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# 抄　　錄

## プロペラの性能と音の大さとの關係に就て

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廣い芝生の中央に孤立して造ったコンクリート臺の上で電動機に依り二翼プロペラの1/3模型を廻轉しコンデンサー・マイクロフォン，增幅器，電氣濾波器及びサーマル・ミリアムメーターより成る電氣的裝置により音の强さ (Intensity) を測定した。

同じ模型に就き風洞試驗をも行ひ，プロペラの幾何學的ピッチの變化がプロペラの性能及び音の大さ (Loudness) に及ぼす影響を研究した．

その結果に依ればプロペラを固定臺上に廻轉した場合に發せられる音の大さ($\log p$；$p$ は音壓)は廻轉數に正比例して增加す．一定廻轉數に於てはパワ (power) と推力とが共にピッチ(翼角)に比例する範圍に於ては音の大さも亦翼角に比例して增す．推力に比して過大のパワを要するが如きピッチに至れば音の大さも亦急激に增加す．

音の大さ ($\log p$) とピッチ (翼角：$\theta$) 及び廻轉數 ($n$) との間の關係を示す實驗式を求めた．

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# On the Relation between the Performance and the Loudness of Sound of an Airscrew.

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## Abstract.

Model airscrews of one third the original size were rotated with an electric motor on an isolated concrete stand built on a wide lawn, and the intensity of sound was measured by means of an electrical arrangement, consisting of a condenser microphone, an amplifier, a suitable electric filter, and a thermal milliammeter.

Aerodynamical properties of the same models were also determined, and the effect of changes in geometrical pitch on the performance and on the loudness of sound studied.

It is found that the loudness of sound (log $p$) emitted when an airscrew is rotated on a fixed stand increases linearly with the number of rotations. At a fixed number of rotations the loudness is proportional to the pitch (blade-angle) in that range wherein both power and thrust are also proportional to the pitch. At pitch for which much power is needed, the loudness of sound also rapidly increases.

Emperical formulæ connecting the loudness (log $p$) of sound, the pitch (blade angle : $\theta$), and the number of rotations ($n$) are obtained.

## 1.

The results of our investigations on the nature of airscrew sound have been published in a number of papers[(1)]. In continuation of these experiments, further determinations were made with the object of obtaining the relation between the performance (strictly spreaking, the statical performance) and the loudness of an airscrew. The results are given in this paper.

## 2.

*Sound Experiment.* Model airscrews were rotated by means of an electric motor on an isolated concrete stand built on a wide lawn, and the intensity of sound was measured electrically. The arrangements for rotating the airscrew model have been fully described in earlier papers.

Two kinds of airscrew models, both of one-third actual size—Kármán type[(2)] and Reed I—which were previously used for determining the pressure-field around the airscrew blade, were employed again in the present experiments. The former, the Kármán type airscrew, was made by shaving forged duralumin, and the latter, the Reed I airscrew, by

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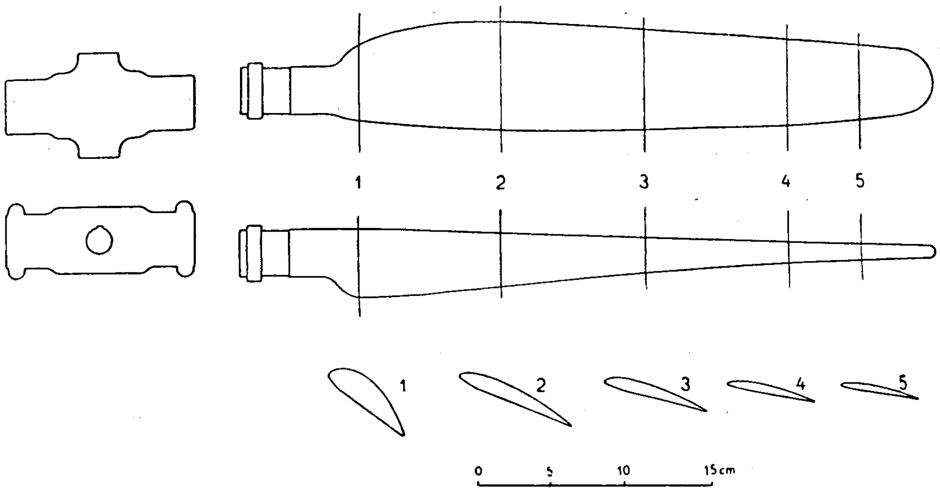
(1) J. Obata, Y. Yosida, and S. Morita: Report Aeron. Research Inst., No. 79 (1932); No. 80 (1932); No. 99 (1933).

J. Obata, Y. Yosida, and U. Yosida: Report Aeron. Research Inst., No. 132 (1935); No. 134 (1936).

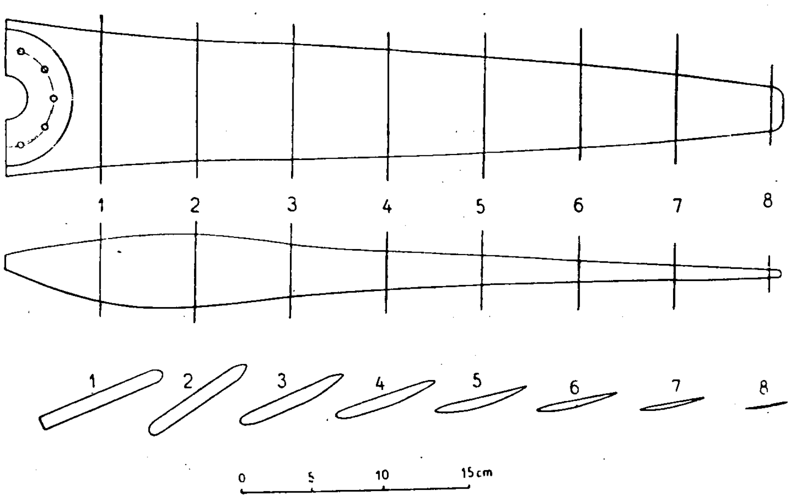
(2) In previous papers, Report Nos. 132 and 134, Kármán type airscrew was described by mistake as $^1/_4$ model.

twisting a thin duralumin plate into the desired shape. The shape of these airscrews are shown in Fig. 1, the dimensions of the original airscrews being as shown in the following table:—

| Airscrew | Diameter | Pitch |
|---|---|---|
| Kármán type | 3·00 m | Variable |
| Reed I | 3·25 | 1·95 m |




**Kármán type airscrew** (1/3 model).




**Reed I airscrew** (1/3 model).

Fig. 1.

Since the object of the present experiments was to study the effect of changes in geometrical pitch on the performance and on the loudness of sound of the same airscrew, as well as to compare the absolute sound intensities of different airscrews having, naturally, different performances, it was necessary to accurately determine the sound intensities at different dates and under somewhat different conditions. Hence, in order to keep the condition of the amplifier as constant as possible, a special decoupling device was provided for the amplifier that had previously used in various sound experiments, special attention being paid to all parts of the electrical arrangement. Fig. 2 is a diagram of the electrical connections of the sound-measuring arrangement, consisting of a condenser microphone, an amplifier, etc.

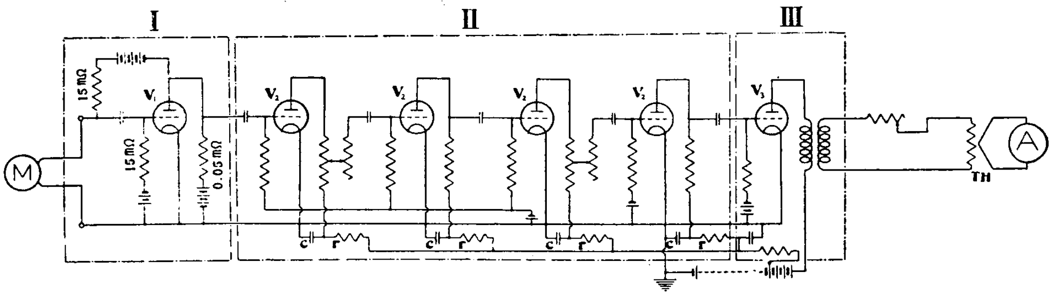



Fig. 2. The sound-measuring arrangement.
[The electrical filter is inserted between I and II]

From previous experiences, the sound was divided into two parts by using two kinds of electrical filters, namely 200-cycle low-pass and 250-cycle high-pass filters, and the output of the amplifier measured by means of a thermal milliammeter. As already mentioned in the previous paper, the intensity of airscrew sound is anything but definite, so that the mean of several successive readings taken every ten-seconds was taken for the final result.

Since the directional properties of the sound emitted by the airscrew models used in the present experiments were already known, the determinations of the sound intensities were made here only in two positions, namely in the plane of rotation and in a direction 30° from it opposite to the direction to which the airscrew would proceed. For the Kármán type model, with which the greater part of the experiments was made, the sound intensity is known to be the largest in this direction.

The airscrew shaft being 2·1 metres above ground, the microphone was placed on the ground facing upward in order to avoid reflections from the ground, at a distance of seven metres from the centre of the airscrew.

