with high lateral tension and relative slackness longitudinally. There are of course difficulties in the hypothesis in matters of detail. But this is only to be expected in the case of so small a mechanism working at such high frequencies and with such minute displacements. Indeed, there are difficulties in any hypothesis, and that of sympathetic resonance seems to deserve careful examination from a new standpoint. Some anatomists have felt considerable difficulty in accepting it, others accept it unreservedly. Some of its critics have obviously not quite grasped the meaning of the hypothesis,

* Communicated by the Authors.

† 'Analytical Mechanism of the Internal Ear': Sir T. Wrightson and Dr. A. Keith. London, 1918. "The Internal Ear," Nature, Aug. 8, 1918. Letters in 'Nature,' Oct. 17 & 31, Nov. 7 & 21, Dec. 5 & 19, 1918, Jan. 9, 1919. "On Sir T. Wrightson's Theory of Hearing," by W. B. Morton, Phys. Soc. Proc. xxxi. Part III. April 1919.

and so unfortunately base upon their mistaken view a criticism which falls wide of its mark.

The term "resonance" used in the present connexion is open to misunderstanding. In the minds of some, it recalls simply the familiar case of the actual *resounding* for several seconds by a lamp-shade of a musical sound originally due to the voice or piano. Taken in this crude sense of the actual reproduction of a sound probably no one, competent to judge, has ever believed in a resonance theory of hearing. But the essential facts of the hypothesis are present in the case just referred to. The lamp-shade has a certain period of vibration natural to it. But when practically the same note is sung, the very feeble vibrations of the air reaching it, being of the right period and repeated hundreds of times, elicit a powerful response.

If the periods had been utterly different instead of nearly alike, the response would have been unnoticeable instead of arresting.

Hence the sufficiently powerful vibrational response of an elastic system to very weak forces, owing to the almost exact tuning between the period of the forces and that of the responder, is of the essence of the theory of sympathetic resonance, whether that responder makes any sound or not. Perhaps *sympathetic response* would have described more precisely what is intended by the commoner phrase sympathetic resonance.

Further, it must be borne in mind that the degree of falling off in response amoung resonators, owing to their mistuning with the forces impressed upon them, depends upon the damping of their own natural vibrations. Thus, theory shows that the more highly the vibrations natural to a responder are damped, the less is the falling off of their response owing to a mistuning of the impressed forces. In other words, the response is more widely spread among a graduated set of responders when they are highly damped, but is more concentrated when the responders are but slightly damped. This may be clearly seen by reference to the plates of previous papers*.

Hypotheses of audition may be approached in a variety of ways. Perhaps the most natural basis is that of dissection and microscopic examination of the anatomical structure of the ear. These investigations have been carried out by a number of workers, among whom it may suffice to mention

* See figs. 1. 2, & 3, Plate VIII. Forced Vibrations, &c., Phil. Mag. August 1918. Plate V. Mechanical "Resonators," &c., Phil. Mag. April 1919.

Bowman, Corti, Deiters, Hasse, Henle, Hensen, Kölliker, Kuile, Reissner, Retzius, Schultze.

But it is not sufficient to regard the internal ear as a structure merely. It must be recognized that it is a working mechanism. Further, it must not be looked upon as a mechanism capable only of *slow* displacements. For it is of the very essence of this mechanism that it is movable at acoustic frequencies, and highly susceptible to very feeble forces provided they alternate at any such frequency.

The question may be asked here, Is it easy to imagine these mechanisms responding to such feeble forces as are usually present except on the principle of forced vibrations? Further, the presence of a graduation in these mechanisms suggests that they are elastic systems with natural periods of vibration which form a series according to their dimensions and other conditions.

Without at all prejudging the case for or against the resonance hypothesis, it is allowable to consider what are the chief facts of audition, and whether they are explicable on the resonance theory. If they appear to be so, we may further ask what number and disposition of responders are needed.

