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No. 610

OPTICO-PHOTOGRAPHIC MEASUREMENTS OF AIRPLANE DEFORMATIONS

By Hans Georg Küssner

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OPTICO-PHOTOGRAPHIC MEASUREMENTS OF AIRPLANE DEFORMATIONS*

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Summary

The deformation of aircraft wings is measured by photographically recording a series of bright shots on a moving paper band sensitive to light. Alternating deformations, especially vibrations, can be thus measured in operation, unaffected by inertia. A handy recording camera, the optograph, was developed by the static division of the D.V.L. (German Experimental Institute for Aeronautics) for the employment of this method of measurement on airplanes in flight. The optograph has several long-distance lenses simultaneously adjustable in any desired position. The paper band runs on interchangeable reels with constant, adjustable speed. The points of measurement are marked by glowlamps or triple mirrors. The method is illustrated by examples.

I. Object of Tests in Operation and Critical Survey of Methods

The dimensioning of airplane wings has hitherto been

*"Optisch-photographische Formänderungsmessungen an Luftfahrzeugen," From Zeitschrift fur Flugtechnik und Motorluftschiffahrt, Sept. 15, 1930, pp. 433-440.

based on the calculation of the stresses and deformations under static loads. Dynamic stresses due to inertia or other variable forces were assumed, when they could be calculated, to have a constant action on the wing structure. When, however, their magnitude was indeterminate, they were covered by an empirical safety increment to the static load.

The desire to reduce the weight and cost of static construction by a better utilization of materials (a problem of vital importance to aircraft) led to the idea of measuring the stresses actually produced in operation. Such measurements had already been made at an earlier date on railway bridges and airplanes.* It was proposed thus to check the validity of the assumptions made for static calculations and to investigate the stresses produced by vibrations and impact forces more thoroughly than had been done before.

The only method of investigation used in operation was the measurement of the elongation of a small experimental length marked on the investigated member. The following methods must be distinguished according to the kind of elongation measurement.

1) Mechanical direct-reading elongation-measuring device with lever transmission, of Huggenberger, Martens-Kennedy, etc.** This method can be used only when the points of measurement are

*W. Hoff, "Die Festigkeit deutscher Flugzeuge," Berichte und Abhandlungen der WGL, No. 8, 1922.

**Steuding, "Messung mechanischer Schwingungen," p. 290.

readily accessible and elongation occurs slowly.

2) Mechanical scratch-recording elongation-measuring device of the D.V.L. type.* It has a greater length of measurement, but no lever transmission. The elongation is scratched with a diamond on a glass or steel plate and measured later with a special microscope.

3) The acoustic distance elongation-measuring device of Schäfer is used, when the points of measurement are not readily accessible.** This method is based on the fact that the pitch of a wire stretched along the test distance varies with the tension. The wire is set in vibration by an electromagnet. The pitch is heard by telephone and compared with an adjustable reference pitch. The pitch of several points of measurement can also be recorded simultaneously by a multiloop oscillograph. This method is used for the measurement of variable phenomena, when the natural vibration of the wire is not disturbed by excessive vibration of the investigated member.

4) The purely electrical-resistance and electrical-capacity methods, for the measurement of high-frequency elongation variations, are based on the change in the resistance of a carbon element*** inserted in the measured length, or on the variation in the capacity of a pair of parallel plates. The variations in several points of measurement are again

*Zeitschrift des V.D.I. 1929, p. 1629.

** Zeitschrift des V.D.I. 1928, p. 1810.

***Steuding, "Messung mechanischer Schwingungen," p. 301.

simultaneously recorded by a multiloop oscillograph. The determination of the points of measurement, the calibration of the tested members and the maintenance of the amplifying units required by this method consume much time and need to be improved.

Only purely mechanical methods have been hitherto successfully used for elongation measurements on starting and flying airplanes. In many cases, however, it is not necessary to investigate the details of the local stress distribution, secondary stresses, etc. in operation, since better results can be obtained by static load tests or by model tests. Tests in operation are rather desired to afford information on the magnitude of the external forces and on the total deformation of the static structure. So long as the frequency of the external forces lies far enough below the natural frequency of the structural components (which is usually the case) the total deformation of the structure gives a better idea of the magnitude of the stresses than a small number of elongation measurements.

II. Optico-Photographic Method of Deformation Measurement

Static structures, such as bridges, boats, airplanes, which require testing in operation, are usually built in such a man- that it is possible to sight along their trusses in the direction of the main axes. Owing to perspective shortening, the deflection of the loaded beam is often visible by sighting prominent points with the naked eye. The optico-photographic method is therefore well suited for measuring the total deformation in operation. It is unaffected by inertia and independent of fixed reference systems. In view of these advantages, it should not be difficult to overcome the often prevalent but no longer justifiable prejudice against the use of photographic methods.* The motion of the points of measurement should be continuously recorded during investigations in operation. Clear photoprints of these points on the sensitive recording band can thus be obtained only when they are much brighter than their surroundings. The method of marking the points by glowlamps was therefore adopted. Figure 1 shows the lamps which were fastened for this purpose to the wing spar of a large airplane. They were arranged in steps, so as to avoid interference between the points of measurement on the recording band. Figure 2 shows the arrangement of the glowlamps on the wing of a Junkers G 24 commercial airplane.