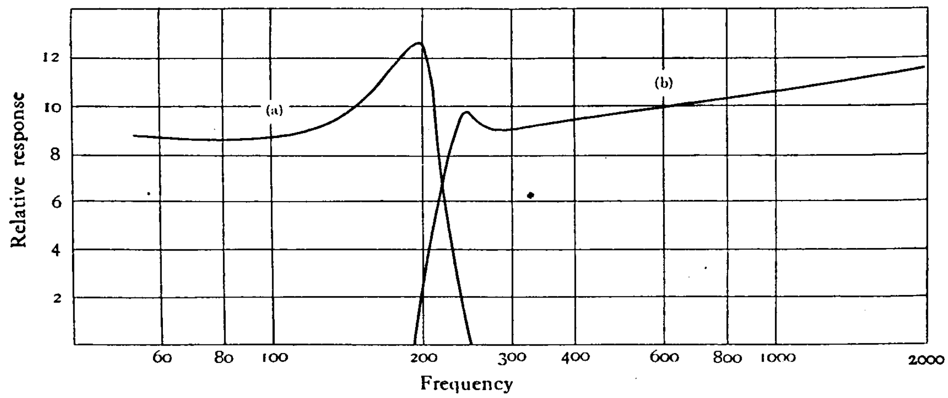


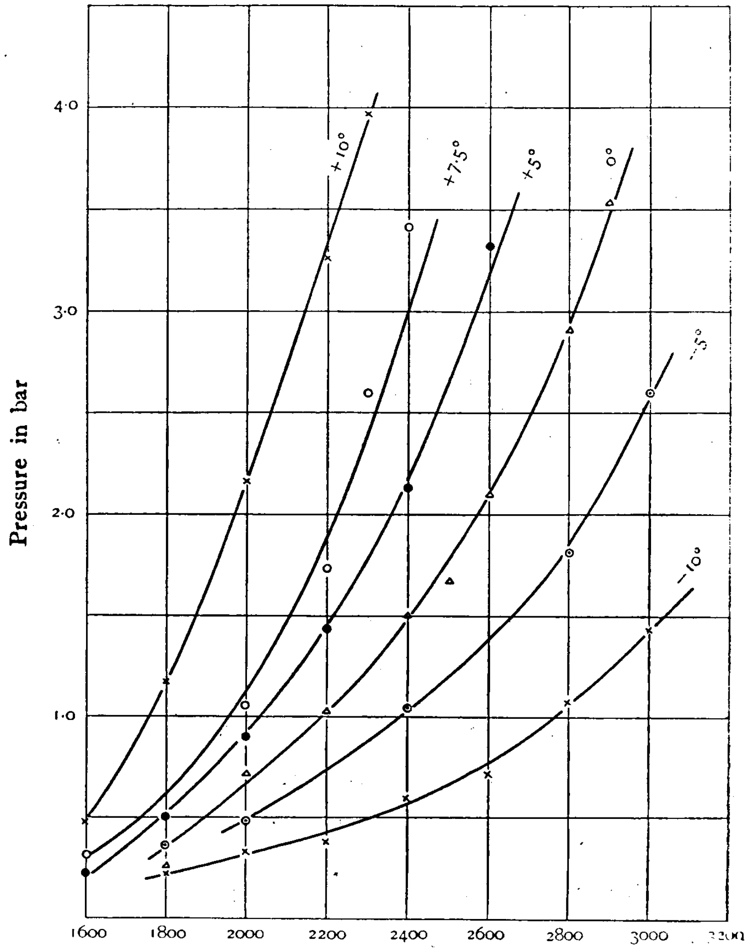

Fig. 3. Frequency characteristics.

(a) with low-pass filter.

(b) with high-pass filter.

As shown in Fig. 3, the frequency-characteristic of the sound measuring arrangement was nearly flat in the frequency region here dealt with, so that the average value of the sound pressure was computed from the reading of the electric current of the output.

Fig. 4 shows the relations between the pressure amplitude and the number of rotations for the sound component below 200 cycles at various pitches (blade-angles). In Fig. 5. similar relations are shown taking the *logarithm* of the pressure amplitude as ordinates. Below 2000 r.p.m., the relation is rather indefinite, while above 2000 r.p.m., the relation between the number of rotations and the logarithm of the pressure amplitude is nearly linear, that is to say, the loudness of sound (strictly speaking, the sensation level) increases linearly with the number of rotations. This result agrees well with that previously obtained.(1) Both



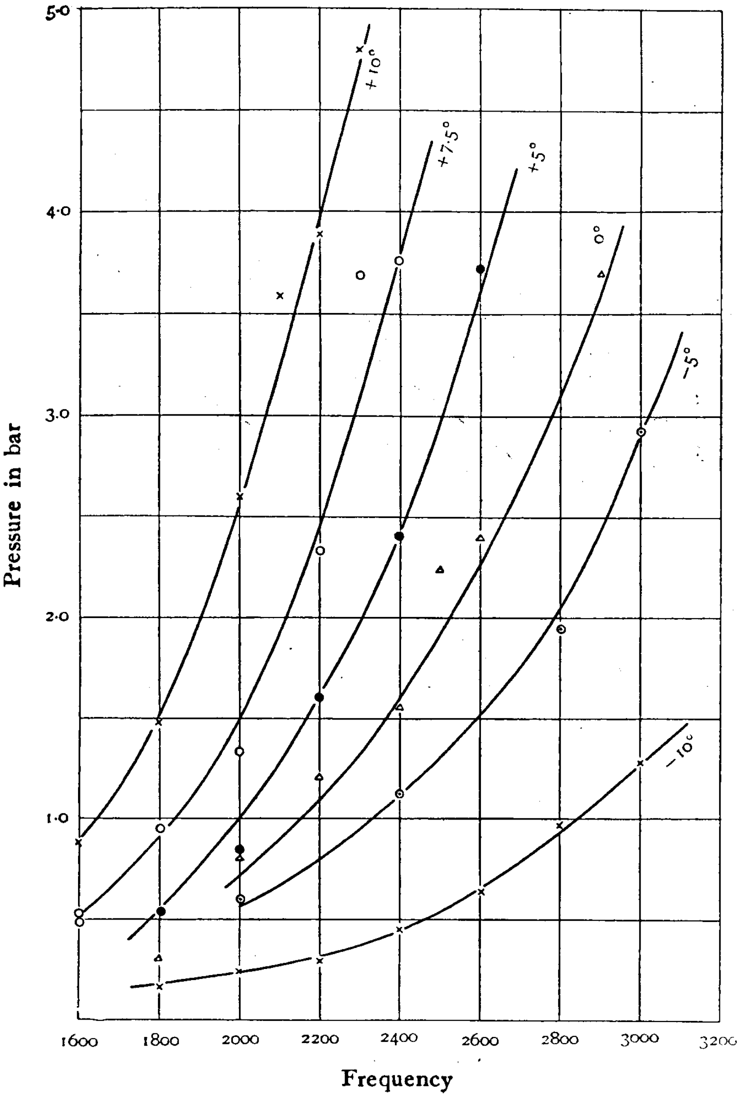

Sound component below 200 cyeles per sec.
[Plane of rotation]
Fig. 4 (a).

in the plane of rotation and in the 30° direction, similar linear relations were found at various geometrical pitches between $-10°$ and $+10°$, the

(1) J. Obata, Y. Yosida and S. Morita, Report No. 80 (1932), p. 400:

$$\log a = Ln + M,$$

where $a$ is the amplitude of the fundamental tone, $n$ the number of rotations per minute $L$ and $M$ constants.

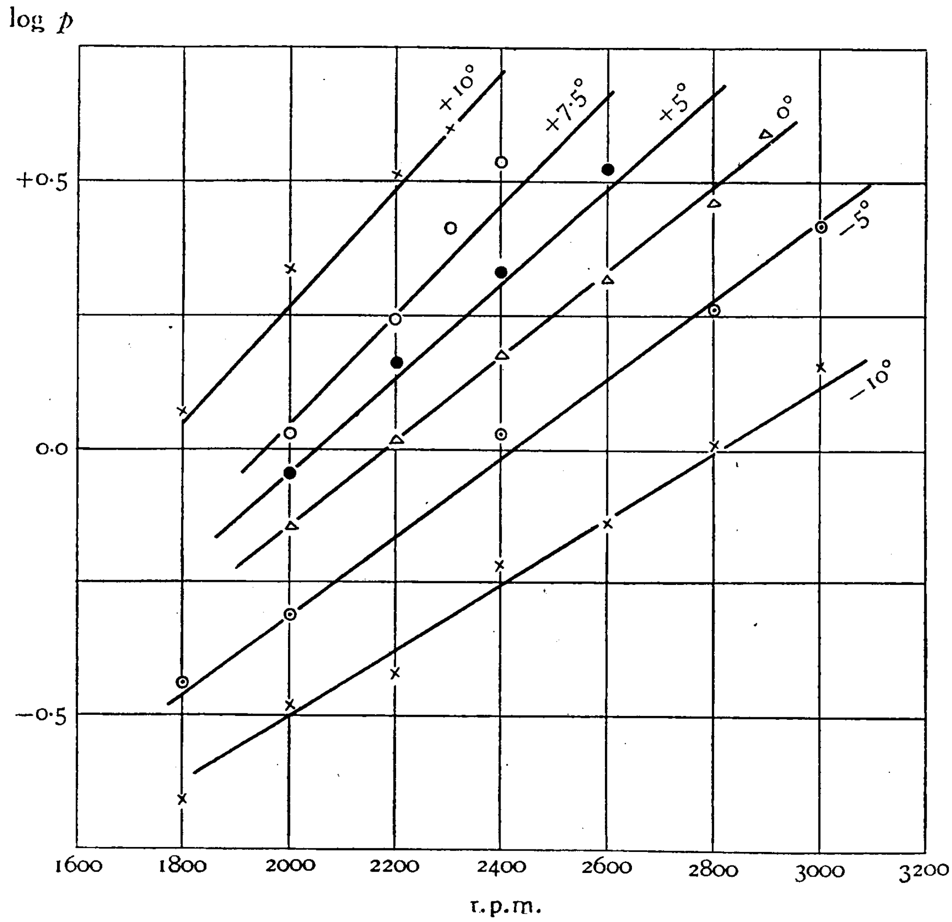



Sound component below 200 cycles per sec.

