REPORT No. 551

AIRCRAFT COMPASS CHARACTERISTICS

By John B. Peterson and Clyde W. Smith

SUMMARY

A description of the test methods used at the National Bureau of Standards for determining the characteristics of aircraft compasses is given. The methods described are particularly applicable to compasses in which mineral oil is used as the damping liquid. Data on the viscosity and density of certain mineral oils used in United States Navy aircraft compasses are presented. Characteristics of Navy aircraft compasses IV to IX and some other compasses are shown for the range of temperatures experienced in flight.

Results of flight tests are presented. These results indicate that the characteristic most desired in a steering compass is a short period and, in a checking compass, a low overswing.

INTRODUCTION

Liquid-damped compasses have been extensively used in the navigation of surface ships, but it was not until their use in faster maneuvering aircraft that the dynamic characteristics of the card became of foremost importance. Numerous attempts have been made to analyze the motion of the liquid-damped compass card (references 1, 2, 3, 4, and 5), on the assumption that such an analysis would aid in the evaluation of the characteristics that a compass to be used in a specified manner should have. These attempts have yielded only approximate solutions, which have not aided the authors materially in clarifying the problem of the selection of suitable compass characteristics.

The data presented herein were obtained at the request, and with the financial support, of the Bureau of Aeronautics, Navy Department. The National Advisory Committee for Aeronautics furnished the financial support essential for the preparation of the report. The authors wish to acknowledge the close cooperation of W. G. Brombacher, National Bureau of Standards, C. L. Seward, Bureau of Aeronautics, Navy Department, and Ira E. Hobbs, lieutenant, United States Navy.

MOTION OF LIQUID-DAMPED COMPASS CARDS

The effect of the liquid that is carried around by the card is as if there were another disk of varying moment of inertia connected to the magnetic card by viscous friction of varying magnitude. The complicated nature of the motion is indicated by the data presented in figure 1, which shows the motion of a Navy IX aircraft compass card after release from rest at a deflection of 30° (solid line) and after release from rest at a deflection of 10.5° (dotted line). The decrement in successive amplitudes of the first motion is far from constant, an observation not in agreement with the usual simplified theories. Although the card comes to rest at the end of the first overswing of 10.5°, the liquid continues in motion and reduces the second overswing, so that the ratio 10.5:2=5.25 of second to third amplitude is much greater than the ratio 30:10.5=2.86 of first to second amplitude. If the card is held steady at a deflection of 10.5° until the liquid has had time to come to rest and then released, the overswing is 3.7° and the ratio is 10.5:3.7=2.84.

![Figure 1: Time-deflection curves for United States Navy IX liquid-damped aircraft compass at a temperature of 20° C.](image-url)
conclusion that a satisfactory analysis of the motion of the card including all of the factors involved would be extremely complicated.

**OPERATING CHARACTERISTICS**

In the absence of a satisfactory theory, the relation between operating characteristics that can be measured in the laboratory and behavior in flight must be determined empirically. For practical convenience, the operating characteristics of a compass are defined by three constants, which can easily be measured in the laboratory as described below. These constants are:

1. The time of swing 30° to 5°, which is closely related to the period of the compass.
2. The overshwing from 30°, which depends principally upon the relative values of the moment of inertia and magnetic moment of the card and the viscosity of the damping liquid.
3. The swirl, which serves as a measure of the effect of motion of the case on the motion of the card.

Following is a detailed description of the methods used at the National Bureau of Standards for determining these characteristics.

**Time 30° to 5°**

The card is magnetically deflected 30° from its equilibrium position, held at this position long enough for the liquid to come to rest, released, and the time observed for it to pass through an angle of 25° toward its equilibrium position. The same test is repeated, deflecting the card 30° in the opposite direction. The position of the compass should not be changed between the two tests. The average of the observed times is defined as the "time 30° to 5°." The purpose of making observations for deflections in both directions is to average out any error due to incorrect setting of the lubber line with reference to the equilibrium position of the card.

**Overswing**

The card is magnetically deflected 30° from its equilibrium position, held at this position long enough for the liquid to come to rest, released, and the overshwing past the equilibrium position noted. The test is repeated, deflecting the card in the opposite direction. The position of the compass should not be changed between the two tests. The average of the two observations is defined as the "overswing." In practice it is convenient to combine the test for the time 30° to 5° and for the overshwing.

