二百六号
(昭和十六年四月発行)
抄録

プロペラのフラッターの研究(其三)
回転薄板の振動及び音響
(プロペラ・フラッターの音響モデル)

所員 理学博士 小幡重一
技手 吉田彌平
嘱託 理学士 牧田康雄

プロペラがフラッターを起した時に発せられる特殊な強烈な音響の性質についてプロペラ・フラッターの研究第一報(航研報告 187 号)に詳しく述べた。続いて其第二報としてフラッターそれ自体の性質に関する詳細なる報告を発表した(航研報告第 202 号)。

以上の研究を遂行して居る間に薄板を回転すると少なくとも音響的にはプロペラのフラッターと同様の現象を示す事を発見したが、此現象は実験的にも亦理論的にも顕著の興味あるものであり、且つプロペラ・フラッターの研究に資する所を欠くないものと信じ、其性質を詳しく研究した。本稿はその概要であるが、結果の概要は既に帝國学士院紀事に発表しております。

回転薄板が成る一定の回転数範囲に於て生ずる特殊の振動はその後発する特殊の音響を分析した結果から推定するにプロペラのフラッターと同様に第一、第二及等の振動よりも成り、共音響は是れ亦製物プロペラのフラッターの音響と同様に回転に依る音と、振動に依る音の外に両者の結合音より成る。而も是等三種の音響成分は夫々全然違った方向性を有する事を巧妙なる実験に依つて示す事を得た。此結果は製物プロペラのフラッターの音から振動に依る音響成分を摘出し振動様式を推定するに有力なる指針を与えるものと信じる。

発光学的方法に依り回転薄板に於ける振動の大きさを測定し、又大気の圧力を種々変化して此特殊振動の発生に対する空気力学的要素の影響をも測定した。

結論に附録として薄板の極めて高い回転数を精密に測定する電気的方法を述べてある。
No. 206.
(Published April, 1941.)

The Vibration and Sound of a Revolving Thin Plate.\(^{(1)}\)

(Acoustical Model of Airscrew Flutter.)

(Investigations of Airscrew Flutter. Part III.)

By

Jūichi Obata, Rigakuhakusi,
Member of the Institute.

Yahei Yosida,
and

Yasuo Makita, Rigakusi.
Research Associate.

Introduction.

The properties of the airscrew flutter were studied and described in detail in Parts I and II of this series of papers.\(^{(2)}\)

These experiments on airscrew flutter were all carried out with actual airscrews, which naturally required a very large equipment and constituted experiments on an unusually large scale. Our great desire, consequently, was to carry out the study of flutter with some kind of model airscrew, which however, was almost impracticable for the following reasons.

As already described in previous papers, flutter is nothing but a phenomenon, in which certain kinds of vibration modes of the airscrew

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\(^{(1)}\) This article, in greatly abridged form, has been published in Proc. Imp. Acad., 16 (1940), 455.


Part II. " " " " No. 202 (November 1940).
blade are strongly excited. However, it is well known in connexion with the vibration of a thin uniform rod, that the frequencies of its natural vibration, flexural as well as torsional, increase in inverse proportion to the length itself or to the square of the length of the rod. By diminishing, therefore, the size of an airscrew, that is, by using a model airscrew, the frequencies of natural vibrations are increased considerably, with the result that an extraordinary high revolution is needed in order to produce the flutter, which evidently is a matter of considerable difficulty.

Fig. 1. The revolving arrangement.

In the course of our experiments on flutter with actual airscrew, it occurred to us that a revolving thin metal plate exhibits a phenomenon, greatly resembling, at least acoustically, the actual airscrew flutter.

Fig. 1 shows the revolving arrangement, in which a thin duralumin plate (20 cm. long, 2-0 cm. wide, and 0-5 mm. thick) is attached to a small electric motor. This plate, which is of simple rectangular form, having initially no angle of attack, that is to say, without any twist,

In the actual airscrew, already described in Part II, the diameter being 3 metres and the natural period of fundamental torsional vibration 590 per second, it is found that flutter occurs at about 1750 r.p.m.
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rotates at first very smoothly without emitting any appreciable sound; but upon attaining a certain number of revolutions a peculiar sound is abruptly emitted, indicating that some sort of vibration is excited. Upon increasing the revolution further, the vibration-sound soon ceases, followed by smooth and noiseless revolution. With still higher revolution, a peculiar sound, which seems to differ in nature somewhat from the previous one, is heard. These phenomena are repeated alternately, the intensity of the emitted sound being increased with increase in revolution.