[30°]

Fig. 4 (b).

inclination of the straight line, however, increasing as the pitch increases. Further, as this increase of inclination with the pitch, excluding the value for $-10°$, seemed also to follow the exponential law, the following

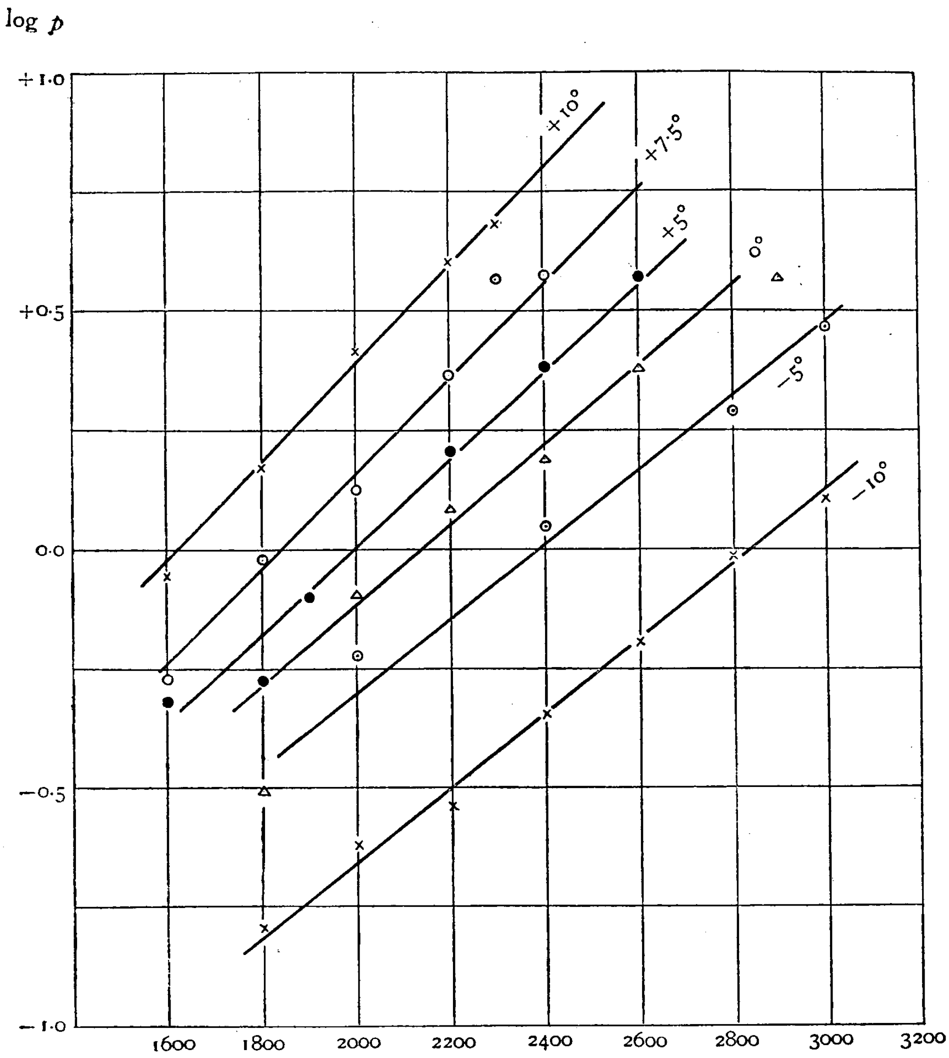



Sound component below 200 cycles per sec.

[Plane of rotation]

Fig. 5 (a).

relations were finally obtained between the loudness of sound (log $p$), the pitch (blade-angle) ($\theta$), and the number of rotations per minute ($n$).




Sound component below 200 cycles per sec.

[30°]

Fig. 5 (b).

## Sound Component below 200 cycles:—

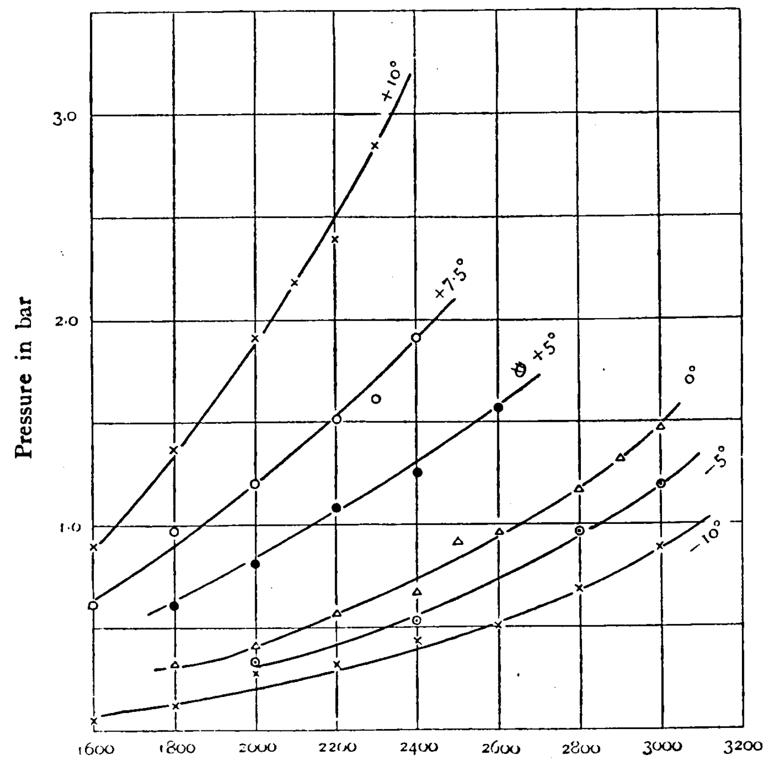
Plane of rotation:

$$\log_{10} p \text{ (in bar)} = 0.0008\, e^{0.023\theta}\, (n-2000) + 0.83\, e^{0.03\theta} - 1.0$$

30° direction:

$$\log_{10} p \text{ (in bar)} = 0.0008\, e^{0.023\theta}\, (n-2000) + 0.87\, e^{0.03\theta} - 1.0$$

As the frequency of the fundamental tone is 66 cycles per second at 2000 r.p.m., above this number of rotations the sound measured by the use of a 200-cycle low-pass filter consists of the fundamental tone and second harmonics. Hence, in order to know the proportion of the intensity of the second harmonics to that of the fundamental tone, several oscillograms were taken at the same position at various numbers

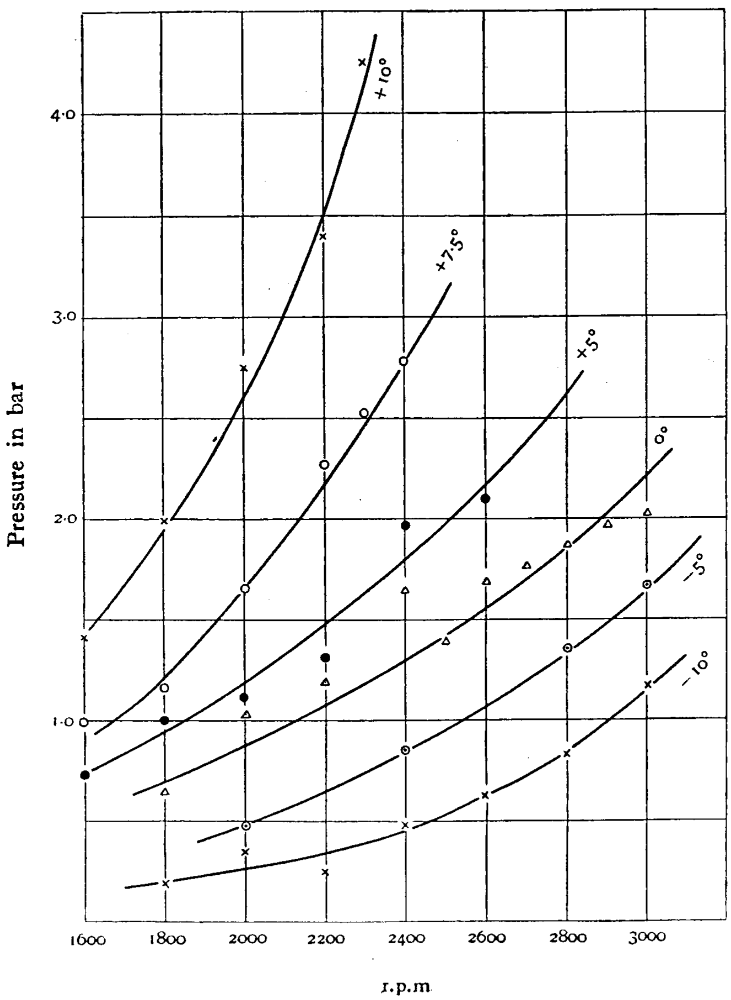



Sound component above 250 cycles per sec.
[Plane of rotation]