The simultaneously sharp photographic reproduction of several widely separated points of measurement is only possible when the focal length is very small in comparison with the distance of these points. However, the displacements of these points on the recording band will then be so small, that they can not be easily measured. Therefore, the focal length of

*This method was first applied to vibration measurements by J. Essers-Kober in the Aerodynamic Division of the D.V.L. (See Luftfahrtforschung, Vol. 4 (1929), p. 107, and 1929 Yearbook of the D.V.L. p. 345).

the lens must not be too small. It should be from 2 to 4% of the mean distance to the points of measurement. In this case, when the camera is exactly focused for a mean distance s, the points located within the range of 0.5 to 1.5 s will also be reproduced with sufficient sharpness on the recording band, provided low-voltage lamps with very short filaments are used and the aperture of the lens is reduced. The maximum depth is reached with an aperture of about 1/70 of the focal length.* Daylight work therefore requires a small aperture, because, otherwise, the lighted background reflects too much diffused light into the camera and darkens the recording band. In outdoor work, reduction of the aperture does not always sufficiently protect the recording band against darkening. In such cases yellow glass plates are placed in the path of the rays. They absorb the blue light from the sky more than the light from the glowlamp.

As already mentioned, the solution of the problem depends chiefly on the difference between the brightness of the lamps and of the background. It is therefore advisable to use glowlamps with very short filaments and to supply them with a stronger current during the test, even at the risk of burning them out more quickly. The white light of the incandescent filaments is particularly efficient in photographic work. The method proved to be practical for various measurements described

*H. Harting, "Die photographische Optik," 2nd edition, p. 83.

below. The weak point of the method is its limited depth of focus, which, however, can be increased by a simultaneous use of several lenses focused for different distances. A greater handicap is the fire hazard due to the electric wiring when the points of measurement are on the inside of an airplane or airship. Danger of explosion may arise in such cases, due to the accumulation of fuel vapors or gas, therefore calling for particularly careful and tedious installation of the electric wiring. These disadvantages can be overcome by the use of "triple mirrors" for marking the points of measurement. A triple mirror consists of three mirror surfaces vertical to one another. It is a corner portion of an accurately ground-glass cube characterized by parallel reflection of all incident light rays. For this reason triple mirrors are also used for signaling.

A light ray thrown by the photographic lens P (Figs. 3 and 4) through the deflecting mirror U on the triple mirror T, is reflected in the opposite direction, passes by the deflecting mirror U (or through it when semitransparent silver plating is used) and produces an image of the lamp L on the recording band R. If the triple mirror is moved, the image travels a corresponding distance on the recording band, but (unlike ordinary mirrors) independently of any incidental rotations of the mirror axis.

If several points are at various distances from the camera, they can all be sharply focused on the recording band, when the respective triple mirrors are provided with suitable focusing lenses V. When the camera lens is exactly focused on an infinitely remote object, the focal lengths of the focusing lenses must equal twice the distance of the triple mirrors from the source of light. The light rays from the triple mirror are then parallel. Since the lens is also adjusted to parallel light rays, it produces sharp images of the points of measurement or rather of the source of light. When the points of measurement are not very remote, the sharpness of the images depends chiefly on whether the source of light is as small as possible. Hence the focal lamp should also have a very short filament. A dismantled focal lamp is shown in Figure 4.

III. The Optograph

A special handy camera, the optograph (Figs. 6 & 7), was developed for the application of this method to measurements on aircraft in flight. The front of a light-metal casing 0 is covered with a revolving head 1, having 7 openings with ball-race sockets 3, in which the lens mounts are rotatable in all directions and can be secured in any position. For recording relatively small displacements, lenses of up to 2 m (6.5 ft.) focal length are used, the photographic field being correspondingly small. Several lenses must sometimes be used simultaneously and secured in different positions for the purpose of recording several unequally remote points of measurement. The only way to fulfill this requirement, without using too much material, is to use long-distance lenses of 0.4 to 2 m focal length. Like the Galilean telescope, the long-distance lens consists of a converging and a diverging system of lenses with focal lengths f_1 and f_2 respectively (Fig. 5). The distance between the two focuses is the optical interval Δ. The focal length of the system is then

$$F = \frac{f_1 \, f_2}{\Delta} = \frac{f_1}{f_2} (K + f_2),$$

where K is the constructive important distance between the diverging lens and the focal plane. At the position of the diverging lens the rays are strongly converged. When the diverging lens is located near the point of insertion of the lens mount, the diameter of the ball-race sockets 3 can be reduced so far, without diminishing the width of the photographic field, that several lenses covering jointly a field of 30° can be mounted side by side. Even then the distortion of the image by the oblique rays is less than 3%. In addition to this advantage, long-distance lenses enable a considerable reduction in the length of the optical system. For ordinary lenses $L = F$, while, for long-distance lenses,

$$L = f_1 + \frac{K^2}{K + f_2} \sim 0.4 \text{ to } 0.6 \text{ F}.$$

The use of long-distance lenses reduces the dimensions of the camera, which is particularly desirable for airplane work.

Increased recording errors are a disadvantage of long-distance lenses. The errors remain within admissible limits, only when certain minimum requirements regarding the focal-length ratio and the photographic angle are met. The relatively small aperture of long-distance lenses, of only 0.1 to 0.02 of the focal length, does not unfavorably affect the photographing of the bright spots, since their luminous intensity depends only on the diameter of the entrance aperture. A greater luminous intensity is often detrimental and must be reduced by reducing the aperture. An entrance diameter of 40 mm (1.57 in.) was found sufficient for a speed of the paper band of 2 to 100 mm/sec. (0.08 - 3.94 in./sec.).

The exact focusing of the image with long-distance lenses is greatly facilitated by the fact that the focal length F is adjustable within wide limits by slight displacements of the converging system of lenses, i.e. by a variation of the optical interval Δ. In order to obviate the necessity of determining, each time, the scale of reproduction of the lens, certain points of measurement should be provided with double marks of known interval, from which the scale directly follows.

The photographic lenses record the luminous marks as dots on a band of sensitized paper which runs in the holder 5. The latter is interchangeable and is held tightly against the housing 0 by the clamping plate 6. A ground-glass focusing screen is used for the adjustment of the lenses.