Since the mathematical theory of forced vibrations remains essentially unchanged for a great variety in the forms of the vibrators, we may reduce the problem to its simplest terms by arranging a set of *simple pendulums* of graduated periods to represent these vibrators. Then their behaviour may be compared with the facts of audition and the agreement or conflict noted. Any conflict, if observed, would seriously discredit the resonance hypothesis. On the other hand, any agreement that may be observed will essentially support the hypothesis in general terms, and might conceivably give some clue as to which parts of the ear could act as responders. For the facts of audition might be reproducible only by a certain number of responders with given frequencies and dampings, and the properties requisite might be possible to certain anatomical structures only.

The anatomical method of studying the subject would probably be best of all could it be carried out in its entirety on a living subject. But as this is impossible and the alternative post mortems are in some respects inconclusive, we seem justified in taking any indirect method of approach that is available. Hence the method of using a set of pendulums, though they are confessedly unlike any structure in the ear, may throw a valuable side-light on the subject by revealing and displaying what number and arrangement of responders would prove adequate to account for the known facts of the case.

It would appear from the experiments thus made and their accompanying photographic records, that about twelve responders to the octave or a total of about one hundred in all, if of suitable damping, would probably suffice to account for some of the chief facts of audition.

And this number is only about one thirtieth of the number of Corti arches present in the human ear. Accordingly on this view the resonance theory would not make the demand for so large a number of structures with separate nerves as its adherents have usually supposed. On the contrary, it leaves a liberal allowance for the possibility of the number of nerve-fibres being much smaller than the number of Corti arches. So that if a single nerve-fibre is distributed to a number of arch segments (as found by Held), this would not necessarily invalidate the resonance theory.

Fundamental Facts of Audition.—We may now review some of the basal facts of audition, so as to set up a standard such that the success or failure of the resonance theory to account for these facts would afford a confirmation or disproof of the hypothesis.

For those whose hearing is normal the following may be taken as fairly representative of the fundamental facts with which we are now concerned.

1. When two different notes at a considerable interval are sounded together, we can hear both notes and estimate their interval, but do not mistake them for a single note of intermediate pitch. Thus C and G sounded together are recognized as forming the interval of the fifth and are not mistaken for a single note of pitch E or E♭. (This is the direct contrary of the case with colour vision in some parts of the spectrum. For, when beams of red and green light are converged on to the same white screen, the impression received is that of yellow, and the unassisted eye furnishes no hint of the dual nature of this composite light which might be a monochromatic yellow for aught we are able to perceive.)

2. When two near notes are sounded successively the small interval between them can be perceived by a specially keen ear down to something of the order of two vibrations in a thousand or one twentieth of an equal-tempered semitone.

3. When two very near notes of almost equal intensities are sounded simultaneously, the difference of their frequencies can be recognized by anyone as the number of beats per second. And this may serve to discriminate an interval

of say one vibration in a thousand, or about the fortieth of an equal-tempered semitone.

4. The range of audition is limited at both ends, each limit varying with the individual, but about eleven octaves are usually audible.

5. Before either limit of audition is absolutely reached, the note is recognized to be very high or very low, but the power of distinct location of pitch is lost, only about seven octaves being musically audible.

6. A musical shake of about ten notes per second on a tone of frequency a hundred and ten per second is heard quite distinctly.

Variables of Responding System.—If a set of vibrating responders is provisionally postulated as existing in the ear, and if in order to test the validity of the postulate we are to make a working model on this principle, it is evident that many variables are at our disposal, and probably the success of the model in accounting for the actual facts of audition, should that prove possible, will depend somewhat upon the right choice of these variables.

The chief variables in question may be stated as follows:—

(*a*) The total range of responders.

(*b*) The musical intervals between adjacent responders.

(*c*) The damping natural to these responders.

(*d*) The constancy or otherwise of the intervals and of the damping throughout the range.