Fig. 6 (a).

of rotations, and analyses made on the records. According to the results of analyses the energy of the second harmonics was found in average to be about one-fourth of that of the fundamental. Further, no definite relation could be found between the magnitude of the second harmonics and the number of rotations. Above relations may therefore be regarded without fear of any serious error as being that which corresponds only to the fundamental tone;

For the component of the sound above 250 cycles (the value obtained by using a 250 cycle high-pass filter), the relation is rather irregular,

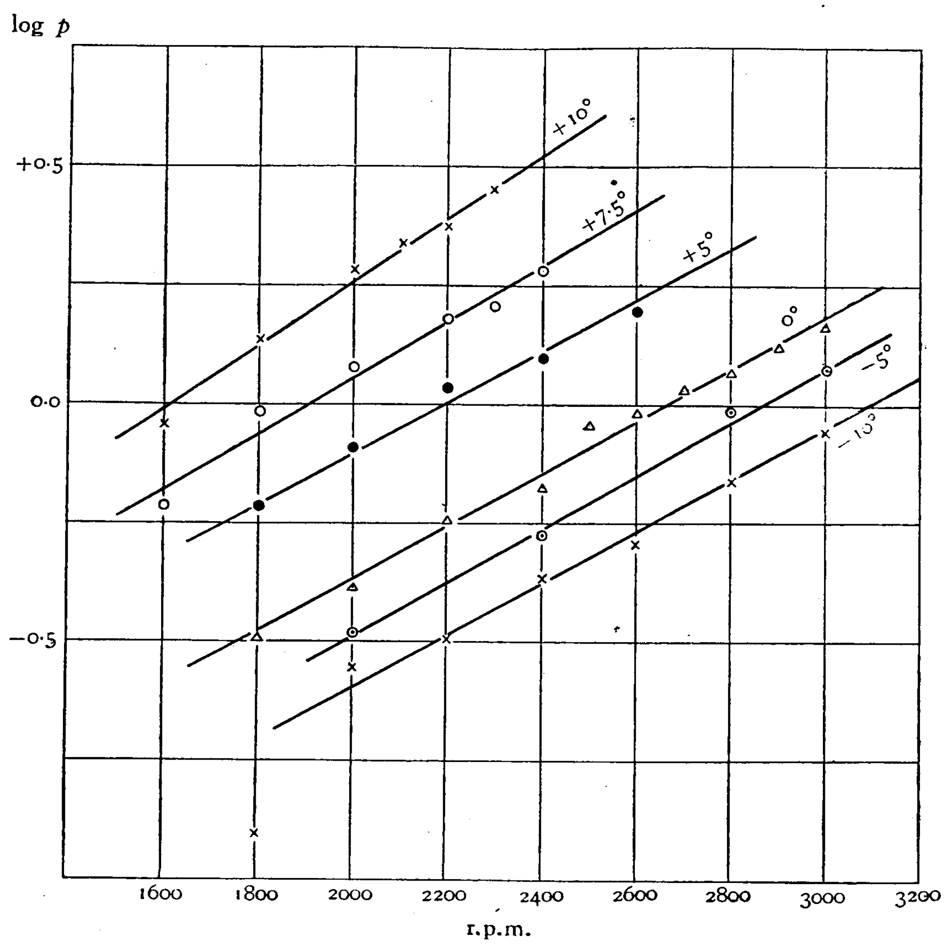



Sound component above 250 cycles per sec.

[30°]

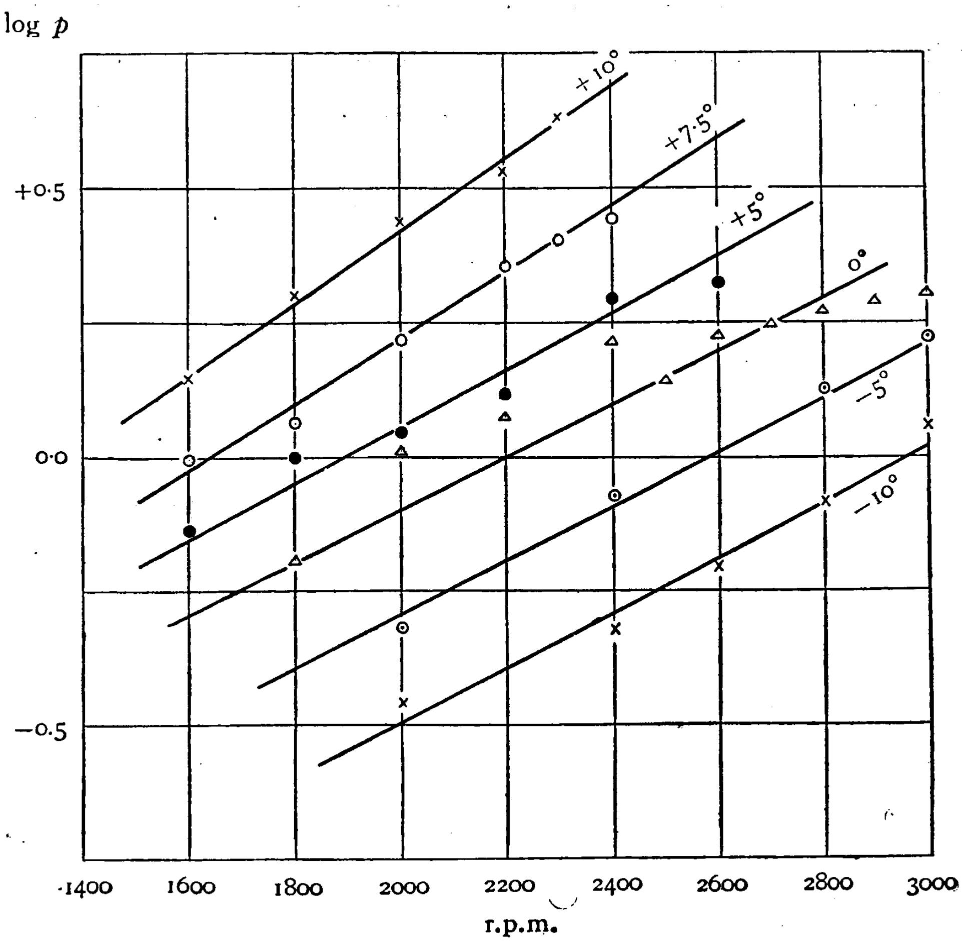
Fig. 6 (b).

as shown in Figs. 6 and 7, especially at pitch $-10^{\circ}$. The fact that a linear relation holds between pitch and the loudness of sound in the range from $-5^\circ$ to $+5^\circ$, and at pitch above $+7{\cdot}5^\circ$ the sound intensity increases rapidly, is similar to the case of the sound component below 200 cycles. Contrary to the previous case, however, the




Sound component above 250 cycles per sec.
[Plane of rotation]
Fig. 7 (a).

effect of pitch here does not increase with the revolution. Thus, for the sound component above 250 cycles the following relations were obtained:




Sound component above 250 cycles per sec.

[30°]

Fig. 7 (b).