This extremely simple experiment, besides seeming to furnish us with some useful hints on the nature of airscrew flutter, also presents interesting problems in the theory relating to the vibration of a revolving thin plate. The phenomenon was therefore carefully studied in the hope that it would throw some light on the mechanism of actual airscrew flutter, the results of which are described in the present paper.

In order to avoid any possible misunderstanding on the nature of the characteristic vibration excited in the revolving thin plate, it should be strongly emphasized that the present phenomenon is neither the usual one in which, by increasing the revolution, various modes of vibration are excited one after another from that of lowest frequency to those of a higher order, nor is the vibration which produces the so-called Aeolian tone, but is one in which it is very characteristic, as will be described later, that both the fundamental and second modes of the torsional vibration are always excited.

Flutter of a Revolving Thin Plate.

Although the mechanism of the characteristic vibration of a revolving thin plate may differ from that of the flutter in an actual airscrew which is produced when the airscrew stalls, the two phenomena seem nevertheless to be very much alike, for which reason we use here the word “flutter” for that peculiar vibration of the thin plate.
This flutter may be produced with a thin plate of duralumin as well as one of steel, the former being however preferable. Plates of various dimensions were tried, as will be described later.

As already mentioned in Part II, a very important point is to ascertain with an actual airscrew whether the flutter continues so long as the revolution is increased, or whether it ceases at some higher revolutions. But owing to the risk of breaking the airscrew, if the revolution were increased after the flutter has once begun, no attempt could be made to verify this point. With the thin metal plates here used, flutter were observed several times, in one case as often as six times, with increase of revolution.

The plate being of thin rectangular form, the frequencies of the various modes of vibration, flexural as well as torsional, can easily be computed. They can also be accurately measured by means of the

Fig. 2.

The arrangement for determining the natural vibration of a non-rotating plate.

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electrical method described in Report No. 191; which was already used in similar determinations for the actual airscrew blade relating to the study of flutter.

In determining the vibration of a non-rotating plate, repeated blows were given to a point near the edge of the blade at its root by means of a simple mechanism that is used in the toy of a drum-beater, as shown in Fig. 2, and the vibration was analysed by an electrical frequency analyser as already described [Report No. 191].

The necessary correction for the effect of centrifugal force was applied to the frequencies of bending vibrations for the revolving plates.

In order to analyse the flutter sound from the revolving thin plate, the sound was picked up by a microphone (either condenser type or velocity type) which was placed at a distance of 30 cm. from the centre of the plate in the direction 45° from the plane of revolution.

As in the case of the flutter of an actual airscrew, the frequencies of the various modes of vibration were compared with the pitches, or frequencies, of the various components that constitute the flutter sound, and the modes of vibration that are excited when flutter occurred, were determined.

Table 1 shows the frequencies of various modes of vibration of the

<table>
<thead>
<tr>
<th>Frequency of vibration</th>
<th>Pitch of sound</th>
<th>Flutter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexural</td>
<td>Torsional</td>
<td>r.p.m. (r.p.s.)</td>
</tr>
<tr>
<td>Obs. Calc. 60</td>
<td>Obs. 340</td>
<td>(I) 3080 (51)</td>
</tr>
<tr>
<td>60 60</td>
<td>Cals. 323</td>
<td>(II) 3600 (60)</td>
</tr>
<tr>
<td>230 240</td>
<td>1040 970</td>
<td>(III) 4000 (73)</td>
</tr>
<tr>
<td>650 660</td>
<td></td>
<td>(IV) 7800 (130)</td>
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<td>1300 1300</td>
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</table>
**Plate 11** Length: 200 mm. Width: 12 mm. Thickness: 0.41 mm.

