抄 録

“プロペラの音の成因に関する研究．”

(II) プロペラ翼附近の圧力変化の測定 (續報)

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本篇は前篇に航空研究所報告第 99 号に承継を公表した実験の継続として、前回の実験に於て気付かれた頃の誤点を除き、回転するプロペラ翼附近の圧力変化を極めて精密、詳細に測定し、翼附近の空気の configuration を明らかにしたものである。

今回は風洞の中央に設置したコンクリート台の上で電動機に依り二翼プロペラの模型 (1/3 或は 1/4) を回転し、圧力変化の測定には翼の根附近では外径 14 mm に過ぎない小型マイクロフォンを使用し、少なく遠距離では外径 33 mm 及び 75 mm のマイクロフォンを用ひた。

プロペラ翼の附近では勿論一つの翼の影響だけが現れるが、本実験に使用した模型 (直徑約 1 m) では回転面では翼の尖端から 4 m 以上、回転面に直角の方向では面から 1 m 以上の距離になると両翼の影響が合成されて来る。是れより遠距離ではプロペラ全体が一つの音源となる。

翼のピッチ (幾何学的) を変更する事は suction 及び pressure の大きさには影響するが、空気の configuration には変化を生じない。
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Investigations on the Origin of the Sound Emitted by Revolving Airscrews.


By

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(With 10 Plates.)

Abstract.

In continuation of the preliminary experiments, the results of which have already been published, further determinations of pressure-variation - in the vicinity of an airscrew blade were made with scrupulous care in order to eliminate every source of error that was noticed in the previous work. Two-bladed model airscrews were rotated on an isolated stand by means of an electric motor, and the pressure-variation determined by condenser microphones, the smallest one being a miniature microphone of only 14 mm. outer diameter. Pressure variations at a number of
points lying at various distances from the blade were determined, and the configuration of the air in the vicinity of the revolving airscrew accurately determined.

In the models (1/3 or 1/4; diameter about 1 m.) used in the present experiments, the effects of both blades are combined at distances greater than 4 metres from the blade-tip in the plane of rotation and 1 metre from the blade-surface in the direction perpendicular to it. At still greater distances, the revolving airscrew as a whole becomes a source of sound with a wave-form resembling a sine curve.

By changing the geometrical pitch of the blade, only the magnitude of the suction or pressure is affected, no change being observed in the configuration of the air, that is, the distribution of the suction- and pressure-centres.

Directional properties of the airscrew sound will be dealt with in a forthcoming paper of ours.

Introduction.

The sound of a rotating airscrew consists of three components: (1) the sound of rotation—that due to pressure difference in the two sides of the blade, —(2) the sound due to vortices produced by the blade, and (3) the sounds emitted by the elastic vibrations of the blades and shaft. The preliminary experiments that were made by us some time ago with a view to ascertain the origin of the sound of rotation, that is to trace the various stages in connection with the formation of the sound, were published in an earlier paper(1).

In those preliminary experiments, a model airscrew was rotated with an electric motor, and the pressure-variation quite close to the blade determined; that is, a condenser microphone of ordinary size was placed near the blade and the pressure-variation both before and after the moment the blade crossed the front of the microphone was recorded by means of an amplifier and an oscillograph.

As stated in the previous paper, the microphone used was a fairly large one of 10 cm. outer diameter, so that the recorded pressure-variations could not have corresponded to those produced when the micro-

phone was not present. Moreover, since in the previous experiments the model airscrew was rotated near a large hard wall of a building, it is obvious that the reflections from the wall might have influenced the results; the experiments were conducted only in the space quite close to the airscrew blade; the results were consequently inadequate for tracing the various stages in the formation of the sound.

Since accurate measurement of the pressure-variations in the vicinity of the airscrew blade is of importance not only in tracing the origin of the airscrew sound, but in that it may throw much light on the nature of the action of the airscrew itself, further exhaustive experiments were made after eliminating all the sources of error just mentioned. The present paper contains the results thus obtained. In order to avoid the effects of wall reflection, the model airscrew was rotated on an isolated stand, and a miniature condenser microphone of only 14 mm. outer diameter was used for determining the pressure-variation in the space quite close to the blade.

Further, in connection with tracing the various stages of the formation of the sound, the directional properties of the sound were also studied in detail, the results of which will be published at no distant date.