## Sound component above 250 cycles:—

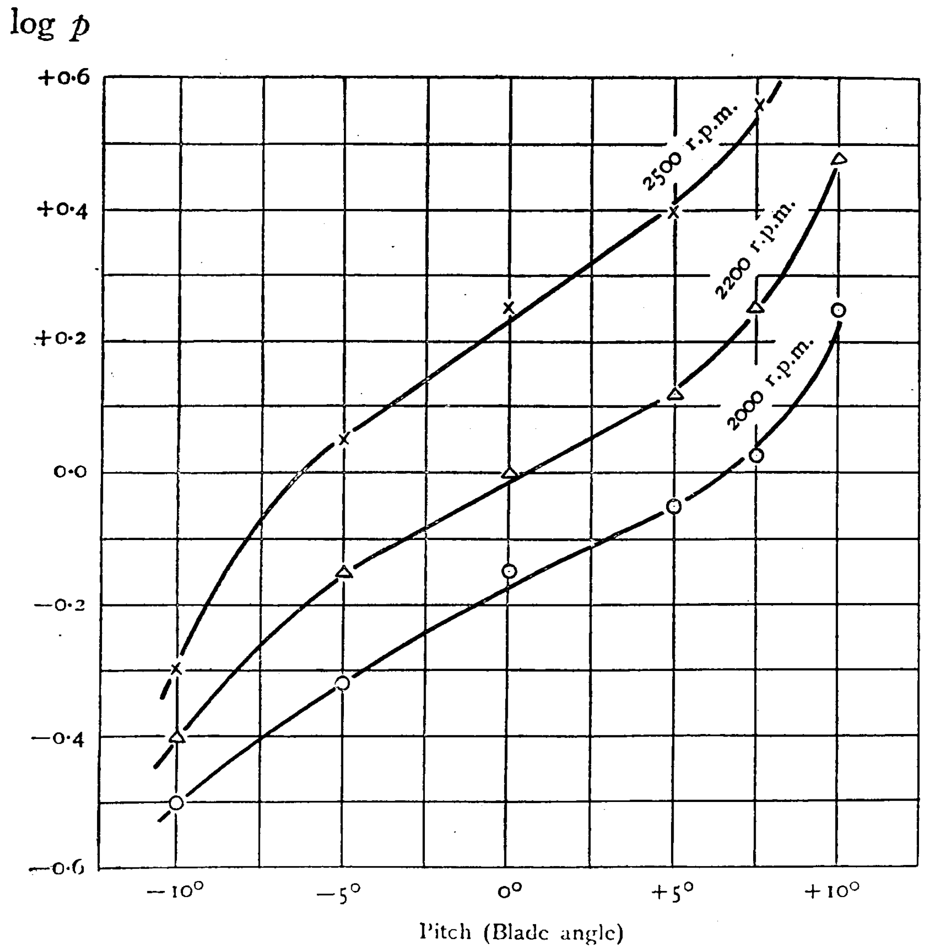
Plane of rotation:

$$\log_{10} p \text{ (in bar)} = 0{\cdot}00051\,(n-2000)+0{\cdot}38\,\theta-0{\cdot}31$$

30° direction:

$$\log_{10} p \text{ (in bar)} = 0{\cdot}00051\,(n-2000)+0{\cdot}38\,\theta-0{\cdot}11$$

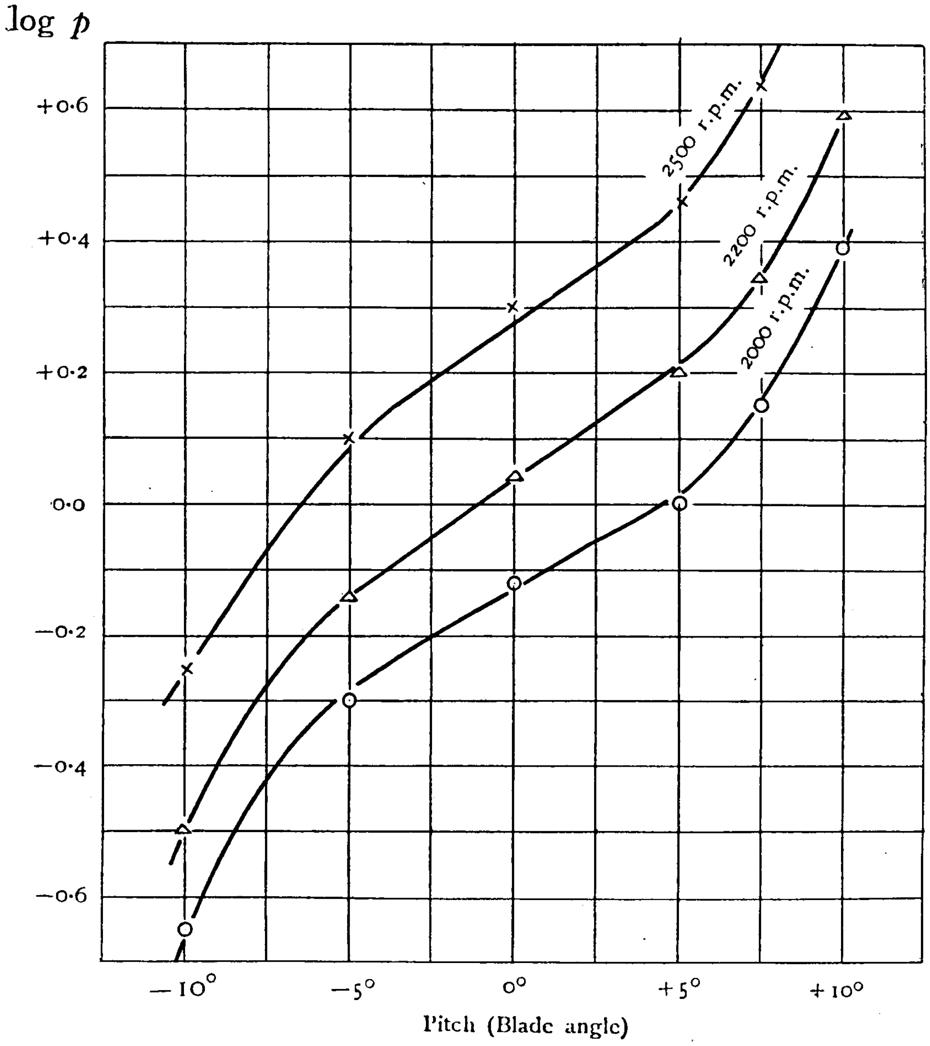
For both sound components, the effect of pitch is much more marked at 2500 r.p.m. than at 2000 r.p.m., that is to say, the effect increases with the number of rotations. Figs. 8 and 9 show the relations




Sound component below 200 cycles per sec.
[Plane of rotation]

Fig. 8 (a).

between $\log p$ and pitch $(\theta)$; and the following table gives the computed loudness $(\log p)$ for range of pitch angle from $-5^\circ$ to $+5^\circ$, in which a linear relation holds between loudness and pitch.




Sound component below 200 cycles per sec.

[30°]

Fig. 8 (b).

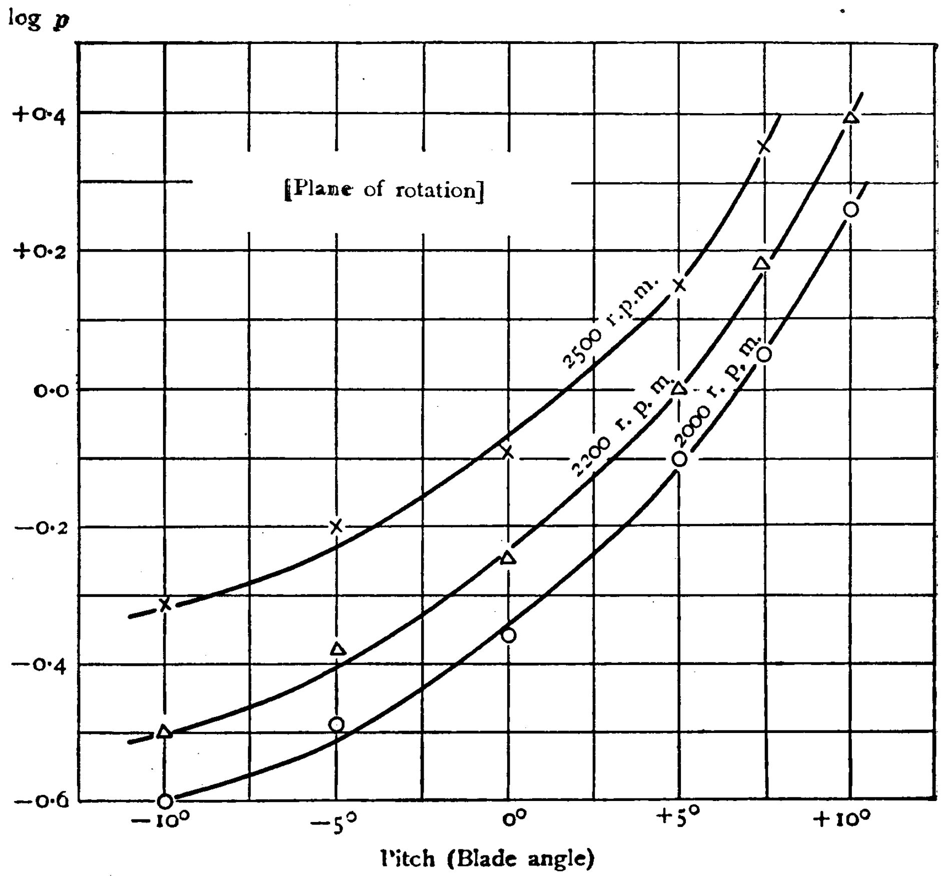



Fig. 9 (a). Sound component above 250 cycles per sec.