<table>
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<th>Frequency of vibration</th>
<th>Pitch of sound</th>
<th>Flutter</th>
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<tr>
<td>Flexural Cals.</td>
<td>Torsional Cals.</td>
<td>r.p.m. Bromide record No.</td>
</tr>
<tr>
<td>Obs.</td>
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<td>537</td>
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<td>230</td>
<td>60</td>
<td>240</td>
</tr>
<tr>
<td>640</td>
<td>660</td>
<td>(III) 8100 36</td>
</tr>
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</table>

**Plate 4** Length: 240 mm. Width: 20 mm. Thickness: 0.51 mm.

<table>
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<tr>
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<tr>
<td>52</td>
<td>(I) 2550 31</td>
</tr>
<tr>
<td>198 208</td>
<td>(II) 2760</td>
</tr>
<tr>
<td>348 334</td>
<td>(III) 3180 32</td>
</tr>
<tr>
<td>1075 1003</td>
<td>(IV) 13560</td>
</tr>
<tr>
<td>550 571</td>
<td>13590 33</td>
</tr>
<tr>
<td>342–350</td>
<td>(V) 4450 34</td>
</tr>
<tr>
<td>1050–1070</td>
<td>(VI) 5340</td>
</tr>
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</table>

**Plate 2** Length: 200 mm. Width: 20 mm. Thickness: 0.51 mm.

<table>
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<tr>
<td>75</td>
<td>(I) 3870 29</td>
</tr>
<tr>
<td>290 299</td>
<td>(II) 4620</td>
</tr>
<tr>
<td>420 401</td>
<td>(III) 5540 30</td>
</tr>
<tr>
<td>820 822</td>
<td>15280</td>
</tr>
<tr>
<td>1320 1204</td>
<td>(IV) 7000 61</td>
</tr>
<tr>
<td>1630</td>
<td>7000</td>
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</table>

**Plate 1** Length: 200 mm. Width: 12 mm. Thickness: 0.51 mm.

<table>
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<tr>
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</tr>
<tr>
<td>290 299</td>
<td>7550 38</td>
</tr>
<tr>
<td>713 665</td>
<td>(II) 7700</td>
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The Vibration and Sound of a Revolving Thin Plate.

Plate 5  Length: 160 mm.  Width: 20 mm.  Thickness: 0.51 mm.

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<th>117</th>
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<th>501</th>
<th>564—595</th>
<th>4800</th>
<th>5700</th>
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<tr>
<td>460</td>
<td>448</td>
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<td>1310</td>
<td>1275</td>
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<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Vibration

Sound

Frequency.

Fig. 3 (a). Analyses of the vibration and sound [Plate 4.]
Sound

(IV_2)

(V)

Frequency.

Fig. 3 a) Continued.

Vibration

Frequency.

Fig. 3 (b) Analyses of the vibration and sound. [Plate 3]
Sound

Frequency.

Fig. 3 (b) Continued. [Plate 2.]
Vibration

Sound

Frequency.

Fig. 3 (c) Analyses of the vibration and sound. [Plate ii.]
The Vibration and Sound of a Revolving Thin Plate.

Vibration

Measuring point:
6 cm. from the tip.
(critical line)

Measuring point:
6 cm. from the tip.
(edge)

15 dB

Frequency.

Sound

6550 r.p.m.

3 dB

Frequency.

Fig. 3 (d) Analyses of the sound and vibration. [Plate 1.]
Fig. 4 (a). Acoustical spectra of the flutter sound. [Plate 2]
The Vibration and Sound of a Revolving Thin Plate.

Fig. 4 (b). Acoustical spectra of the flutter sound. [Plate 4.]
thin plates and the pitches of the various components of the flutter sound, the numbers in heavy type being the frequencies measured, as described above.

Briefly speaking the results of acoustical study of the flutter of the revolving thin plate, it is found that the excited vibrations are in all cases torsional, no bending vibrations being observed—a fact confirming our conclusion that in the flutter of an actual airscrew the excited vibration is torsional.
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This conclusion was further confirmed by another experiment in which the vibration of the revolving thin plate was determined optically by attaching a minute mirror to the surface of the plate. The details of this experiment will be described in a later page.

In Fig. 3 are reproduced typical records of analyses of the vibration and flutter sound, and in Fig. 4 the acoustical spectra that were obtained by correcting these records of flutter sound with the frequency characteristic of the microphone.