We must also suppose that

(*e*) a certain order of discrimination of relative amplitudes of vibrations of different responders is possible by means of the nerves attached to them.

Obviously these variables must be chosen so as to accord as far as possible with the facts of audition previously enumerated. Thus the facts under headings 1, 2, and 3 give some clue to the smallness of the interval between adjacent responders and also show that the damping must not be *too large*. Otherwise the sharpness of resonance would not be great enough to facilitate location of pitch.

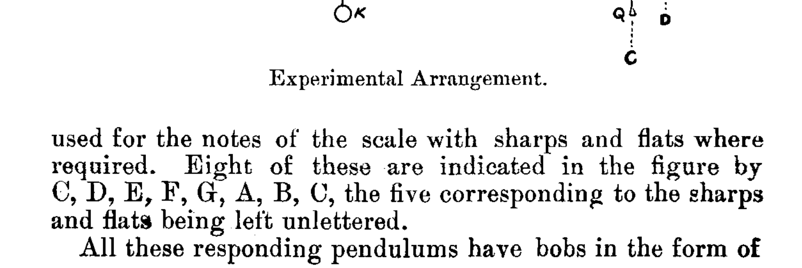
The facts of limited range of audition and loss of exact sense of pitch near ends (headings 4 and 5) show that the range of responders should extend to about seven octaves.

From the sixth fact as to the clearness of a shake, Helmholtz concluded that the expiring tone is reduced to one tenth of its original amount in the fifth of a second. If therefore the ear has vibrational responders, their natural damping at this pitch must correspond to a logarithmic decrement of the order $\lambda=0{\cdot}06$. This shows that the damping must not be *too small*.

We have thus obtained some light on (*a*), (*b*), and (*c*), but not upon (*d*), which would require more refined examination.

Further, it should be pointed out that these facts of audition do not lead us to any exact determination of the variables at our disposal in the set of responders. On the contrary, they suggest values of a certain order of magnitude, or furnish us with approximate upper and lower limits. Thus it would be sometimes possible to account for the facts of the case with certain values of the variables or to account for them equally well by changing one variable, some other being adjusted in compensation. For example, the less the damping of the responders, the sharper is the resonance and the easier would it be to locate the pitch of maximum response. But a greater damping of the responders, leading to less sharpness of resonance, could be compensated by an enhanced discrimination of relative amplitudes of responding vibrations near the maximum.

Experimental Arrangements.—No attempt has been made to set up the whole seven octaves of responders postulated, but only a single representative octave, which suffices for experimental tests. In order to have a definite and constant interval between adjacent responders throughout the octave, they were set at distances from one end, and adjusted to lengths, which formed a geometrical progression. And it seemed desirable to make the intervals correspond musically to those of the tempered chromatic scale. Thus the ratio of adjacent pendulum lengths was $\sqrt[6]{2}$, the ratio of periods being accordingly $\sqrt[12]{2}$. Thus the thirteen responders for the one octave may be referred to by the letters



Experimental Arrangement.

used for the notes of the scale with sharps and flats where required. Eight of these are indicated in the figure by C, D, E, F, G, A, B, C, the five corresponding to the sharps and flats being left unlettered.

All these responding pendulums have bobs in the form of paper cones and weighted with a ring of copper wire (like those used in Mechanical "Resonators," Phil. Mag. April 1919). These hang by suspensions of black thread from the stout cord HJI, to which is attached the driving pendulum JK whose true length must be reckoned from J'. It is adjustable to various required lengths by a tightener as shown. A second cord is shown by HML, from which is suspended a second driving pendulum MN (of virtual length M'N) and whose bob N is equal in mass to the bob K. These two cords are connected by the wooden bridge T, thus the two driving pendulums are only loosely coupled to each other but each acts quite distinctly upon the set of responders.

The camera lens is along the line HJ produced so that in the photographs all the responding pendulums will seem to hang from the same point. Further, the responding bobs all lie along a straight line QH in order that each responder shall experience the same driving influence (see "Forced Vibrations," p. 176, Phil. Mag. Aug. 1918).