[$\log_{10} p$ (in bar)] Range of pitch (−5°∼+5°)

| | r. p. m. | Sound component below 200 cycles | Sound component above 250 cycles |
|---|---|---|---|
| Plane of rotation | 2500 | 0·036 θ+0·24 | 0·038 θ−0·04 |
| | 2200 | 0·029 θ | 0·038 θ−0·20 |
| | 2000 | 0·024 θ−0·16 | 0·038 θ−0·31 |
| 30° direction | 2500 | 0·035 θ+0·31 | 0·038 θ+0·12 |
| | 2200 | 0·030 θ+0·05 | 0·038 θ+0·02 |
| | 2000 | 0·025 θ−0·11 | 0·038 θ−0·11 |

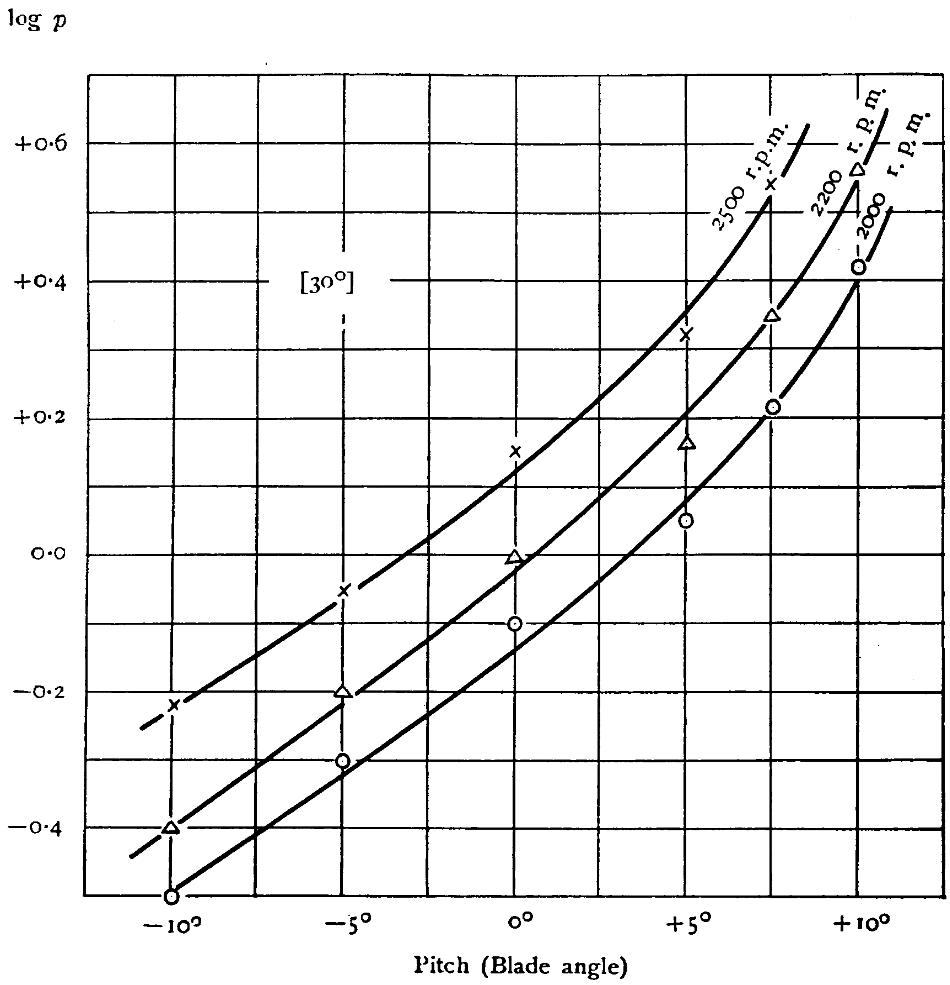



Fig. 9 (b). Sound component above 250 cycles per sec.

*Wind Tunnel Experiments.* Wind tunnel experiments were carried out in the 3 meter wind tunnel of the Institute with the aid of a tower type airscrew balance.

In this type of balance there is no difficulty in measuring the thrust, but in measuring the torque, which is done by suspending the airscrew-motor combination on two knife-edges at the lower part, there is considerable difficulty. This is due to two causes, the first one being the difficulty of placing the balance exactly in direction of the wind, while the second is that of adjusting the knife-edges in such a way as not to introduce any apparent torque due to the thrust component. So important is this adjustment, that even a few hundredths of a degree would bring about a considerable error in the result.

In the present balance the rear end of the shaft (marked A in Fig. 10.) ends in a mechanism that measures directly the torque trans-

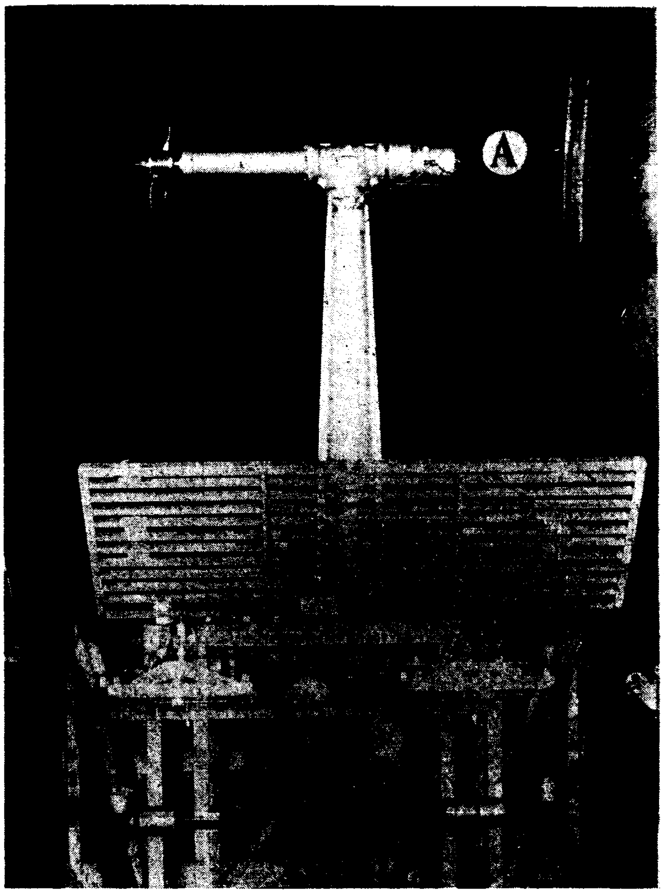
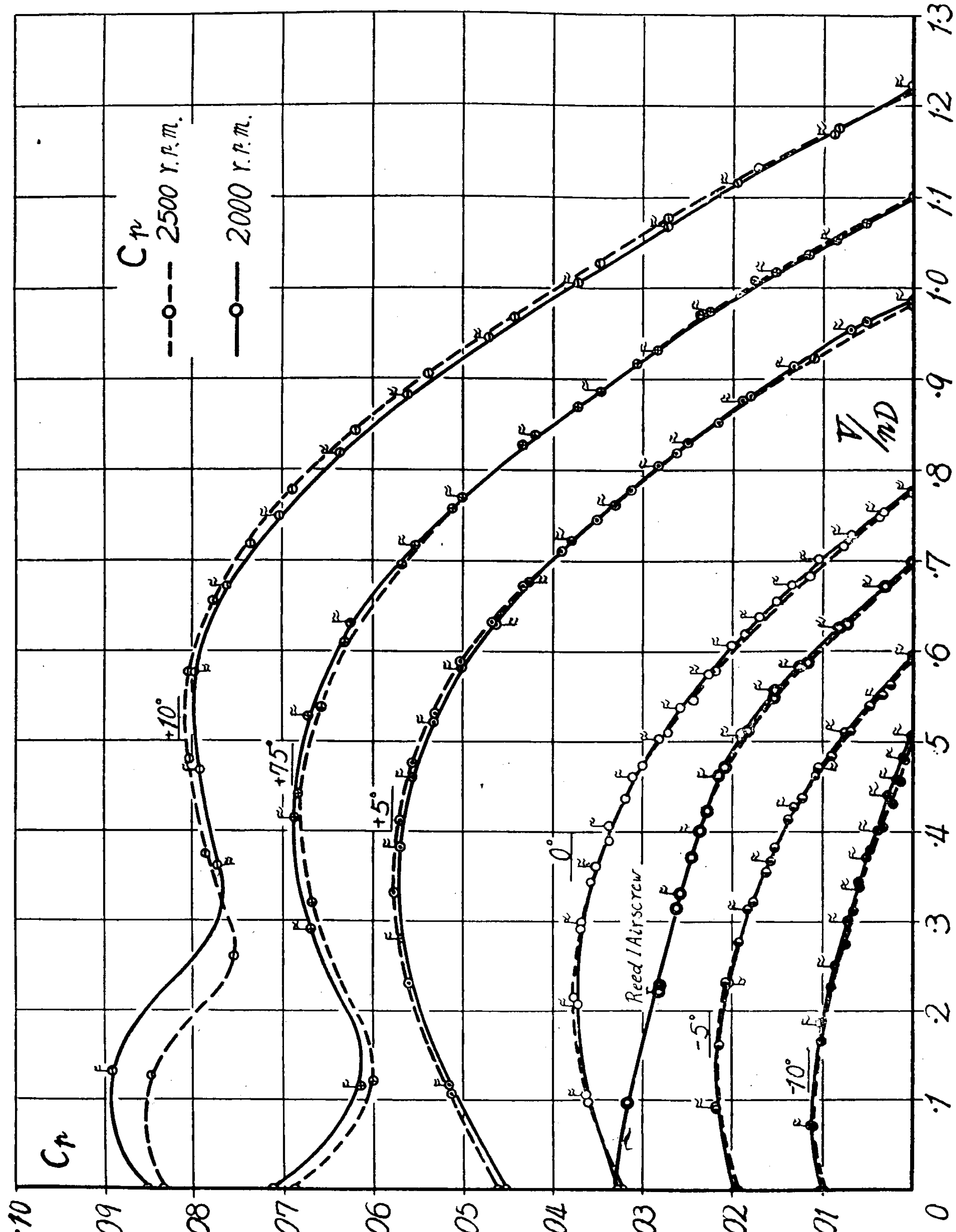