In this connection, it is worthy of note that in the case of the sound of an actual airscrew, the lowest component is that which has the pitch \( p_0 \) corresponding to the product of the number of blades and the number of revolutions, whereas in the case of sound from the thin plate, the frequency of the lowest component corresponds to the number of revolutions itself. It is here indicated by \( p_0 \). This fact may perhaps be due to the unbalance between the blades as well as to the lack of symmetry in the twist caused by rotation.

Inspection of the records of analyses or the acoustical spectra will show that, although the flutter is observed several times, upon increasing the revolution, the nature of the sound, or strictly speaking, its acoustical spectra, differs alternately, that is, according as whether the sound is from those marked here in odd numbers (I, III, V) or in even numbers (II, IV, VI). Listening to the sound, one is rather surprised by the fact that the sound in the latter cases, closely resembles that of the actual airscrew flutter.

Further, it was noticed that with the production of the peculiar sound, that is to say, when the flutter occurred, a thrust was caused in every case, indicating the presence of a constant twist in addition to the torsional vibration; in other words, asymmetry of torsional vibration on both sides of the position of equilibrium. The presence of this thrust can easily be shown by placing a lighted cigarette in front of the revolving plate, the smoke of which is promptly sucked in.

No change in the direction of the thrust was observed by turning
the plate inside out, or by using different plates; the cigarette smoke is always sucked in; in other words, the action is opposite to that of an ordinary electric fan—a fact that may be explained by the effect of the motor.

**Nature of the Flutter Sound.**

(1) *General description.* On comparing the frequencies of the various modes of vibration with the pitches of the various components of the flutter sound, it is found that flutter sound consists, as in the case of actual airscrew flutter, in addition to the sound of rotation as well as those due to the torsional vibration of the blade, of a number of combinational tones(1) that are formed by these two different kinds of sound, namely,

\[
\text{flutter sound consists of } \begin{cases} \text{components of the sound of rotation,} \\ \text{components of the sound due to vibration,} \\ \text{combinational tones of these two.} \end{cases}
\]

In Fig. 4 the components of the sound of rotation are indicated by \( p_0, p_1, \) etc. the sound due to torsional vibration by \( t_1, t_2, \) and the combinational tones by \( t_m \pm p_n. \)

The sound that contains a number of combinational tones gives us a sensation quite similar to that of an actual airscrew flutter.

(2) *Directional properties.* Referring to the acoustical spectra of the flutter sound shown in Fig. 4, it will be seen that very often the amplitudes (or intensity) of the combinational tones are larger than those of their components or primaries, which fact requires some explanation.(2) As to the various components of the flutter sound, it is not an easy matter to tell their origin, that is to say, whether it is a

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(2) E. Waetzmann already found a difference tone which had an amplitude several times greater than either primary; ZS. f. Phys., 1 (1920), 271.
component of the sound of rotation, whether it is due to vibration, or whether it is a combinational tone, so that with the hope of obtaining some means of distinguishing these various kinds of sound, an attempt was made to determine their directional properties, that is, the distribution of the intensity around the sound source for each component.

![Image](image_url)

Fig. 5. The arrangement for determining directional properties of the flutter sound.

Fig. 5 shows the arrangement for determining the directional properties. The electric motor, to which the thin plate was attached, was set on an iron stand, which was rotated by another motor (placed in a box shown in the lower part of Fig. 5) around a vertical axis, passing through the centre of the thin plate.
The experiment for determining the directional properties of each component separately was somewhat elaborate.

The rotating arrangement was placed in a so-called "dead" room, where the walls, ceiling and floor are thoroughly coated with sheets of coarse blanket and hemp-cotton duck to prevent the reflection of sound.

The rotating arrangement was operated from an adjoining room in which the electrical frequency analyser, oscillograph, and other equipment were placed.

First, the thin plate is rotated and the frequency analyser operated, and the scale of the variable air condenser in the analyser is stopped at a certain point corresponding to a certain component in the spectrum, that is, $p$, $t$, or $t \pm p$, the directional properties of which is to be determined. By means of a change-over switch, an oscillograph of the usual Duddell type is then switched in, in place of the vibrator or recorder of the analyser. The rotating arrangement is then made to work, the motor together with the revolving thin plate, being rotated about a vertical axis, and the relative position between the revolving plate and the microphone which is placed at a distance 60 cm. from the centre of the plate, is slowly changed, making one revolution about the vertical axis in about one minute.