**Swirl**

The compass is mounted on a motor-driven turntable, and turned through an angle of 90° at a rate of 30° per second. During the turn, a swirling motion is transmitted to the damping liquid, and some of this motion is transmitted to the card. The maximum deflection of the card from its true position, which occurs after the turn has been completed, is noted and defined as the "swirl."

These three operating characteristics are affected in the first order of magnitude by two variable factors, (1) the temperature and (2) the horizontal magnetic field strength. It has been determined by experiment that temperature affects only the viscosity and density of the damping liquid. Temperature has a negligible effect on the magnetic moment of the permanent magnets. The International Critical Tables give 0.0002 per degree centigrade as the temperature coefficient of magnetic moment of cobalt magnet steel. This amount to a change of 1 percent for a 50°C change in temperature. The magnetic moment increases as the temperature is decreased. Variation of the operating characteristics with viscosity of the damping liquid is both more conveniently and more accurately determined by filling the compass with mineral oil having the required viscosity at room temperature than by changing the temperature of the compass. It is not necessary to make a separate determination of the effect of density, since the density of the liquids used can be expressed as a function of the viscosity alone.

**DAMPING LIQUIDS**

The method developed by Cragoe (reference 6) for representing changes in viscosity of liquids with changes in temperature and composition has been used. The reader is referred to Cragoe's article for full details of the method, but a short description will be given here. Cragoe has found that, to a very good approximation, a certain function of absolute viscosity (or of kinematic viscosity) for which the name "liquidity" has been suggested, is linearly related to temperature, that its reciprocal is linearly related to pressure, and that a linear mixture rule is applicable to such a function.
where \( \eta \) is the absolute viscosity, and \( \varphi \) is the specific volume, both in cgs units; \( A \) and \( B \) are the same constants in the two equations. The numerical value of \( A \) is \( 5 \times 10^{-4} \) and that of \( B \) is \( 1000 \log_{10} 20 \).

Figure 2 shows the relation between the kinematic liquidity \( L' \), and the kinematic viscosity \( \eta \). The relation between kinematic liquidity and temperature for some representative compass liquids is shown in figure 3.

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Figure 2 shows the relation between the kinematic liquidity \( L' \), and the kinematic viscosity \( \eta \). The relation between kinematic liquidity and temperature for some representative compass liquids is shown in figure 3.

\[
L'' = L_1' + (1 - x)L_2'
\]

\( L'' \) = the kinematic liquidity of the mixture.

\( L_1' \) and \( L_2' \) = the kinematic liquidities of the component liquids.

\( x \) = the fraction by weight of component No. 1.

The rule does not, however, apply to mixtures of alcohol and water as will be seen by reference to the curves for these liquids in figure 3. The viscosity data on alcohol and water have been taken from Bingham and Jackson (reference 7).

Figure 4 shows that except for the alcohol-water mixtures, which also showed an anomalous behavior in figure 3, the density is a single-valued function of the liquidity for all the liquids considered. In other words, the density of the damping liquid varies with the liquidity, independent of the particular mineral oil used. For example, if the liquidity of vacuum oil at \(-15^\circ C\), is equal to the liquidity of mineral spirits at \(15^\circ C\), the densities are also approximately equal.

The data at \(16^\circ C\) shown in figure 4 were obtained by actual measurement of the density and liquidity of damping liquids. The densities at \(-15^\circ C\) and \(40^\circ C\) were extrapolated on the basis of the value at \(16^\circ C\).

**Figure 2.** Temperature-liquidity curves for compass damping liquids.

**Figure 4.** Density-liquidity curves for compass damping liquids.
FIGURE 5.—Characteristics of United States Navy NBII aircraft compass.

FIGURE 6.—Characteristics of United States Navy IV aircraft compass.

FIGURE 7.—Characteristics of United States Navy V and VA aircraft compasses.

FIGURE 8.—Characteristics of United States Navy VI and VIA aircraft compasses.

FIGURE 9.—Characteristics of United States Navy VB and VC aircraft compasses.

FIGURE 10.—Characteristics of United States Navy VII aircraft compass.
FIGURE 11.—Characteristics of United States Navy VII and VIIIA aircraft compasses.

FIGURE 12.—Characteristics of United States Navy VIIIB aircraft compass.

FIGURE 13.—Characteristics of United States Navy VIII aircraft compass.

FIGURE 14.—Characteristics of United States Navy IX aircraft compass.

FIGURE 15.—Characteristics of United States Army B8 aircraft compass.

FIGURE 16.—Characteristics of United States Army D4 aircraft compass.
Figure 17.—Characteristics of KT6S aircraft compass.