Experiments.

Of the various model airscrews used in previous experiments, only two—Reed metal II and Kármán type metal—were used in the present experiment, the former being a one-third model made by twisting thin duralumin plate and the latter a one-fourth model made by shaving forged metal (duralumin). The shapes of these airscrews are shown in

(1) The air-flow near an airscrew was studied photographically by Prof. A. Tanakadate more than twenty years ago [Comptes Rendus, 151 (1910) 211], and quite recently T. Suhara and others studied the same problem by means of an ultra-high-speed cinematograph for an airscrew revolving with various tip-speeds up to 525 m/sec. [Journ. Aeron. Res. Inst., No. 115 (March 1934), 80; in Japanese].
Fig. 1, the dimensions of the original airscrews being as shown in the following Table:

<table>
<thead>
<tr>
<th>Airscrew</th>
<th>Diameter</th>
<th>Pitch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reed II</td>
<td>2.95 m</td>
<td>2.50</td>
</tr>
<tr>
<td>Karman</td>
<td>3.00</td>
<td>Variable</td>
</tr>
</tbody>
</table>

Fig. 1. Shapes of the model airscrew.
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Fig. 2. Rotating arrangement.

Fig. 3. Support of the miniature microphone.
The arrangement for rotating the model airscrew as well as that for supporting the miniature condenser microphone are shown in Figs. 2 and 3. A 10-H.P. electric motor, made as noiseless as possible, was set on an isolated concrete stand, the height of the shaft being 2-1 metres from the ground. Condenser microphones of three different sizes, 14, 13, and 75 mm. in outer diameter, were used for recording the pressure-variations in the vicinity of the blade or the sound at distant positions. All these microphones were constructed in our workshop, and carefully calibrated with the aid of a Rayleigh disc. The frequency-characteristics of the microphones are shown in Fig. 5; their constructional details will be published elsewhere.

(From left to right) 75 mm. microphone, 14 mm. microphone, the same mounted, 33 mm. microphone mounted.

Fig. 4. Microphones.

The smallest or miniature microphone, the sensitivity of which is naturally low, was used for recording the intense pressure-variations quite close to the rotating blade, and the largest one for recording pressure-variations or sounds several metres away from the airscrew,
while the medium 33 mm. sized one was used at positions intermediate between these two extremes. As shown in Figs. 2 and 3, the miniature microphone was placed in position by means of a long steel tube projecting from an iron frame work. The first-stage amplifier, which was contained in a very small brass box, was attached to the frame work by means of springs, and a long shield cable was used to connect it to the main amplifier and the oscillograph set in the laboratory room.

![Graph of Frequency Characteristics of Microphones](image)

143: 14 mm. microphone.  
754: 75 mm. microphone.  
332: 33 mm. microphone.

Fig. 5. Frequency characteristics of the microphones.

Both in the front- and reverse-sides(1) of the blade, the microphone was always placed facing the blade; while in the plane of rotation it was placed perpendicularly to the plane. Records were also obtained in the plane of rotation by directing the microphone to two other directions. No difference however was found when they were compared with that obtained by placing it perpendicularly to the plane, that is, by directing it towards the tip of the blade.

In the previous experiment the resonant frequency of the microphone was one of the sources of annoyance. As will be observed in Fig. 5,

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(1) The space on the side of the blade facing the direction in which the airscrew would proceed is called the "front-side" and the other the "reverse-side".
no such trouble was found in the miniature microphone used in the present experiment, its frequency-characteristic being fairly flat in the frequency region here dealt with.

Pressure-variations at more than fifty different points were recorded for the Reed II model. Positions of the greater part of these points are shown in Fig. 6, those of very distant points being omitted. At points less than 60 cm. from the blade tip, the miniature microphone was employed, while at greater distances than this the large microphones were used. Thus, for the Reed II model, the experiments were carried out in considerable detail, while for the Kármán type model, pressure-variations only at the most important positions were recorded at three different geometrical pitches of the blade, namely, 0° and ±5°. By means of electrical contacts made on the airscrew shaft, the instant at

![Fig. 6. Recorded positions (Reed II).](image-url)
which the blade crossed the front of the microphone was recorded together with the pressure.

More than one hundred records of pressure-variation were thus obtained, some of which are reproduced in Fig. 7, Pl. 8-17.