Results and their Significance.—Plate II. gives six reproductions of time exposures of the responders actuated by two drivers of widely differing periods, the slower of the two being gradually increased in length from figure to figure throughout the series. In fig. 1 it is obvious that the length of the driver is about midway between those of the responders whose bobs are third and fourth from the bottom. Or, in musical terms, we might say that the pitch of the driver was about midway between E♭ and D, the E♭ being slightly favoured. In the second figure we may, in like manner, refer to the pitch of the driver as being slightly nearer D than E♭, since the bob third from the bottom responds better than the fourth. In the third figure, the third bob from the bottom responds much better than any other, but the fourth shows a distinctly better response than the second. Hence the pitch of the driver is recognized as distinctly sharper than D. In the fourth figure the driver is still slightly sharper than D, whereas in the fifth it is slightly flatter than D. In the sixth figure the driver is distinctly flatter than D. Hence, in five steps we have passed over about a quarter of a tone, giving an average interval of a twentieth of a tone, or ten logarithmic cents.

It is evident by inspection of these figures that pitches midway between the adjacent ones given would be discernible as differing one from the other. Thus between figures 1 and 2 with fourth bob favoured and third bob favoured we might have had another case with neither favoured. Hence, with nervous discrimination of relative amplitudes equivalent to our perception of these figures, it would be possible to discriminate between successive notes differing in pitch by only the twentieth of an equal-tempered semitone or five logarithmic cents. And this is just about what a good ear can accomplish.

In the case of the six figures of Plate II. it should be noted that the shorter driver is allowed to swing the whole time, and in no way interferes with the discrimination of pitch of the longer one as seen throughout. And this is known to be the case with hearing when the other note is neither too near in pitch nor too loud.

Hence the six figures of this Plate corroborate the facts of audition 1 and 2 in our list. Indeed, fact 1 was supported also by photographs 1–18 on plates V. and VI. of the paper on Mechanical "Resonators," &c. (Phil. Mag. April 1919). Further, photographs 14 and 15 of plate VI. in that paper showed by flash exposures the presence of beats, which obviously allow of a finer discrimination of pitch between simultaneous notes. And this constitutes our *third* fact of audition.

As for fact 4 of audition, any finite set of responders would obviously accord with that experience.

Photographs 7–12 (Pl. III.) are devoted to the test of fact 5, which is the failure to recognize with precision pitches lying near either limit of audition. Thus in figures 7–9 we test the upper limit on the supposition that our single octave represents the top of the whole set of responders in the ear. In fig. 7 the responder second from the top has maximum amplitude, in fig. 8 the driving pendulum has been shortened so that the shortest pendulum responds best. In fig. 9 the driving pendulum was shorter than any responder, but that fact can scarcely be inferred from inspection of the figure, so that the exact location of pitch is lost. Indeed, as soon as the pitch of the driver passes beyond either limit of the pitches of the set of responders, so that no one bob exhibits a maximum vibration with a falling off above and below, the exact location of pitch must be lost.

For the lower limit of this single representative octave of responders the gradual failure to locate the pitch is illustrated by photographs 10–12. In fig. 10 the pitch is evidently between the lowest and the second, that is between what we have called C and C♯. In fig. 11 it is about at the lowest C, and in fig. 12 it is still lower, but by an amount which cannot be precisely inferred from the figure.

It may be noted that although by a set of responders, the exact pitch is not detectable for notes near either limit, it is yet clearly recognizable whether the note in question is near the upper or lower limit of the range. And this corresponds with one of the facts (5) of audition as already pointed out.