The space variation in the amplitude of the component is thus recorded on the bromide paper of the oscillograph-drum. By means of electric contacts made at every 10° interval (shown at the middle part of Fig. 5), the position or direction of the plane of revolution of the thin plate relative to the microphone is recorded, together with the amplitude variation. Fig. 6 shows some of these records that indicate the space variation in the amplitude.

By means of a simple circuit containing oxide-rectifiers (Fig. 7), the output of the amplifier can easily be rectified so as to indicate the space distribution of the amplitude in the form of a continuous curves. In Fig. 8 is reproduced one of these continuous curves that indicate the
Fig. 6 Directional properties of the sound.
space variation in the total output of the sound due to Flutter III of the plate No. 3.

From either of these records, as shown in Fig. 6 or Fig. 8, the space-distribution can easily be converted into the usual polar curves. In Fig. 9 are given a number of such polar curves thus obtained for various components.

Although the centre of the revolving plate was situated at least 2 m. from the well padded walls, the reflection from it could not be wholly avoided. Owing to the unstable fluttering condition, it was moreover somewhat difficult to keep the revolutions strictly constant, with the result that the polar curves are not exactly symmetrical on either side of the plane of rotation.

However, the results thus obtained rather exceeded expectations, the origin of each component being very clearly distinguished by differences in the space distribution of the amplitude, that is, by the polar curves.

The sound of rotation indicated here by \( p \), really consists of two parts, (1) the one due to the production of thrust, (2) the other due to the thickness of the blade, displacing air in both directions perpendicular to the path of the blade.

Now, referring to the polar curves showing the space distributions of the amplitude, there are evidently three different kinds:

(a) The component that has a maximum in the direction of the plane of rotation, or some point very near it [Fig. 9 (a)]. This component evidently corresponds to the sound of rotation.\(^{(1)}\)

(b) The component that has a maximum at the direction perpendicular to the plane of rotation, Fig. 9 (b), evidently corresponding to the one due to torsional vibration of the blade.

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\(^{(1)}\) As to the directional property of this component, refer to:


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Fig. 7.

S: Stepping device for 50° and one revolution.

Fig. 8. Directional properties of the sound. (Rectified curve).
Pitch: $n = 1010 \sim$
Wave length: $\lambda = 34$ cm.

(a) Sound of rotation: $p_n$
(Page 137, Bromide 61, Component No. 631)

(b) Sound due to torsional vibration: $t_1$
(No. 624)

(c) Combinational tone: $t_1 + p_0$
(No. 623)

(d) Combinational tone: $t_1 - p_0$
(No. 624)

Fig. 9 (1) Directional properties of the components of the flutter sound. [Plate 2. Flutter IV.]
The Vibration and Sound of a Revolving Thin Plate.

Pitch:  \( n = 1320 \sim \)
Wave length:  \( \lambda = 26 \text{ cm} \).

Sound due to torsional vibration:  \( t_2 \) (No. 64).

Combination tones:

Fig. 9 (2). [Plate 2, Flutter IV]. Continued.

Vibration sound:  \( t_1 \)
(No. 50).

\( n = 1440 \sim \)
\( \lambda = 24 \text{ cm} \).

\( n = 1210 \sim \)
\( \lambda = 28 \text{ cm} \).

\( n = 430 \sim \)
\( \lambda = 79 \text{ cm} \).

\( n = 1310 \sim \)
\( \lambda = 26 \text{ cm} \).