**Results.**

As to the general nature of the pressure-variations no difference was of course found compared with that obtained in the previous experiments, so that the results previously obtained will be briefly described.

Fig. 8 shows the general character of the pressure-variations both before and after the moment the blade crossed the front of the microphone, in the front- and reverse-sides as well as in the plane of rotation. It will be seen, that in the fron-side the initial impulse is suction, which changes to pressure as soon as the blade crosses the front of the microphone. The order is contrary in the reverse-side, that is to say, pressure comes first in the side to which the slip-stream flows out. In the plane of rotation, the impulse is simply suction.

![Diagram showing pressure variations](image-url)

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**Fig. 8.**

Instant at which the blade crosses the front of the microphone.
Since, in the present experiments a miniature microphone was employed, the record may be regarded as accurately giving the pressure-variation at each point, that is to say, the maximum values of the suction and pressure, as well as the instant at which they attain the largest values, can be very accurately determined for each position.

In the records or oscillograms reproduced in Fig. 7, Pl. 8-17 the horizontal direction is the time-axis, and as will be observed, the time-interval between the maximum suction and maximum pressure is usually of the order of one-thousandths of a second, being shortest at a point 8.3 cm. inwards from the tip, where the amount of pressure-variation is also the largest.

In plotting the results in graph, the distance, instead of the time, traversed by each point, was taken as one of the variables, and the manner of the pressure-variation determined for various positions in the front side along a line 5 cm. from the blade in the horizontal plane containing the airscrew shaft is given in Fig. 9. The results of similar determinations for the reverse-side are shown in Fig. 10. The circles in Figs. 9 and 10 are the paths traversed by each point, the distance of which from the tip are given on the horizontal line, the scale along the circular path being the linear distance from the horizontal position. Thus, the records or oscillograms reproduced in Fig. 7, Pl. 8-17 indicate the relations between the time and the pressure-variation, whereas the diagrams given in Figs. 9 and 10 are the relations between the distance and the pressure-variation.

As just mentioned, the time-interval between the two events—maximum suction and maximum pressure—differs with the measured point, being shortest at a point 8.3 cm. from the tip. On the other hand, the linear distance between these two events is, as shown in Figs. 9 and 10, almost the same at every point quite close to the blade. It becomes larger as the point recedes farther outwards from the tip, the magnitude of the pressure-variation naturally becoming smaller with increased distance from the tip. In other words, Figs. 9 and 10 may
be regarded as showing the configuration of the air in the vicinity of the blade (in the vertical planes, 5 cm. from the blade in the front- and reverse-sides). Or it may be conceived that the blade in its revolution follows such configuration of the air around it.

As will be seen from Fig. 7, Pl. 8-17, the pressure-variations are very accurately recorded for the front-side, definite results being obtained as just mentioned. In the case of the reverse-side, however, the pressure changes rather indefinitely on account of the slip-stream, the pressure-variations thus occurring at instants other than those in which the blade crosses the front of the microphone. In the configuration of the air in the reverse-side of the blade (Fig. 10), it is interesting to note that the maximum pressure occurs some time preceding that instant when the blade crosses the front of the microphone.

Since owing to the very complex nature of the configuration of the air around the blade, the reader may experience some difficulty in getting a clear conception of the aerial configuration merely from Figs. 9. and 10, to make it clearer, a cross-sectional view based on the same data is shown in Fig. 11.

It will be seen from Figs. 9 and 10, that in the space outside the blade-tip, the suction-centres gradually fall behind the blade as the distance from the tip increases; that is to say, the instant of maximum suction gradually approaches that in the revers-side, whereas the pressure-centres in the front-side, fall similarly behind the blade, separating farther and farther from those in the reverse-side.

As already shown in Fig. 6, pressure-variations at a considerable number of positions were determined, the results here given having been derived from these numerous data, although, in order to avoid confusion, only a few of them are shown in Figs. 9 to 11.

From the determination of the frequency-characteristic of the microphone, its absolute sensitivity for pure tone was estimated as 0.6 mm/bar at 800 hertz and 0.45 mm/bar at 2000 hertz, the scale being the deflection on the oscillographic record. Although the pressure-variation here
Reed II. [Front-side]

Fig. 9. Pressure-variations at various positions.
Reed II.  [Reverse-side]

Fig. 10.
dealt with is an impulse and not a continuous sound wave, in deriving the foregoing results the sensitivity of the microphone for such impulse was assumed to be the same as that for a continuous sound-wave having a period or wave-length equal to the duration of the impulse.