The paper band runs from a supply reel 7 (Fig. 7) over a guide reel 10 to a receiving reel 8, reels 8 and 10 being driven by an electric motor 14 over the spur wheel 12 and the friction wheel 13 in such a manner that the speed of the paper band is constant during the test. In passing over reels 8 and 10 the paper band is kept taut by the brake 11, on the one hand, and by the slide clutch 9 (two slotted tubes engaged by friction), on the other hand (Fig. 8). After the test, the holder is closed by slide 16. It can now be lifted out, after releasing the clamp plate 6. In the dark room the exposed paper band is removed for development from the receiving reel 8, after removing the lid 15, and a new paper band is placed in the holder. The length of unexposed band remaining at any moment in the holder is shown by the counter 17, which records the revolutions of the guide reel (10 revolutions equal 1 m), thus indicating the length of band already exposed. The speed of the band is recorded by a time mark. By the flashing of a small glowlamp in the lamp housing 18, a dot of light is projected on the paper band through a total-reflection prism. The glowlamp circuit is broken by a small spring contact lever connected with the armature of a contact clock and making contact at intervals of 0.6 second. Details of the test are directly recorded on the paper band by a second glowlamp mounted in the lamp housing 18 and supplied with current through a Morse key. The speed of the paper bands of several optographs can be synchronized by a contact on the friction wheel 13 which flashes a control lamp in the switch box at every revolution.

When several optographs are operated simultaneously, they should be connected in parallel with a common central switch. A switch box for two optographs is shown in Figure 11. It contains the contact clock for the time marks, the rheostats for the electric motor, the control lamps, an ammeter, a Morse key, and the necessary switches and fuses.

IV. Installing the Optograph

For taking pictures on the ground, the optograph camera is best mounted on a motion-picture-camera tripod with rotatable head (Figs. 6a and 6b). On an airplane in flight, however, the optograph must have an elastic support to protect it from the high-frequency vibrations due to the inertia forces of the engine, since no clear diagrams can otherwise be obtained. The natural vibrations of the optograph on its elastic support should be correctly damped, in order that vibrations due to starting and landing shocks may vanish quickly. On the other hand, the damping should not be too strong, so as to avoid increasing the perceptible resonance range of the support up to the high-frequency vibrations of the fuselage.

Any rotation of the optical axis under the action of the natural vibrations of the optograph should be prevented by a suitable form of support, since errors of measurement proportional to the amplitude of the rotation are otherwise made. According to the example in Figure 9, the greatest relative error at small amplitudes of rotation α_0 is:

$$\Delta \xi = \frac{x' - x}{x} = \left[\frac{l(a_2 - a_1)}{h_1 a_2 - h_2 a_1} + \frac{h_1}{a_1} + \frac{h_2}{a_2}\right] \alpha_0 .$$

Parallel displacements of the optical axis do not, however, affect the deformation line corresponding to a position of rest. Tennis balls and sheets of sponge rubber have hitherto made the best shock absorbers for the installation of optographs on airplanes (Figs. 10 and 11).

V. Examples

1. Deflection measurements on the wing of the flying boat "Do X 1."- The elastic lines of the wing of the Do X 1 were measured in flight in order to obtain information regarding the stresses in large airplanes. The test installation is shown in Figures 10 and 11. The deflections of the front and central spars at rest were measured under the weight of the wing alone. Portions of the recording bands are shown in Figures 12 to 15. Several elastic lines of the wing, as derived from these records by means of the Zeiss measuring microscope, are shown in Figure 16. The accuracy of measurement varies between 0.02 and 0.1 mm,

according to the grain of the photographic paper and the sharpness of the lines. The error of measurement for the deflection of the wing tip accordingly approximates 0.4 to 2%. Errors due to shrinking of the paper, inaccurate drawing of the lenses and rotation of the optical axis seldom exceed 2% and can be accurately determined or avoided. Deflections measured in squalls and in leveling-off maneuvers were compared with those in steady, straightaway flight.

2. Deflection measurements on the wing of a "G 24" commercial airplane.- The measurements were made in broad daylight, as the lamps had to be fitted on the outside of the wing (Fig. 2). Hence the direct admission of light from the sky had to be very carefully avoided by stopping down the lens, inserting yellow filters and placing vignettes before the recording band. As shown in Figures 17 - 19, quite satisfactory records can be obtained under these conditions even with a clear sky. The elastic lines derived from these records are shown in Figure 20. The maximum deflection in leveling off from a dive with a total weight of 4.7 metric tons is 1.41 times that measured in steady straightaway flight, but only 1.32 times that measured in squalls.

3. Investigation of the horizontal tail surfaces of the "Do X 1" at rest.- In order to determine the best type of bracing for the horizontal tail surfaces, forced vibrations were imparted to them by a rotating unbalanced mass. The set-up of the optograph is shown in Figure 21. There are three lenses for

simultaneously recording the three widely separated points of measurement. A section of the recording band is shown in Figure 22 and the corresponding resonance curve in Figure 23.

4. Vibration tests.- In order to determine the damping characteristics of certain materials used in aircraft construction, vibration tests were made with test bars at different frequencies. The pictures were taken with a lens of 10 cm (about 4 in.) focal length in such manner that the motion of the end of the bar was amplified on the recording band. Figure 24 shows the test arrangement. Note the axial loading of the test bar which was increased nearly to the ultimate buckling load, in order to reduce the speed of vibration and the friction of the air. Portions of the recording band with vanishing oscillations are shown in Figures 25 and 26.

5. Fatigue tests.- A welded steel airplane spar was tested for durability by H. Hertel in the laboratory of the Static Division of the D.V.L. The spar was set in vibration by a rotating unbalanced mass with the simultaneous application of a static load. The test arrangement is shown in Figure 27. The points of measurement were marked by small glowlamps. The static load was suspended by rubber cords to avoid disturbing the vibrations. Figure 28 shows the portion of the recording band in which the fatigue rupture of the spar occurred. Note the decrease in the amplitude of the vibrations shortly before the rupture.