Figure 18.—Characteristics of KT6S aircraft compass.

Figure 19.—Characteristics of British 8.10 aircraft compass.

Figure 20.—Characteristics of Morel Petits model 28 aircraft compass.

Figure 21.—Characteristics of Debris type 800 aircraft compass.

Figure 22.—Effect of magnetic field intensity on the characteristics of Navy VB aircraft compass at 20° C.

Figure 23.—Effect of magnetic field intensity on the characteristics of Navy V19 aircraft compass at 20° C.
Aircraft Compass Characteristics

Liquidity, the trade names and liquidities of which are:

- Kinematic
  - Spirit - 420
  - Oil - 470
  - Mineral spirits - 800
  - Vacuum oil - 935

A liquid of any intermediate liquidity may be obtained by mixing two of these mineral oils in the proportions given by Cragoe's equation for mixtures. Although the foregoing figures are representative, the liquidities of individual samples have been found to vary as much as ±5 percent.

### Magnetic Field Strength

The standard horizontal magnetic field strength at which the time of swing, overswing, and swirl were measured, was 0.18 gauss, which is an average value for the United States. In order to give an idea of the variation in characteristics to be expected from variation in horizontal field strength, two representative compasses were tested at field strengths between 0.06 and 0.42 gauss. The characteristics of the two compasses for this range of field strength are shown in figures 22 and 23.

### Magnetic Moment

A modification of the method described by Sanford (reference 9) for measuring the magnetic moment of a compass without arresting the card was employed. In the method a magnetometer is used to measure the change in the strength of the magnetic field caused by the presence of the compass.

The magnetometer is a short piece of magnetized cobalt steel suspended from a phosphor bronze strip at the center of a coil of known dimensions. The magnetometer is set up so that the axis of the coil is horizontal and parallel to the magnetic meridian. A torsion is applied to the suspension to cause the magnet to take a position perpendicular to the magnetic meridian and perpendicular to the axis of the coil, which will be called the "zero" position. When

### Table I

<table>
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<td>IV</td>
<td>V</td>
<td>VB</td>
<td>VI</td>
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<td>2</td>
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<td>200</td>
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<td>10.5</td>
<td>10.5</td>
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<td>15.4</td>
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<td>Card weight in liquid, grams</td>
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<td>M</td>
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<td>M</td>
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<td>625</td>
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</table>

A. Type S, Q, 2 large compass (British).
B. Morel-Pont model 20 compass (French).
C. Deffie type 500 compass (French).
D. Mineral oil.
E. 50 percent ethyl alcohol (by weight).
F. 50 percent ethyl alcohol (by weight).

Magnetic moment for each type of compass, as derived by this procedure, is given in table I.

### Flight Tests

In Navy practice there are two distinct uses of a compass. It may be used as a steering indicator, the pilot steering the airplane according to its indications. It may be used as a checking compass to check occasionally the course of an airplane that is being steered on a straight course according to the indications of a directional gyro.

In an attempt to compare compasses of different characteristics in flight, a series of tests were made on compasses in pairs. As representative of the results
obtained in this series of tests a part of the comparative
tests on Navy IV and VIB compasses are shown in
figures 24 and 25. In the steering tests the pilot
steered by the compass and an observer took about
30 readings per minute on a directional gyro. In the
checking tests, the pilot steered by the directional
gyro and an observer took readings on the compass.

Each compass was tested on north and on south
courses, both as a steering compass and as a checking
compass. As a steering compass, the performance is
worse on a north course because of the northerly
turning error. When an airplane turns from a north
course, the centrifugal acceleration of the turn causes
the compass card to tilt out of the horizontal position
into such a position that the earth's vertical magnetic
field will cause the card to deflect in the direction in
which the airplane has turned. It is easily possible
for the card of any unstabilized compass to turn faster
than the airplane, indicating to the pilot a turn in the
opposite direction. At the magnetic equator there is
no northerly turning error and south of the magnetic
equator the southerly turning error becomes trouble-
some.

The results of these tests are shown in table II. The
values given are the average deviations of the readings
from a straight line faired between the plotted points.
Comparisons should be made only between two com-
passes of the same pair, because another pair may have
been tested at another time when the air may have
been rougher or smoother. It is assumed that the air
conditions remained constant during the time required
to test one pair.