Reed II. Cross-sectional view.

Fig. 11.

Further, it should be mentioned in this connection that in taking the oscillograms reproduced in Fig. 7, Pl. 8–17, the sensitivity of the recording arrangement was so adjusted by changing the notch in the input potentiometer of the amplifier that sufficient deflection was obtained on the film. Hence, the amplitude on the oscillogram does not directly correspond to the actual pressure.
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Distance from the tip.

Kármán 0°. [Front-side]

Fig. 12.
Distance from the tip.

Kármán 0°. [Reverse-side]

Fig. 13.
Figs. 12, 13 and 14 show results of similar determinations for the Kármán type model at three different geometrical pitches, namely, 0° and ±5°.

Owing to the irregular shape of the Reed II airscrew, the pressure-variation in the space outside the tip is fairly indefinite, especially in the reverse-side. In contrast to it, in the Kármán type airscrew, which has a smooth shape, much more definite pressure-variation was found.

Throughout the present experiments the number of revolution was always 2500 r.p.m. The Reed II model consumed 45 amperes (at
200 volts), and the Kármán type model consumed 40, 30, and 23 amperes at geometrical pitches of +5°, 0°, and -5°, respectively. The absolute magnitude of the pressure-variation was found roughly correspond to the consumed current or power.

**Pressure-Variation in the Plane of Rotation.** The pressure-variations in the plane of rotation were determined at various points from 2.5 cm. to 5 m. from the blade-tip along a horizontal line passing through the axis of revolution, the results for the Kármán type airscrew being summarized in Fig. 15.

In the plane of rotation, the impulse is simply a suction, which does not change to pressure, and as shown in the following Table, the magnitude of the impulse (suction) was found to decrease inversely proportional to the square of the distance from the blade-tip.

<table>
<thead>
<tr>
<th>Distance from the tip</th>
<th>Maximum suction</th>
<th>Distance from the tip</th>
<th>Maximum suction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reed II airscrew</td>
<td>Kármán type airscrew (Pitch 0°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 cm</td>
<td>2020 bar</td>
<td>2.5 cm</td>
<td>1440 bar</td>
</tr>
<tr>
<td>5</td>
<td>980</td>
<td>5</td>
<td>460</td>
</tr>
<tr>
<td>10</td>
<td>380</td>
<td>10</td>
<td>160</td>
</tr>
<tr>
<td>20</td>
<td>104</td>
<td>20</td>
<td>23</td>
</tr>
<tr>
<td>30</td>
<td>56</td>
<td>40</td>
<td>9.7</td>
</tr>
<tr>
<td>40</td>
<td>30</td>
<td>80</td>
<td>4.6</td>
</tr>
<tr>
<td>60</td>
<td>17</td>
<td>200</td>
<td>1.1</td>
</tr>
<tr>
<td>100</td>
<td>9.1</td>
<td>400</td>
<td>0.5</td>
</tr>
<tr>
<td>200</td>
<td>4.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>1.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In Fig. 15, however, the impulses at all points are shown in the same scale, the items here dealt with being only the duration of the impulse and the time-lag of the instant of maximum suction behind that instant the blade crosses the front of the microphone. It will be observed in Fig. 15, that the duration of the suction increases as the distance,
becoming almost equal to the half period of revolution at a point 4 metres from the blade-tip. Thus, upon going farther from this point, the suction becomes rather indefinite, showing that the action from both blades is combining at such great distance.

Utilizing the knowledge of the time-lag of the suction-centres, an effort was made to determine the velocity of propagation of the suction-centre. This velocity being very large in the vicinity of the blade, a very accurate knowledge of the instant when the blade passes the horizontal position is necessary for determining its value, which, however, not being easily obtained, no more definite statement is possible than that in the space within 2 metres from the blade-tip, the impulse propagates with a velocity greatly exceeding that of sound.

*Plane of rotation. Karman [90].*

*Fig. 15.*
Fig. 16. Kármán: [0°].
Effect of Distance from the Blade, in the Front-and Reverse-Sides.