6. Drop-hammer test of a shock-absorbing landing-gear strut.- Drop-hammer tests of the elastic and damping properties of an oleopneumatic landing-gear strut were conducted by F. Michael in the Static Division. The motions of the cylinder and piston were recorded by means of triple mirrors. Figure 29 shows the test installation and Figure 30 the sharp curves obtained for a free fall of 25 cm (about 10 in.). The damping action was such that the strut rebounded from the ground after the first impact.

VI. Conclusions

The many possibilities of using optographs for deformation measurements are indicated by the examples given. The light ray as a recording factor, unaffected by inertia and friction, can not be replaced by mechanical recording devices, when there is no fixed reference system or when a synchronous record of the motions of several widely separated test points are to be obtained. On the other hand, deformation measurements, especially in operation, are indispensable auxiliaries for the determination of maximum stresses in static structures and help to increase the safety and economy of operation.

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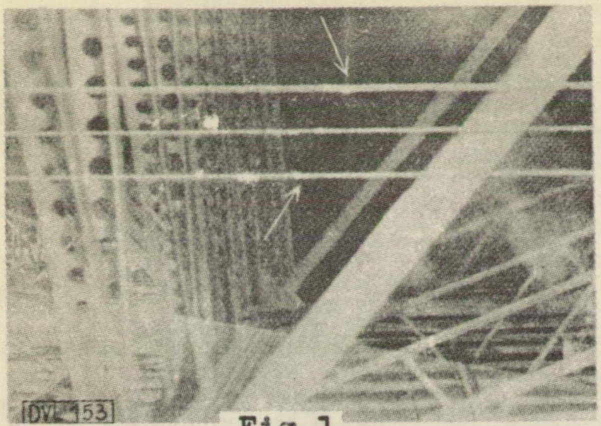