Fig. 9 (3). [Plate 9, Flutter III].
Pitch: \( n = 1030 \sim \)
Wave length: \( \lambda = 33 \text{ cm.} \)

Sound of rotation: \( p_m \) (Page 137, Bromide No. 30, Component No. 51.)

\[ \begin{align*}
&n = 435 \sim \\
&\lambda = 78 \text{ cm.}
\end{align*} \]

Vibration sound:
\( t_1 \)
(No. 652)

\[ \begin{align*}
&n = 460 \sim \\
&\lambda = 74 \text{ cm.}
\end{align*} \]

\( t_1 - p_0 \)
(No. 651)

\[ \begin{align*}
&n = 1320 \sim \\
&\lambda = 25 \text{ cm.}
\end{align*} \]

Vibration sound:
\( t_2 \)
(No. 66)

\[ \begin{align*}
&n = 1250 \sim \\
&\lambda = 27 \text{ cm.}
\end{align*} \]

\( t_2 - p_0 \)
(No. 66)

Combinational tones:
Fig. 9 (4). [Plate 2, Flutter II].
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Combinational tones:

Fig. 9 (5). [Plate 1, Flutter I].

Pitch: \( n = 710 \sim \)
Wave length: \( \lambda = 48 \, \text{cm} \)

Vibration sound: \( t_1 \) (No. 56)

Combinational tones:

Fig. 9 (6). [Plate 1, Flutter II].
(c) The component that has a maximum in a direction intermediate between these two, Fig. 9 (c), undoubtedly corresponding to the combinational tone of these two.

The nature of the space distributions of the amplitude having been thus thoroughly known, continuous determination around the sound source was omitted for those components, the spectra of which are given in Fig. 10; but the polar curve of each component was estimated by means of the records of analyses obtained at three different positions, such as reproduced in Fig. 10, and written on the bromide paper superposed on the record of amplitude of the respective component.\(^1\) It shows the great complexity of the sound, which consists of various components having different polar curves, that is, of different origins.

Further, it will be noticed that, of the polar curves given in Fig. 9, the form of those shown in (2) No. 64, (3) No. 67, and (4) No. 66, somewhat differ from that of others, showing a number of maxima and minima. This fact may undoubtedly be explained by the short wave-length of the sound. In these cases, the wave-length is so short as to comparable with the size of the motor, that the diffraction effect

\(^1\) The origin of the component \(p_0\) as well as the directional property of its sound have not yet been thoroughly studied; this component seems to differ somewhat in nature from \(p_1\), \(p_2\) etc.
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caused by the latter results in giving such peculiar form to the polar curve.

The fact thus revealed concerning the nature of the revolving thin plate, that the sound component of various origins each exhibits a different directional property, may be true in the case in actual airscrew flutter, whence it may readily be concluded from the foregoing results that in order to pick up the vibration-sound in studying airscrew flutter, the most effective way is to place the microphone on that line along the axis of rotation of the airscrew.\(^{(1)}\)

In addition to the sound analysis by means of the frequency analyser, oscillograms of the wave-form of the flutter sound were also taken by placing the microphone at a distance of 60 cm. from the centre of the plate, either in front of the plate or in the direction 50° from the plane of rotation, some of which are reproduced in Fig. 11.

**Optical Determination of the Vibration.**

The salient features of the peculiar vibration of the revolving thin plate have been made clear by the acoustical study so far described. In order to confirm these results of acoustical determinations, and to obtain, if possible, some quantitative result relating to the magnitude of torsional vibration of the thin plate, certain further optical determinations were attempted.

A minute mirror, diameter about 3 mm., was pasted on the surface of the plate at a point near the blade tip, and by means of the arrangement shown in Fig. 12, the image of a light source \(A\) was focussed on a semitransparent scale held in a horizontal position.

If the inclination of the light beam as well as the position of the

\(^{(1)}\) Quite recently, Mr. R. Kanayama of the Military Aeronautical Research Laboratory, at Tatikawa, Tokyo-fu, made some experiments in order to test our present conclusion regarding the directional properties of the various components of the sound of actual airscrew flutter, and obtained results agreeing fairly well with our expectations described above.
Fig. 11. Wave forms of flutter sound, showing differences at different number of revolutions and different directions.
(Mike: No. 752; Kōken amplificer.)
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Flutter IV. Front. 18 db.

Fig. 11 (a) [Plate 2] Continued.

Plate 1. Flutter I. Front [90°]. 8 db.

Flutter II. Front. 12 db.

Fig. 11 (b) [Plate 2]
horizontal scale are so adjusted that the reflected light from the mirror falls on the scale when the thin plate comes into a vertical position, the light beam is deflected horizontally by the torsional vibration of the plate, and the horizontal broadening thus produced of the image on the scale is clearly equivalent to twice the angle of twist caused by the torsional vibration.