Finally, similar determinations were made along lines perpendicular to the plane of rotation. In the front-side, experiments were carried out along a line passing through a point 8.3 cm. (inwards) from the blade-tip (the point of largest pressure-variation), while in the reverse-side the microphone was moved along a line passing through the tip to avoid the effect of slip-stream, the results for Kármán type model being shown in Fig. 16. At a distance of 60 cm. from the blade (i.e. perpendicularly from the plane of rotation), the duration of the suction becomes so long as to reach the period of half revolution; hence the effects of both blades are combined at a greater distance than this. By changing the geometrical pitch of the blade, only the magnitude of the suction or pressure is affected, no change being observed in the configuration of the air, that is, the distribution of the suction- and pressure-centres.

No essential difference was found for Reed II model as compared with the Kármán type airscrew.

From the results so far obtained in tracing the origin of the lower partials of the airscrew sound, it may be concluded that in the models used in the present experiments, the effects of both blades are combined at distances greater than 4 metres in the plane of rotation and 1 metre in the front-side. At still greater distances, the revolving airscrew as a whole becomes a source of sound with a wave-form resembling a sine-curve.

In the present paper the pressure-variations in the vicinity of the airscrew blade, which naturally constitutes the origin of the airscrew sound, has been very thoroughly described. A forthcoming paper of ours will deal with the nature of the airscrew sound, with special reference to its peculiar directional properties.
In conclusion, our best thanks are due to Mr. Y. Yamazaki, who designed the arrangement for rotating the airscrew model and paid very frequent attention for its smooth running, and also to Messrs. U. Anzai and S. Ōuti, who assisted us throughout the experiments.
Front-side. (5 cm. from the blade.)

Distance (inward) from the tip.

35 cm.

Position: 1.

25

Position: 2.

16.6

Position: 3.

8.3


Tip.

Position: 5.

(outward)

5 cm.


10

Position: 7.

15

Position: 8.

Fig. 7(i). Reed II.
Reverse-side. (5 cm. from the blade.)

Distance (inward) from the blade.
8.3 cm.

Position: 14.
Tip.

Position: 15.
(outward)
5 cm.

Position: 16.
(outward)
10 cm.

Reed II.
Fig. 7 (ii).
Front-side. (2.5 cm. from the blade.)

Distance (inward) from the tip.
8.3 cm.

Position: 41.

Tip.

Position: 42.

(Outward)
8 cm.

Position: 43.

Reverse-side. (2.5 cm. from the blade.)

Position: 51.

Tip.

Position: 52.

(Outward)
5 cm.

Position: 53.

(Outward)
8 cm.

Reed II.

Fig. 7 (iii).
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Plane of rotation.  

Distance from the tip.  
2.5 cm.  

Position: 22.  

5  


20  

Position: 27.  

60  


100  

Position: 30.  

400  

Reed II.  
Fig. 7 (iv).
**Front-side.** (Along a line perpendicular to the blade.)

Distance from the blade.

10 cm.

Position: 61.

Position: 62.

15

Position: 63.

20

Reverse-side.

Position: 71.

10 cm.

Position: 72.

15

Position: 73.

20

Reed II.

Fig. 7 (v).
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Front-side. (5 cm. from the blade.)

Position: 2.

Distance (inward) from the tip.
25 cm.

Position: 3.

16-6


8-3

Position: 5. (Tip)

Tip.

Position: 5. (Tip)

Tip.

Position: 7.

(outward)
10 cm.

Kármán. (Pitch: 0°)

Fig. 7 (vi).
Reverse-side. (5 cm. from the blade.)

Position: 11.

Position: 12.


Position: 14.

Position: 16.

Kármán. (Pitch: 6°)

Fig. 7 (vii).
Plane of rotation.


Distance from the tip. 2.5 cm.

Position: 23.


40

{ 14 mm. } (microphone)

Ditto.

40 cm.

{ 33 mm. } (microphone)

200

{ 33 mm. } (microphone)

200

{ 75 mm. } (microphone)

Kármán. (Pitch: 0°).

Fig. 7 (viii).
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Front-side.

Position: 1.

Distance (inward) from the tip.
35 cm.

Position: 2.

25

Position: 3.

16-6


8.3

Position: 5.

Tip.

Reverse.

Position: 10.

Position: 11.

Position: 12.


Position: 14. (Tip)

Kármán. (Pitch: $-5^\circ$)

Fig. 7 (x).