Fig.1

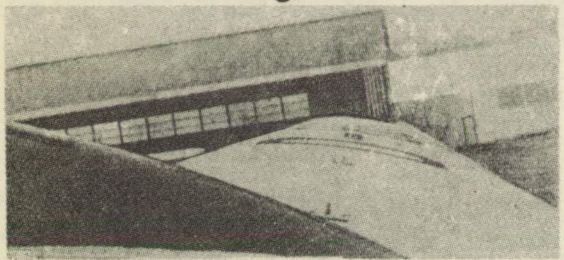


Fig.2

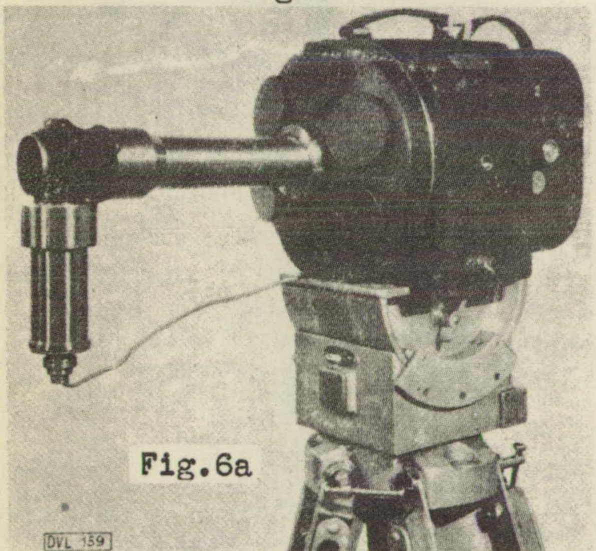


Fig.6a

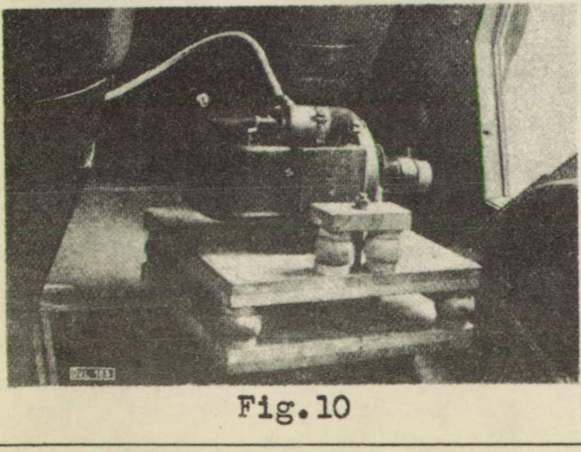


Fig.10

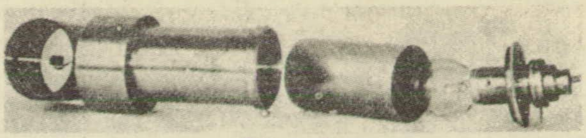


Fig.4

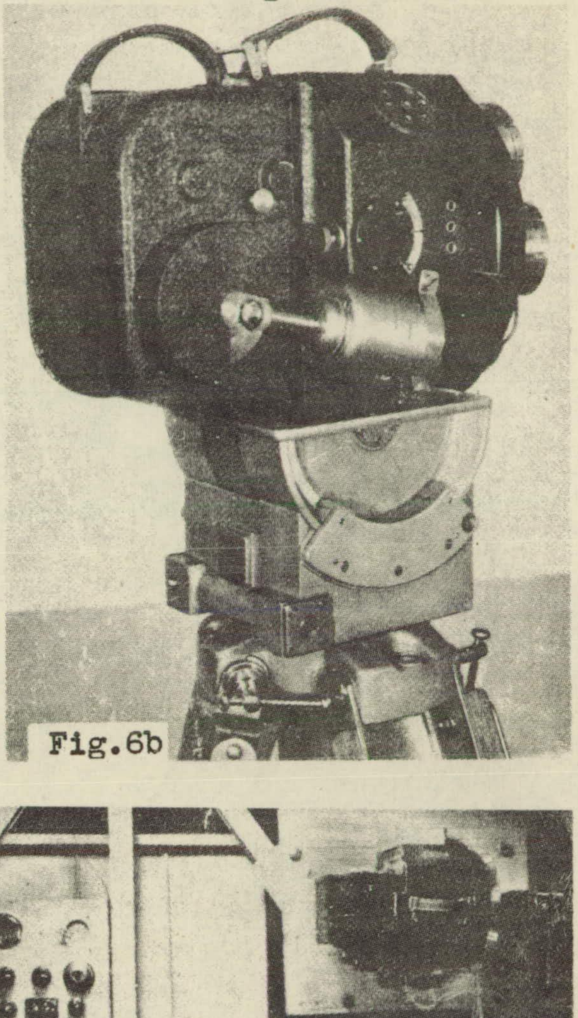


Fig.6b

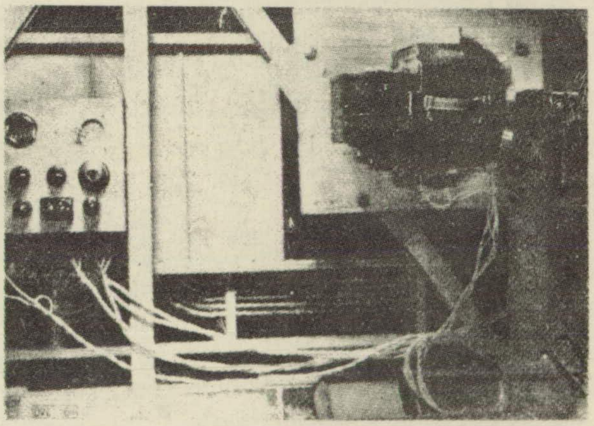


Fig.11

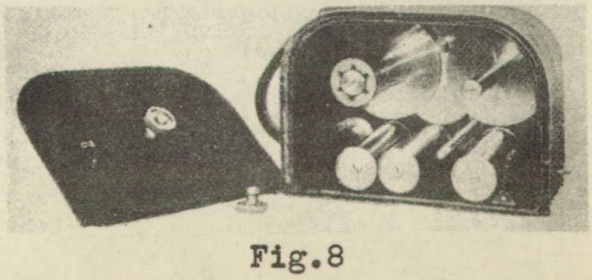


Fig.8

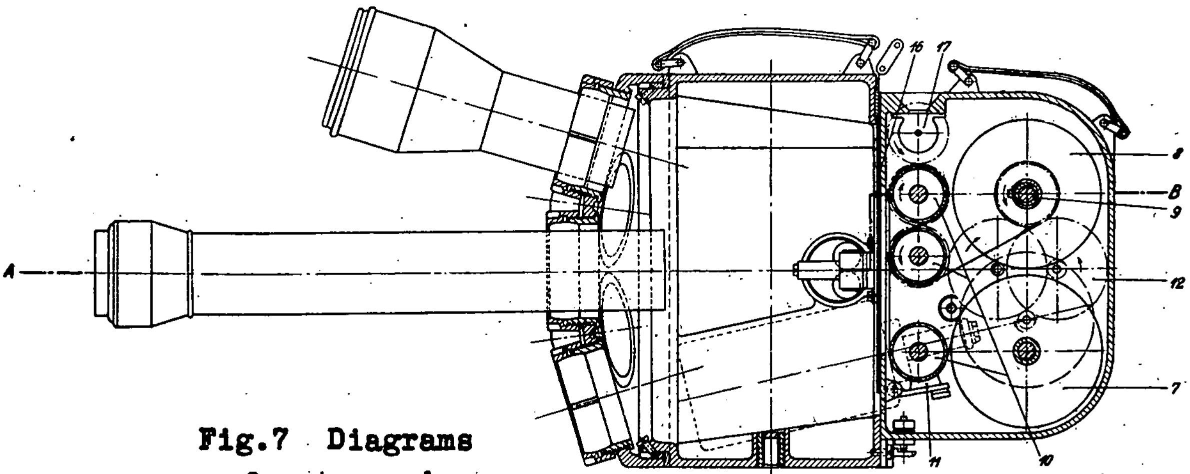
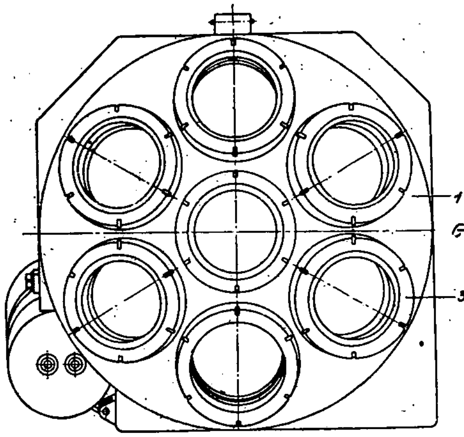
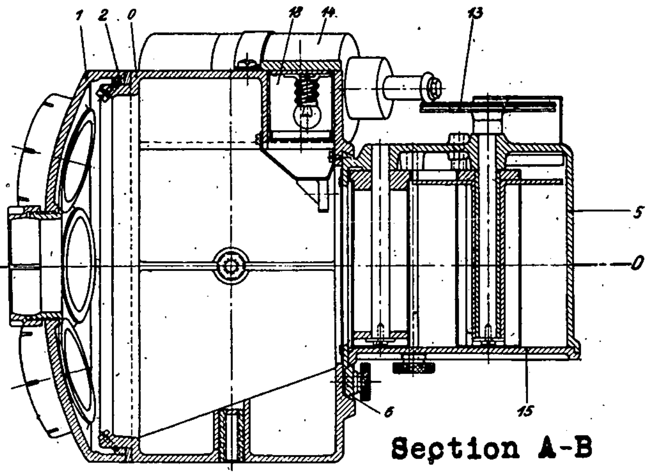


Fig.7 Diagrams of optograph.