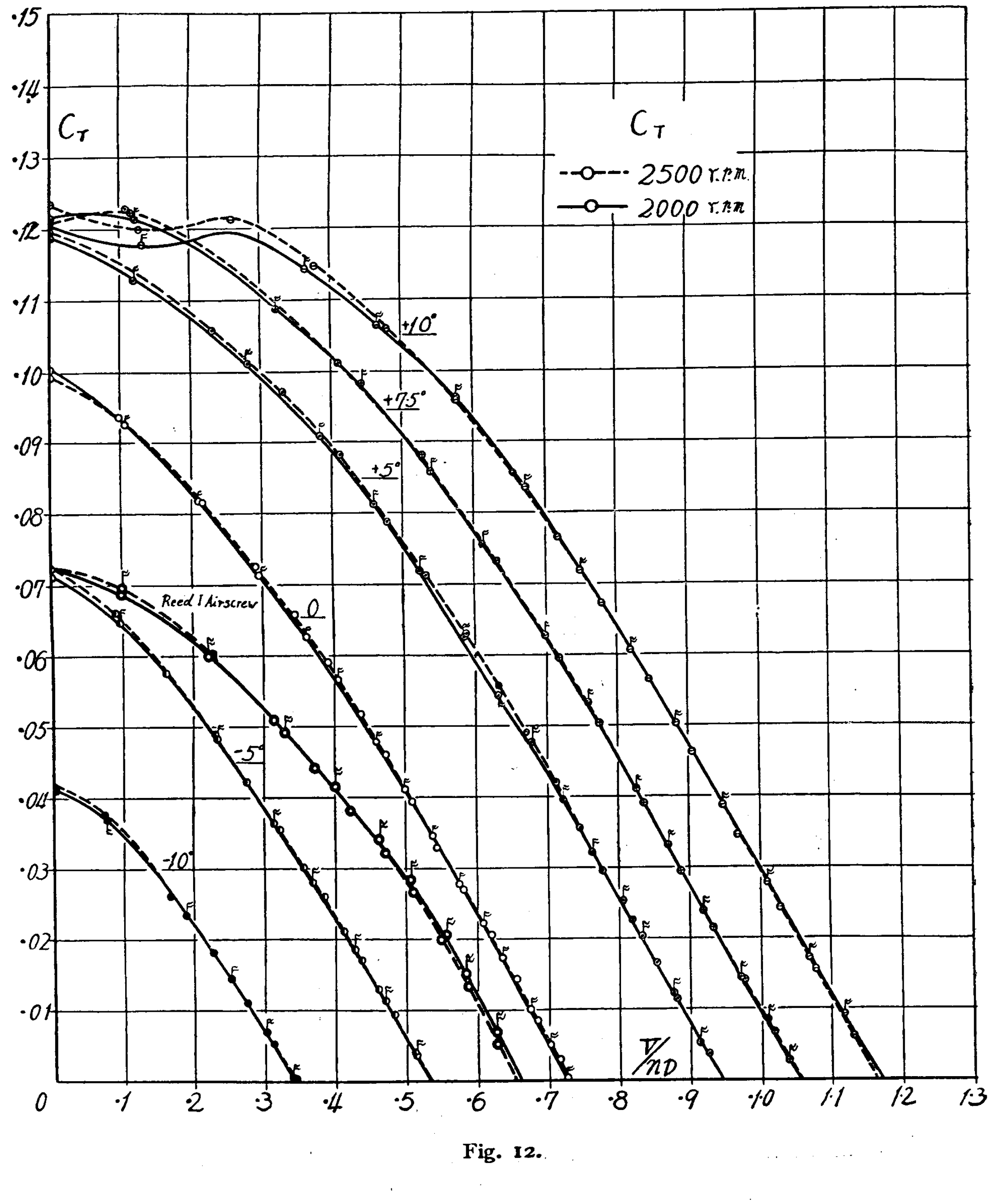

Fig. 10. Airscrew balance with cover removed.

mitted through it to the shaft driving the airscrew. Before mounting the airscrew we adjust the balance as follows: First the fun brake is mounted in place of the airscrew, and the torque transmitted through the mechanism, while what is indicated on the torque balance (marked



$C_p$
2500 r.p.m.
2000 r.p.m.
+10°
+7.5°
+5°
0°
-5°
-10°
Reed I Airscrew
V/nD
·10
·09
·08
·07
·06
·05
·04
·03
·02
·01
0
·1
·2
·3
·4
·5
·6
·7
·8
·9
1·0
1·1
1·2
1·3


Fig. 11.


Cт
·15
·14
·13
·12
·11
·10
·09
·08
·07
·06
·05
·04
·03
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·01
0
·1
·2
·3
·4
·5
·6
·7
·8
·9
1·0
1·1
1·2
1·3
Cт
2500 r.p.m.
2000 r.p.m.
+10°
+7·5°
+5°
0
Reed I Airscrew
-5°
-10°
V/nD

Fig. 12.

B in the figure) is noted. The airscrew is then mounted and run at the static condition (turning the balance 90 degrees to the direction of the wind tunnel axis) and the number of revolutions adjusted until the torque indicated by the mechanism on the shaft becomes equal to the value previously determined. Usually the torque indicated on the torque balance differs from the value determined previously in the case of the fan brake experiment. This is because the component of thrust due to the imperfect adjustment appeared as a part of the torque. The knife

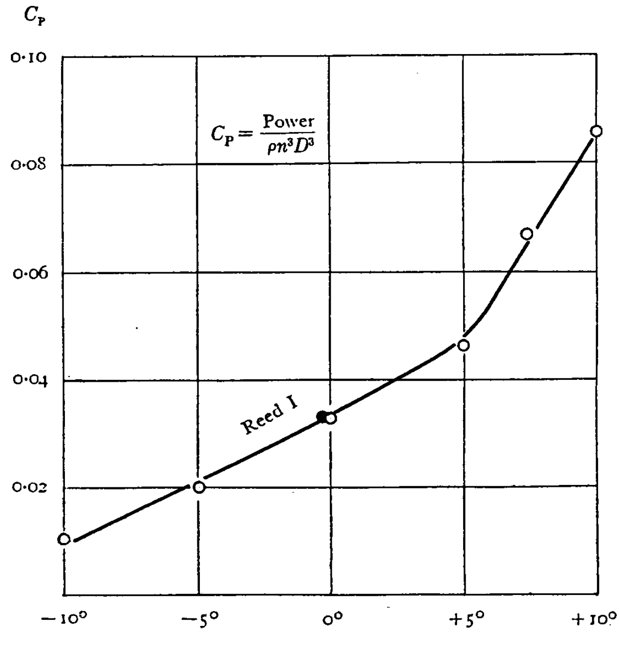



Fig. 13. $C_P$.

edges are adjusted until the torque becomes equal in both cases. Then the airscrew is removed for the second time and the balance brought to its original position. The motor is run at the desired speed and due note taken of the torque indicated on the mechanism, which represents the frictional torque of the shaft. Finally the airscrew is brought into position and run at the same speed, and the wind speed then increased gradually till the torque indicated on the mechanism corresponds to the previously determined value. Here the airscrew is working at zero torque, while usually the torque read off from the torque balance differs from zero. Since this is principally due to the inclination of the shaft to the direction of the wind, the balance position (angular) is adjusted until the torque balance indicates also zero. The adjustment is thus complete and the experiments are ready to be carried out. The final adjustment must be repeated for each experiment. Measurements were made at two different rotations, namely, 2000 and 2500 r.p.m. Since the sound experiments were made on a stationary airscrew, they corre-

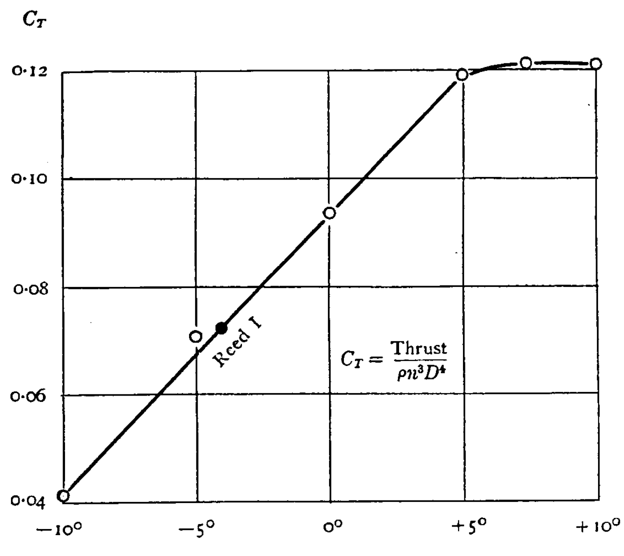



Fig. 14. $C_T$.