Referring to fact (6) of audition, the test corresponding to a musical shake was carried out as follows. The two driving pendulums were set to what we may call the notes D and E (that is the bobs third and fifth from the bottom of the series). One driver was started while the other remained at rest, and in a short time the maximum vibration of the corresponding bob was elicited, the other bobs exhibiting the ordered amplitudes and phases characteristic of forced vibrations. Then the first driver was stopped and the second started. After five or ten vibrations the new pitch was clearly established, as shown by the ordered state of things with the new maximum. So there is here quite sufficient damping to make clear shakes possible. And we have previously seen that the damping is small enough to give fairly sharp resonance and so render possible a fine discrimination of pitch.

Summary and Conclusion.

1. The present position of the resonance theory of audition is reviewed. The subject is acknowledged to be controversial. But the endeavour is made to throw a side-light upon it by the trial of a graduated set of pendulums used as responders to other pendulums as drivers. In actual form these pendulums make no pretensions to represent any structures to be found in the ear; but in their essential behaviour they do typify such mechanisms as are postulated for the ear by the resonance theory. This typical representation may be possible and useful, because we can apply to it the theory of forced vibrations in its most essential aspects.

2. Six facts of audition are then recognized as fundamental. These include a much finer discrimination of pitch than one for each responder and the failure to locate pitches quite exactly when they lie near either limit of audition.

3. Twelve photographs of the responding pendulums in action are taken and here reproduced.

4. These experimental results nowhere conflict with the above six facts of audition.

Indeed, for their explanation it suffices to have a set of suitably damped responders and their associated nerves of about twelve to the octave over a range of seven octaves, or say about a hundred in all. The supposed necessity for a much larger number of nerves and consequent conflict with some anatomical results are thus removed.

5. Any hypothesis like the resonance theory in question must be very difficult to prove to the hilt by any number of confirmatory experiments. But, if it is essentially at variance with facts, its disproof should be comparatively easy.

Nottingham,
March 20, 1919.

XII. *Note on the Vapour Pressure and Affinity of Isotopes.* *By* F. A. LINDEMANN, *Ph.D.**

IT was shown in a recent paper that isotopes must be separable both by fractionation and by chemical means †. At that time it was not possible to give any quantitative estimate of the differences in vapour pressure or affinity, since data were lacking as to the physical properties. This omission may now be repaired, since the melting-points of two sorts of lead of atomic weight 207·19 and 206·34 have been found to be identical within the limits of error of the experiment ‡.

It has been shown that the melting-point may be regarded as the temperature at which the average amplitude of oscillation of the atoms is equal to the distance between them §. This distance is obviously the distance between the centres of two neighbouring atoms minus the diameter of the atom which is presumably defined by some electronic orbit. Since the spectra of isotopes are practically identical, the outer electronic orbits are presumably identical, so that the diameters of the atoms may be regarded as identical. On the other hand, the densities are proportional to the atomic weights ‖, from which we may conclude that the distances between the centres of neighbouring atoms are identical. It follows from this that the amplitudes of oscillation at the melting-point are identical.

As is well-known there are two alternative views which give the same formula for the atomic heat. According to the first, a linear oscillator of frequency ν can only absorb or

* Communicated by the Author.