Section C-D

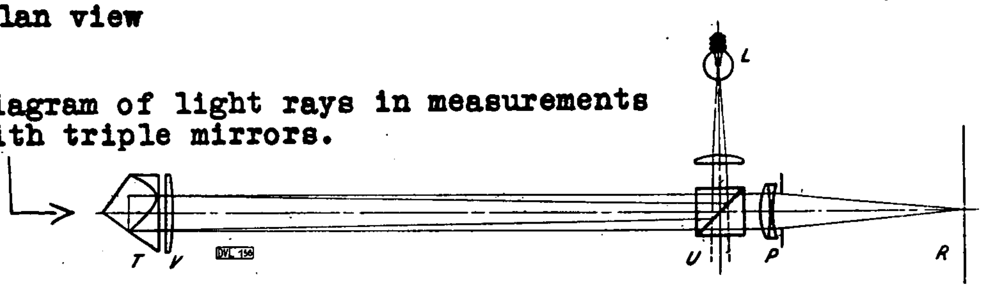


Plan view



Section A-B

Fig.3 Diagram of light rays in measurements with triple mirrors.



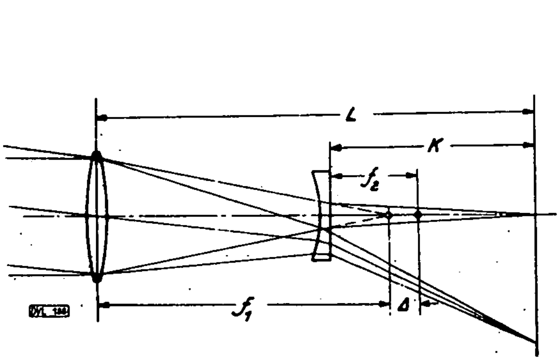


Fig.5 Path of light rays in a long-distance lens.

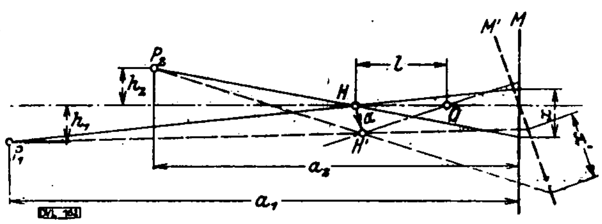


Fig.9 Error of measurement during rotation of camera. P, points of measurement; H, optical center of lens; O, pivot of camera; M, ground-glass plate.

Figs.12 to 15 Portions of recording band; deflections of DoX1.

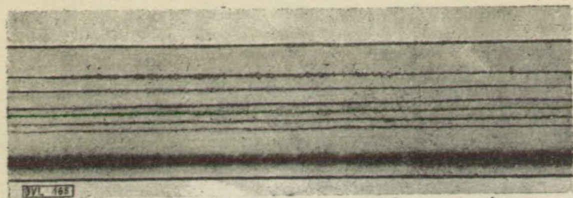


Fig.12 Rocking on the water.

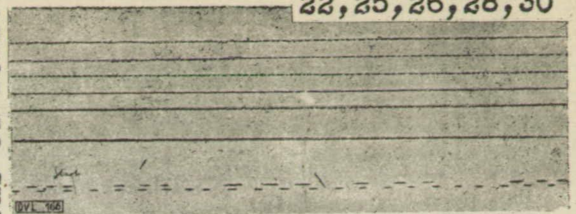


Fig.13 Record of a start.

Fig.14 Landing, recorded on still band.

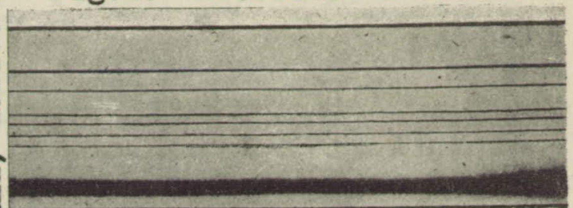


Fig.15 Straight level flight.

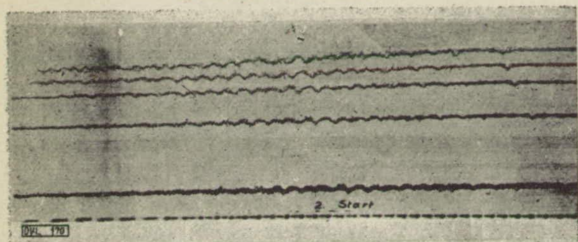


Fig.17 Record of a start.

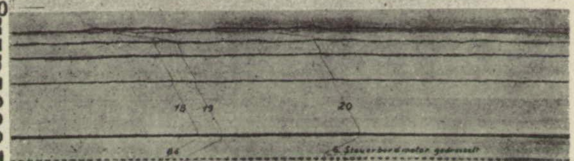


Fig.18 Vibrations with throttled starboard engine.

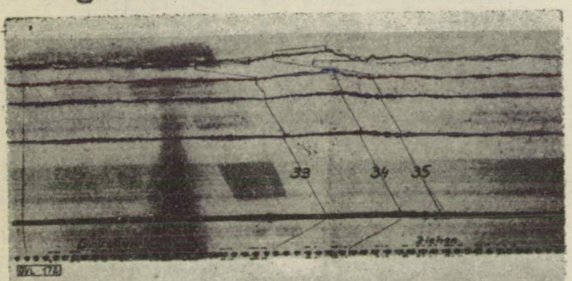


Fig.19 Pushing and pulling of the control stick.