If, on the other hand, the arrangement is so adjusted that the reflected light falls on the scale when the thin plate comes into a horizontal position, the broadening of the image corresponds to the magnitude of the bending vibration.

In this way, the magnitudes of the torsional as well as bending vibrations can be accurately determined. The results show that torsional vibration is always strongly excited, whereas bending vibration is almost negligible; the latter is very feebly excited, and that only in the case of thin and long plates.
Experiments under Reduced Pressure.

In order to determine the effect of change in aerodynamical force by reducing the air pressure, the arrangement was placed in a large glass bell jar, and similar optical determinations were made under various pressures. By means of the optical arrangement described

![Diagram of the arrangement for optical determination.](image)

Fig. 12. The arrangement for optical determination.

![Graph showing the decreasing aspect of the amplitude of torsional vibration with decreasing of atmospheric pressure.](image)

Fig. 13. The decreasing aspect of the amplitude of torsional vibration with decreasing of atmospheric pressure.
above the magnitude of torsional vibration can easily be determined from outside the bell jar, the results being summarized in Figs. 13 and 14.

It will be seen that by reducing the pressure, the range of the number of revolutions within which the characteristic vibration is excited, are increasingly diminished, and at 500 mm. pressure, the vibration excited at the lowest revolution disappears. On further increasing the revolution, excitation of vibrations of types I, II, III, IV, and so on, cease one after the other, and finally, at a pressure of about 1/8 atmosphere, vibrations of all types up to V, cease.

In Fig. 14 the shaded areas indicate the regions of the number of revolutions, within which each type of characteristic vibration is excited.
Further, it is found, as shown in Fig. 15, that the fluttering range widens logarithmically with the increase of revolutions.

All the experiments so far described were carried out with a thin duralumin plate with no initial angle of incidence. It was shown in the previous paper that in the case of an actual airscrew, flutter does not occur when the blade angle is sufficiently reduced. For this reason it was desirable to know the effect of giving an initial angle of incidence to the thin plate, to accomplish which experiments were made by combining two duralumin plates with a simple hub in such a way that there will be a certain angle between the two plates, with the results as summarized in the annexed Table.

The angle of incidence here means the angle of each plate to the plane of rotation, the size of the plate being $15 \times 2 \times 0.06$ cm each.
Table 2. Number of revolutions at which flutter occurs.

<table>
<thead>
<tr>
<th>Flutter No.</th>
<th>Angle of incidence</th>
<th>0°</th>
<th>2°</th>
<th>5°</th>
<th>10°</th>
<th>30°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I.</td>
<td>2020</td>
<td>3020</td>
<td>4300</td>
<td>2000</td>
<td>Flutter does not occur at 4000 r.p.m.</td>
<td></td>
</tr>
<tr>
<td>II.</td>
<td>2260</td>
<td>3500</td>
<td>2400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III.</td>
<td>2540</td>
<td></td>
<td></td>
<td>2730</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV.</td>
<td>2910</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V.</td>
<td>3400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Contrary to the case of an actual airscrew, increasing the angle of incidence reduced the case with which the flutter occurred; at an angle of incidence of 30°, flutter did not occur even at 4000 r.p.m.

Appendix.

Determination of the Number of Revolutions.

Since, in the present experiment, a small electric motor that happened to be in our laboratory, was utilized to rotate the thin plate, a special device was tried with satisfactory result in order to determine the
number of revolutions without loading the armature by any mechanical contacts, nor by any electromagnetic contrivance.

Fig. 16 shows the arrangement for determining the number of revolutions. A small piece of iron, the end of which was polished in a suitable shape, was attached to the end of the motor-shaft. A light beam from an electric lamp was reflected by the polished surface to a photocell enclosed in a metallic cover, and placed obliquely with respect to the direction of the axis of the motor. The intensity of the light beam falling on the photocell thus changes with the revolution of the motor, so that by turning the polished surface to suitable shape, a sinusoidal current, the frequency of which corresponds to the number of revolutions, could be obtained as the output of the circuit containing the photocell. The frequency of the alternating current, i.e. the number of revolutions, can easily be determined by means of the usual reed-type electric frequency-meter.