Although definite conclusions should not be drawn
from the results of the few tests presented here, there
is a strong indication that the short-period compass is
ter for steering and the long-period compass with a
low overswing is better for checking. It is the belief
of the authors that the yawing oscillations of an air-
plane being steered according to the indications of a
compass may vary greatly with different pilots. Prac-
tically all of the flight data of this report were obtained
by the junior author and by Ira E. Hobbs, lieutenant,
United States Navy. It is very desirable that flight
tests be continued with other compasses, other pilots,
and automatic pilots. Probably also, photographic
methods of recording the instrument readings should
be utilized.

The results of these flight tests can be explained on
the basis of the difference in the periods of the compass
and the yawing of the airplane. An airplane steering
on a north course, according to the indications of a
compass, oscillates with a period longer than the period
of the compass, while an airplane steered according to
the indications of the relatively stable directional gyro
oscillates with a period shorter than the periods of the
compasses in this group. The curves of figure 24 show
clearly that the period of the yawing oscillation of the
airplane steered according to the indication of a com-
pass on a north course is much longer than the period
of the compass by which it is being steered (approxi-
mate periods, airplane, 60 seconds; compass IV, 19
seconds; compass VIB, 30 seconds).

<table>
<thead>
<tr>
<th>Compass</th>
<th>Time, 50° to 5°</th>
<th>Overswing</th>
<th>Swirl</th>
<th>Steering error</th>
<th>Checking error</th>
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<td>8.0</td>
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<td>1.1</td>
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<td>6.5</td>
<td>3.1</td>
<td>2.4</td>
</tr>
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TABLE II
RESULTS OF FLIGHT TESTS ON COMPASSES
FIGURE 25.—Summary chart, time of swing against temperature.

FIGURE 26.—Summary chart, time of swing against liquidity.

FIGURE 27.—Summary chart, overswing against temperature.

FIGURE 28.—Summary chart, overswing against liquidity.

FIGURE 29.—Summary chart, swirl against temperature.

FIGURE 30.—Summary chart, swirl against liquidity.

FIGURE 31.—Summary chart, swirl against liquidity.
DISCUSSION

The curves for time of swing, overshwing, and swirl shown in figures 5 to 21, for the individual compasses are summarized from various points of view in figures 26 to 34. Figures 26, 27, and 28 show the variations of time of swing, overshwing, and swirl with temperature. Figures 29, 30, and 31 show the variations of the same quantities with liquidity. Figures 32, 33, and 34 show the variations of time of swing, overshwing, and swirl, one relative to the other. The variations in the characteristics were obtained by varying the liquidity of the damping liquid.

It is very probable that low time of swing, low overswing, and low swirl are desirable characteristics for good performance in flight. These requirements are not simple to meet because low overshwing and low swirl are conflicting requirements as may be seen in figure 34. Low overshwing may be obtained by the use of weak magnets and a viscous damping liquid but their use causes a long time of swing and a high swirl. A low swirl and a short time of swing may be obtained by the use of strong magnets and a thin damping liquid of low viscosity but a high overshwing is thereby produced.

Opposite extremes of performance are shown in figures 32, 33, and 34 by the British S. O. 2. compass and the French Morel Petit model 28 compass. The low overshwing and low swirl of the S. O. 2. compass are obtained by the use of an extremely light and relatively fragile magnetic card. It has been the experience of the authors that this instrument is too fragile for service use. The magnetic moment is so low that the pivot must be in perfect condition if excessive friction is to be avoided. On the other extreme, the Morel compass has a very heavy floated card and a high magnetic moment. Practically all American compasses have characteristics between the British and French extremes. Of the American compasses in this report, only the Navy VIII and IX and the two KT compasses have cards with floats.

The curves of figures 32, 33, and 34 are an aid in the selection of compasses for flight tests. As an example of the use of these curves it will be seen that by a suitable choice of damping liquids the Army B8 and Navy VIB compasses may be given any of the following characteristics at any selected temperature of the compass.

The chief reason for the difference in characteristics of the B8 and the VIB is the difference in size of the card. The B8 card has a diameter of 1¾ inches and the VIB card has a diameter of 4 inches. The clearance
between the bowl and the card is approximately the same for both compasses.

<table>
<thead>
<tr>
<th>Compass</th>
<th>Time 30° to 5°</th>
<th>Over-swing</th>
<th>Swirl</th>
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<tr>
<td>B5</td>
<td>8.0</td>
<td>8.4</td>
<td>15</td>
</tr>
<tr>
<td>VIB</td>
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**REFERENCES**


**NATIONAL BUREAU OF STANDARDS, WASHINGTON, D. C., December 14, 1935.**