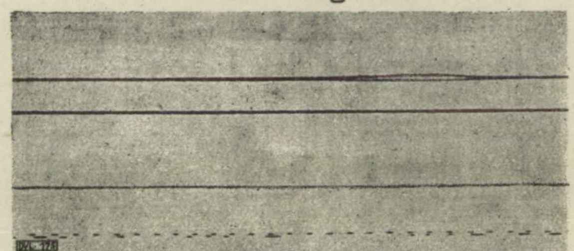


Fig.22 Section of recording band. Forced vibrations of horizontal tail surfaces.

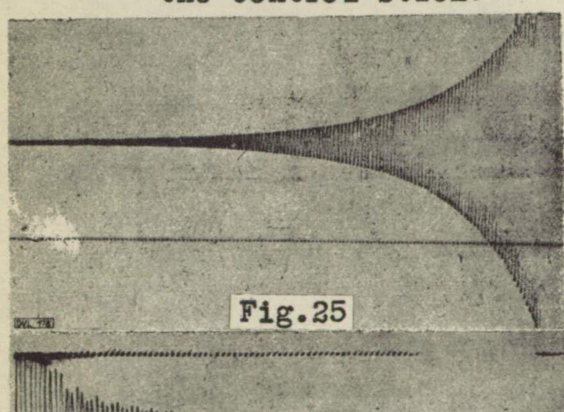


Fig.25

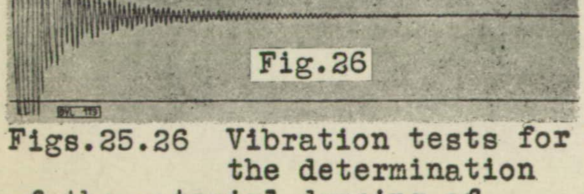


Fig.26

Figs.25.26 Vibration tests for the determination of the material damping of spruce and pine.

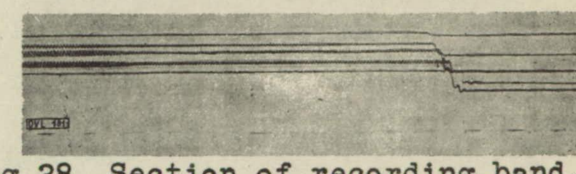


Fig.28 Section of recording band. Fatigue rupture of spar.

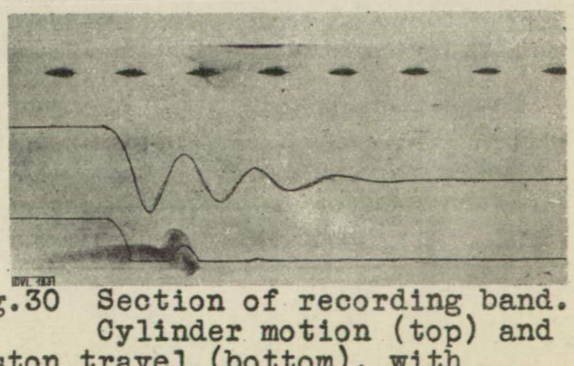


Fig.30 Section of recording band. Cylinder motion (top) and piston travel (bottom), with triple mirrors.

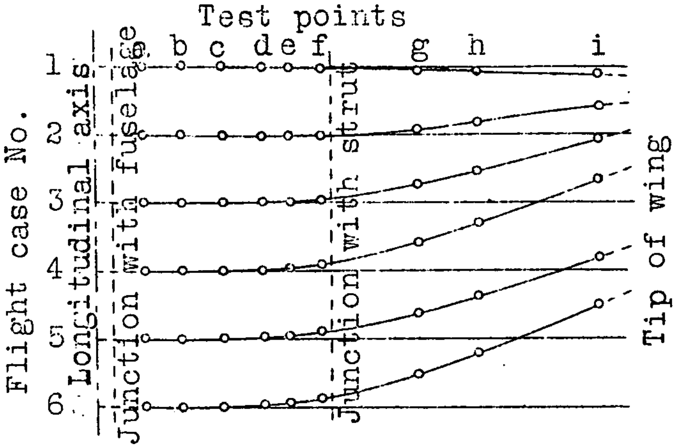


Fig.16 Elastic lines of wing of DoX1 in flight.

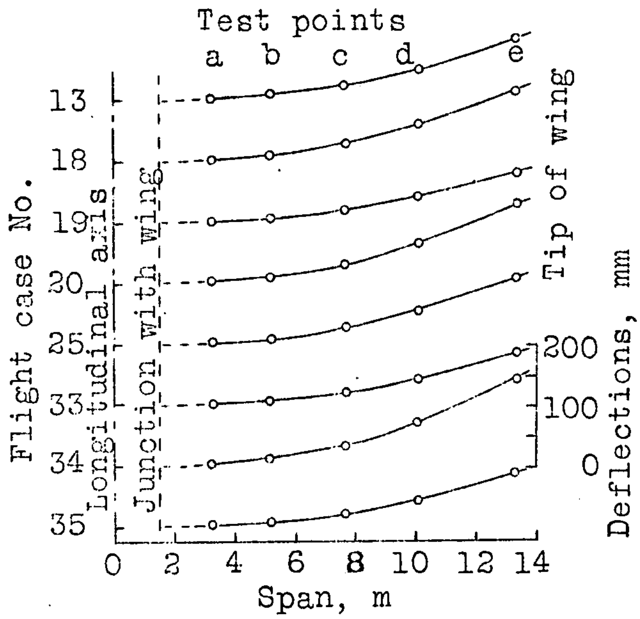


Fig.20 Elastic lines of G 24 wing in flight.