spond to the case $V/nD = 0$ in the wind tunnel measurements. In the wind tunnel experiments, this static condition was obtained as already mentioned by turning the airscrew balance 90 degress. In Figs. 11 and 12 are given the results of the wind-tunnel experiments. The relations between the pitch (blade angle) ($\theta$) and the power coefficient ($C_P$) as well as the thrust coefficient ($C_T$) are given in Figs. 13 and 14. It will be seen that both power and thrust coefficients increase linearly as the pitch (blade angle) increases from $-10°$ to $+5°$. Further, although the power coefficient increases rapidly at blade-angles above $+7 \cdot 5^\circ$, no remarkable increase of thrust accompanies it. This indicates the beginning of the partial stalling of the blade element. Fig. 15 gives the static thrust-power coefficient $k$ defined by

$$k = C_T / C_P^{\frac{2}{3}} \cdot \rho^{-\frac{1}{3}} D^{-\frac{2}{3}} .$$

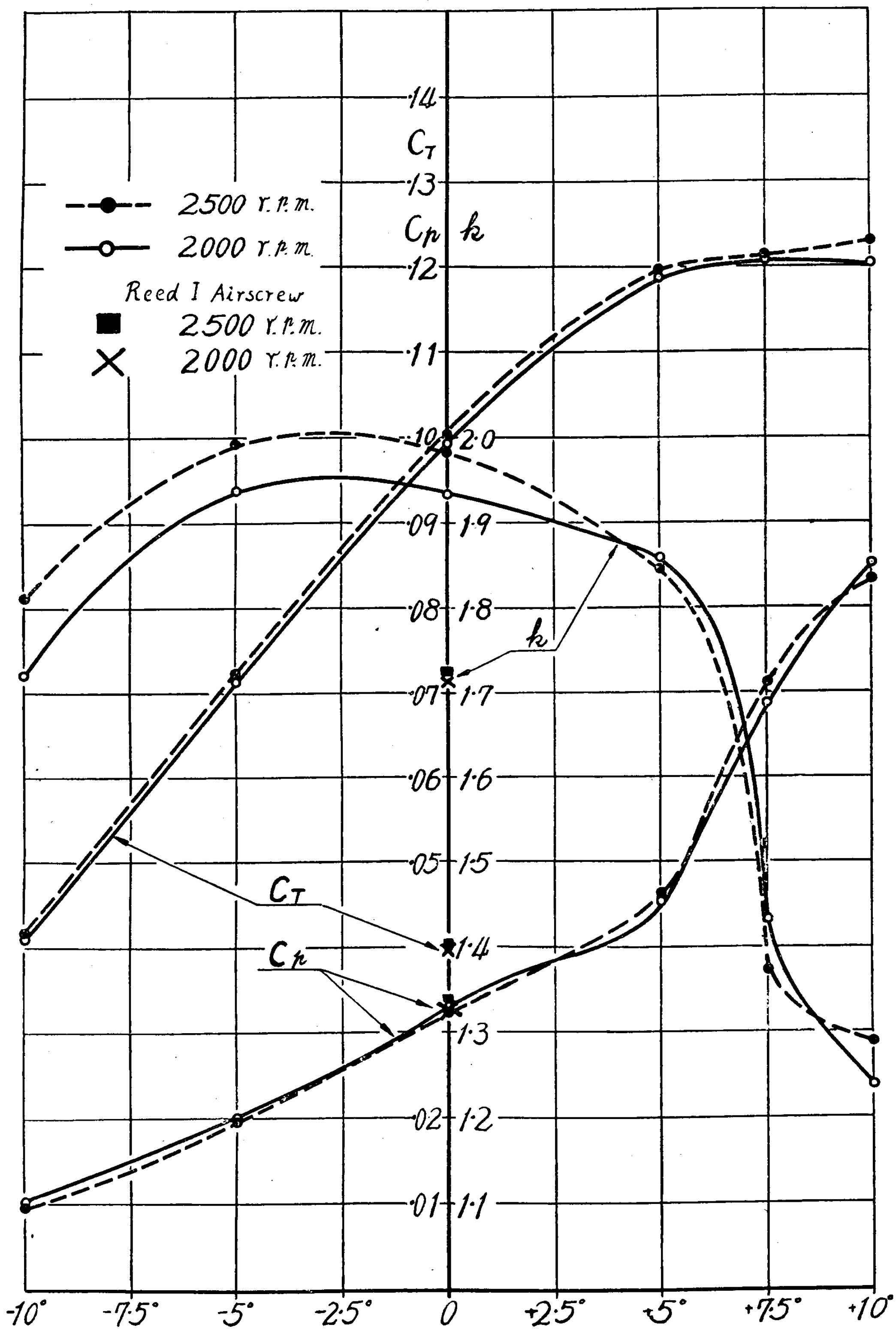
This coefficient begins to fall down slightly below a pitch of $+7 \cdot 5^\circ$, showing that the mean profile resistance coefficient of the blade element suddenly became large, indicating clearly the stalling of some of elements. At $-10^\circ$ pitch, $k$ is also smaller. This, however, is not due to the stalling; it merely shows that the distribution of the blade angle along the radius became so unfavourable that the mean profile resistance coefficient became large.

*Comparison of the Sound-and Wind Tunnel Experiments.* As already described, the loudness of the sound determined by the use of a 200 cycle low-pass filter increases linearly with the pitch in the range from $-5^\circ$ to $+5^\circ$, while an abrupt increase in loudness takes place at pitch $+7 \cdot 5^\circ$. This pitch (blade-angle) certainly corresponds to the one where the linear relation between the power and the thrust is lost.

To sum up, for the airscrew model used in the present experiments the loudness of the sound emitted when it is rotated on a fixed stand is proportional to the pitch (blade-angle) in that range wherein both power and thrust are also proportional to the pitch. At the pitch for which much more power is needed, the loudness of sound also rapidly increases.

*Reed I Airscrew.* For the Reed I airscrew model, which was made by twisting duralumin plate, the following reasults were obtained.

The loudness of sound is in general greater than that of the Kármán type model, that is, with regard to the component below 200 cycles the



·14
$C_T$
·13
$C_p$ k
·12
·11
·10 2·0
·09 1·9
·08 1·8
·07 1·7
·06 1·6
·05 1·5
1·4
1·3
·02 1·2
·01 1·1
2500 r.p.m.
2000 r.p.m.
Reed I Airscrew
2500 r.p.m.
2000 r.p.m.
k
$C_T$
$C_p$
-10°
-7·5°
-5°
-2·5°
0
+2·5°
+5°
+7·5°
+10°
Pitch (Blade angle)


Fig. 15. *k*.

loundness corresponds to that of the Kármán type at pitch $+5°$, and for the component above 250 cycles to that of the Kármán type at pitch $+7.5°$. The relation between the number of rotations and the loudness of sound is essentially the same as that for the Kármán type. Notwithstanding that the Reed I model consumes almost the same power as compared with the Kármán type model, its thrust is fairly small; namely, as shown in the following table, the power coefficient ($C_P$) of the Reed I is roughly equal to that of the Kármán type at pitch $0°$, whereas the thrust coefficient ($C_T$) of the former corresponds only to that of the latter at pitch $-4°$. Such low efficiency of the Reed I model can partly be attributed to its comparatively rough surface. These values of $C_P$ and $C_T$ for the Reed I model are shown by black circles on the curves for the Kármán type model [Figs. 13 and 14].

[Table of $C_P$ and $C_T$]

| Kármán type model | $C_T$ | | $C_P$ | |
|---|---|---|---|---|
| | 2000 r.p.m. | 2500 r.p.m. | 2000 r.p.m. | 2500 r.p.m. |
| $+10°$ | 0·1205 | 0·1234 | 0·0851 | 0·0834 |
| $+7.5°$ | 0·1206 | 0·1174 | 0·0670 | 0·0706 |
| $+5°$ | 0·1188 | 0·1196 | 0·0460 | 0·0462 |
| $0°$ | 0·0993 | 0·1004 | 0·0328 | 0·0321 |
| $-5°$ | 0·0714 | 0·0724 | 0·0199 | 0·0195 |
| $-10°$ | 0·0411 | 0·0416 | 0·0104 | 0·0098 |
| Reed I model | 0·0725 | | 0·0331 | |

For the Kármán type model the following relations were obtained between the pitch angle ($\theta$) and $C_P$ and $C_T$:—

$$C_P = 0{\cdot}022\,\theta + 0{\cdot}032 \qquad (-10° \sim +5°)$$

$$C_T = 0{\cdot}0058\,\theta + 0{\cdot}10 \qquad (\quad ,, \quad)$$

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