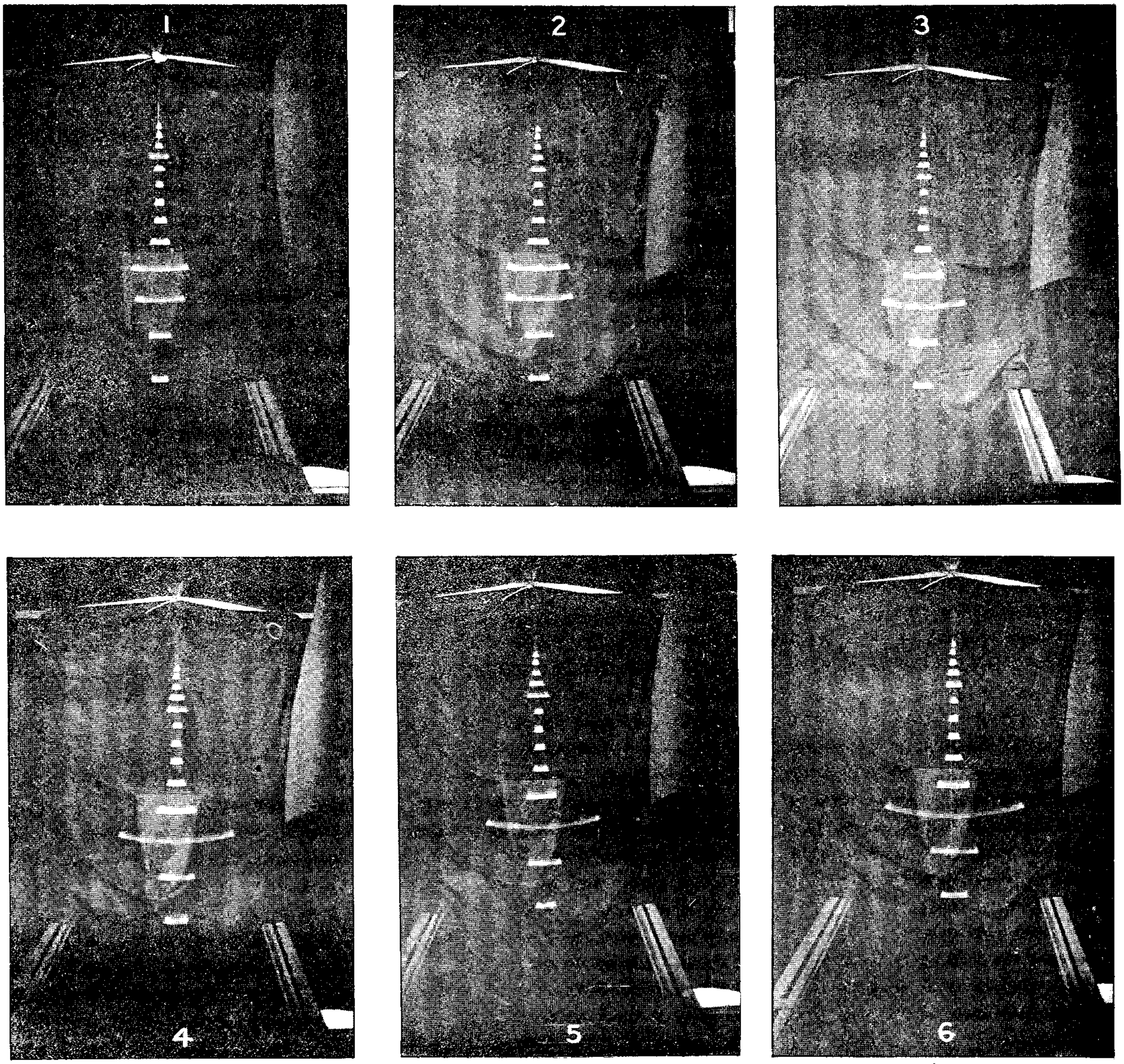
† F. A. Lindemann & F. W. Aston, Phil. Mag. xxxvii. p. 523 (1919).

‡ T. W. Richards, 'Presidential Address to American Association for the Advancement of Science' (1918).

§ F. A. Lindemann, *Phys. Zeitschrift*, xi. p. 609 (1910).

‖ T. W. Richards, *loc. cit.*

Phil. Mag. Ser. 6, Vol. 38, Pl. II.