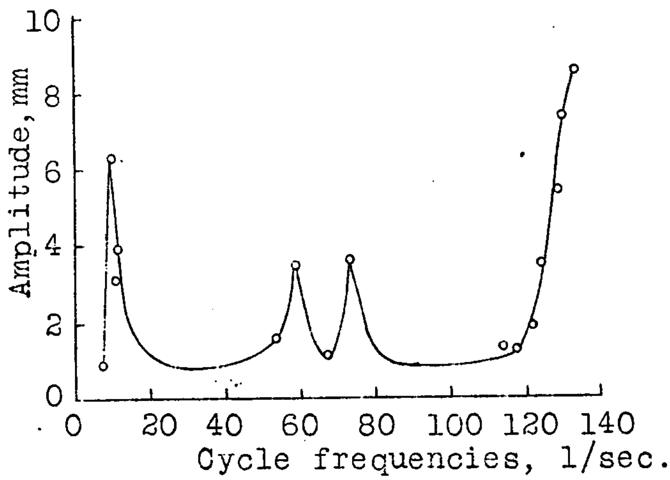


Fig.23 Resonance curve of tail-surface vibrations.

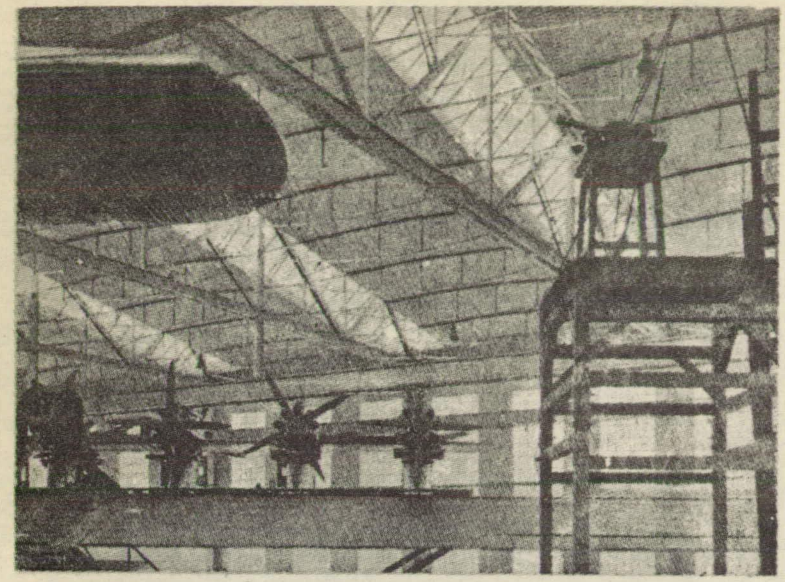


Fig.21 Optograph mounted for measurements on the tail surfaces of the DoXl flying boat in the hangar.

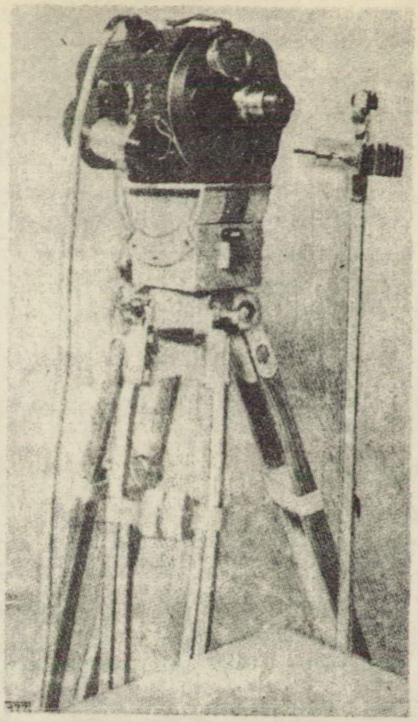


Fig.24 Test installation for the determination of material damping

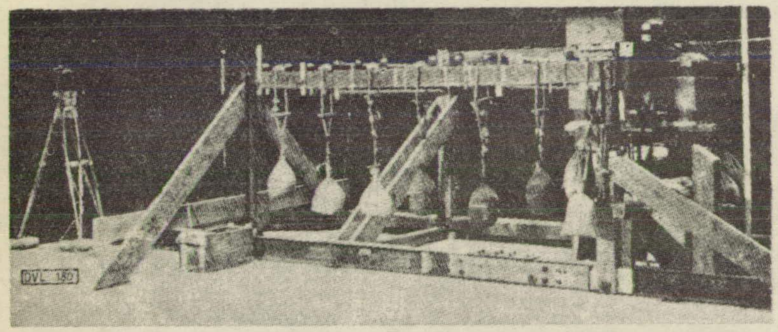


Fig.27 Test installation for fatigue tests of a steel spar.

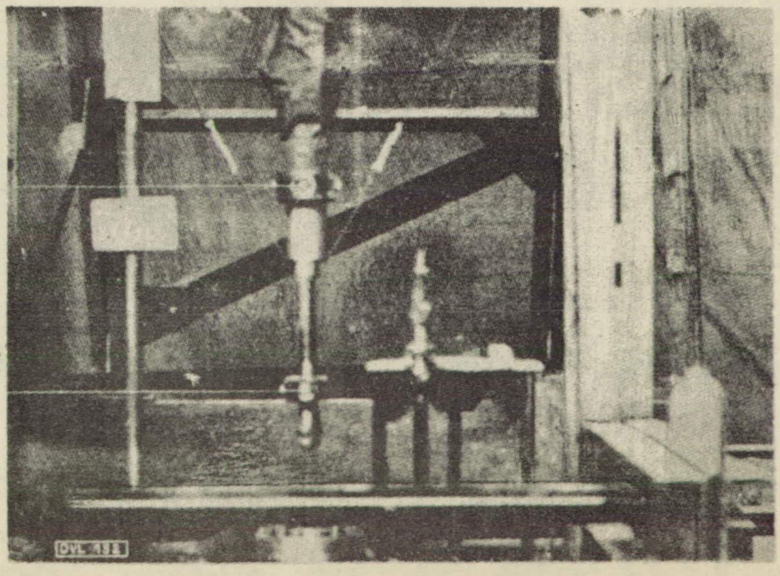


Fig.29

Drop-hammer test of shock-absorbing strut.