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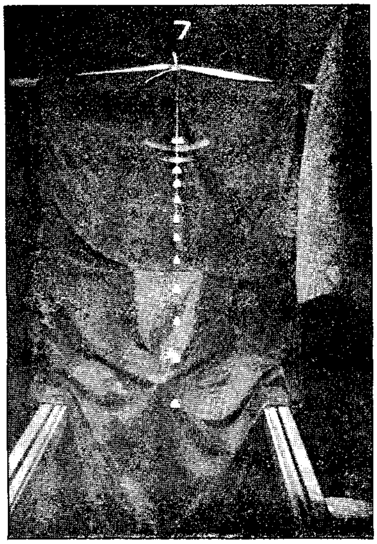
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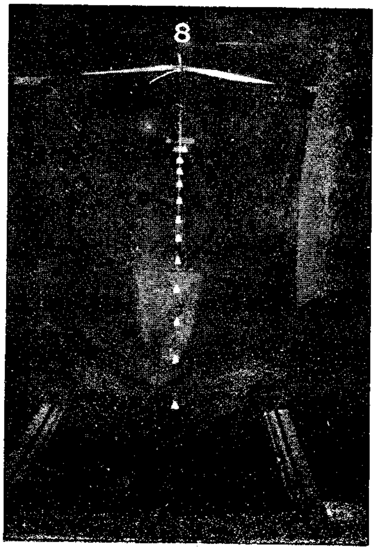
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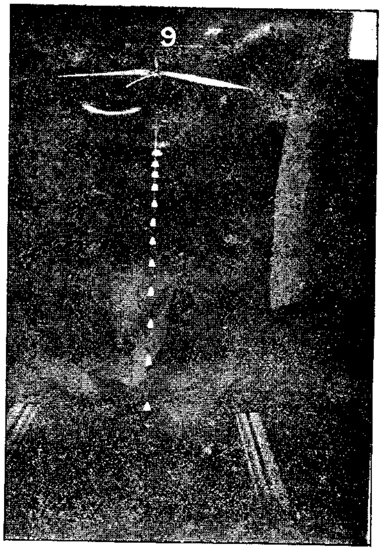
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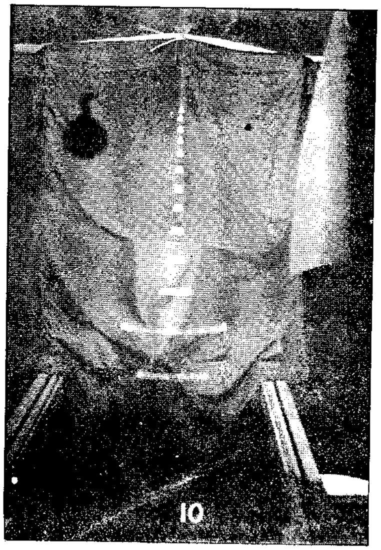
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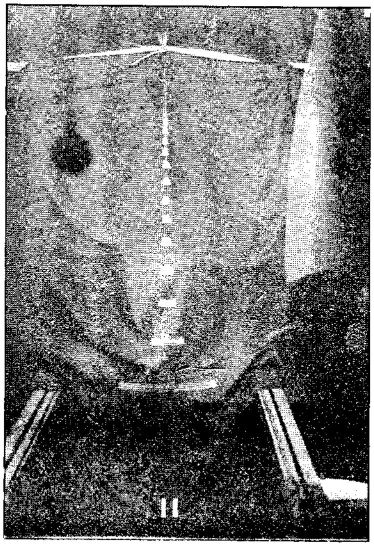
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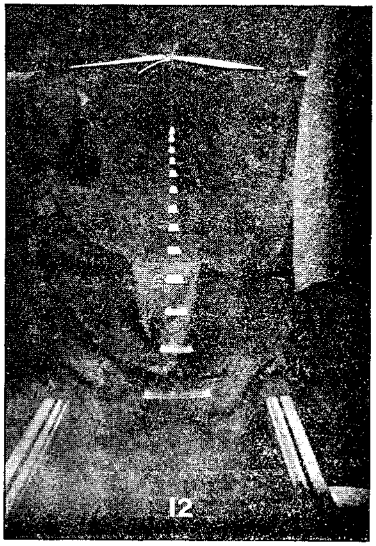
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