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A New High-Speed Indicator for Internal Combustion Engines.

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Abstract.

In this new indicator, which is of the optical type, the natural frequency of the moving part is made very high by greatly diminishing the motion, while the decrease in sensitivity is compensated by lengthening the arm of the optical lever to 3~4 metres. The natural frequency is 7000~10,000 per sec. Although the indicator is connected directly to the engine cylinder, a special device prevents the engine vibration from affecting the pressure indication.

1. Introduction.

As the pressure in the cylinder of a high-speed internal combustion engine varies very rapidly, the indicator must fulfil the following two conditions in order that it may accurately indicate the pressure.

(1) *The connection to the cylinder must be direct.* Since most indicators have pistons or diaphragms which receive the pressure, the path from the cylinder wall to the indicator must be short enough to allow

the varying pressure in the cylinder to be transmitted to the indicator without undue lag. This necessitates the indicator being mounted on the cylinder itself. Some indicators are fixed to a stand near the engine and connected to the cylinder by pipes, but such an arrangement is not suited for measuring rapidly varying pressures.

(2) *The natural frequency of the moving part of the indicator must be high.* The natural frequency of the moving part must be high enough to permit the pressure on the piston or the diaphragm of being indicated accurately. Usually the most abrupt change in the rate of pressure variation occurs near the beginning and the end of the explosion, so that under ordinary conditions the moving part will be able to follow this change without much error, provided the natural frequency is of the order of 5,000 per sec.

We shall now examine how far these conditions are fulfilled by the high speed indicators at present in use. These may roughly be classified as follows:—

(a) Micro-indicators,
(b) Optical indicators,
(c) Stroboscopic indicators,
(d) Electric indicators.

In type (a) the motions of the moving parts are of necessity made small in order to fulfil the second condition above mentioned. Their natural frequencies however are not high enough, being only about 1,000 per sec., even in the best of their kind. Most indicators of type (b) do not fulfil the first condition. Moreover their natural frequencies are not so high. Type (c) was devised as satisfactory results could not be obtained with either (a) or (b). But this type can be discarded as continuous indicator diagrams cannot be directly obtained. Some indicators of type (d) work fairly well, but it is not easy to make accurate quantitative measurements with them. The authors, a few years ago, made a piezo-electric indicator[1] which though satisfactory, was found inconvenient for the engine laboratory.

2. The Principle of the New High-Speed Indicator.

Some electric indicators, though troublesome to use, are fairly satisfactory. In this type, pressure variation must first be transformed by some means or other to electric current variation. For instance, in a certain indicator the deflection of a diaphragm due to pressure is transformed to variation in current by the same principle as that of a condenser microphone. This current variation has then to be recorded by an oscillograph, but before the current is applied to the oscillograph it must be amplified, because the oscillograph of high natural frequency requires a current of certain intensity.

It is apparent that all these complicated contrivances were devised solely for the ultimate purpose of causing the mirror of the oscillograph to turn round a certain angle, but as the motion of the mirror is very small, we have the paradoxical result that the final motion of the mirror is smaller than the original motion of the diaphragm. It will be much simpler then to move the mirror directly by means of the diaphragm. The advantages of such a device are obvious; for besides being simple, the direct connection will eliminate all errors arising through transmission. By diminishing the motion of the mirror to the same order as those of the oscillographs, it is very easy to fulfil the second condition above mentioned.

The method of moving the mirror directly by means of the piston or diaphragm is not at all new. It is the one generally used in ordinary optical indicators. But as their motions are relatively large, their natural frequencies are not very high. The natural frequency however can be made sufficiently high by diminishing the motion, and the

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decrease of sensitivity compensated by lengthening the arm of the optical lever. But this principle has not been adopted in ordinary optical indicators on account of engine vibration. If indicators are mounted directly on the cylinder in order to fulfil the first condition, they will vibrate with the engine. Even were the first condition ignored and they were fixed on a stand near the engine and connected to the cylinder by short pipes, the engine vibration will still be transmitted more or less. If the motions of the moving parts due to the pressure are very small and the optical lever very long, then the effect of vibration will be very strong, and in extreme cases, it would be impossible to tell whether it was the vibrations or whether it was the variations of pressure that are recorded in the diagram.

But if the effect of engine vibration could be eliminated by some special device, it is evident that accurate measurement could be obtained by increasing the natural frequency of the moving part and compensating the resulting lack of sensitivity by lengthening the optical lever. This problem has been solved very simply as follows. Fig. 1 shows one of the arrangements to eliminate the vibration effect. L is a lens fixed to the indicator body. M_1 and M_2 are mirrors, and the angle between them, which is about 90°, is slightly changed by the motion of the piston or the diaphragm. Slit S is placed at the focal distance from the lens L, the focal length of the lens now used being 3~4 m.

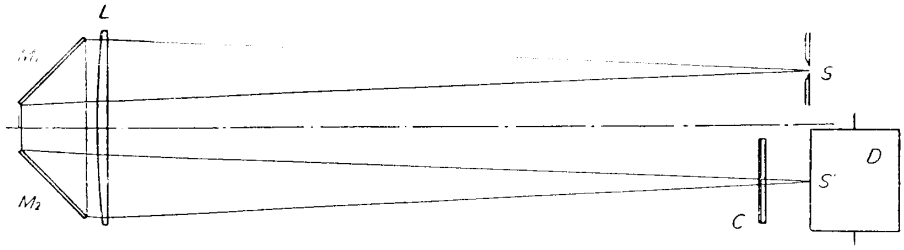

Fig. 1.

The light-beam from slit S which passes through lens L and is reflected on to mirrors M_1 and M_2, passes L again and then a cylindrical lens of short focal length *C*, and finally converges to a point on a rotating drum *D*. The slit, the cylindrical lens, and the drum form a group set apart from the engine. This arrangement eliminates the vibration effect however much the engine, and of necessity the indicator body, may vibrate.

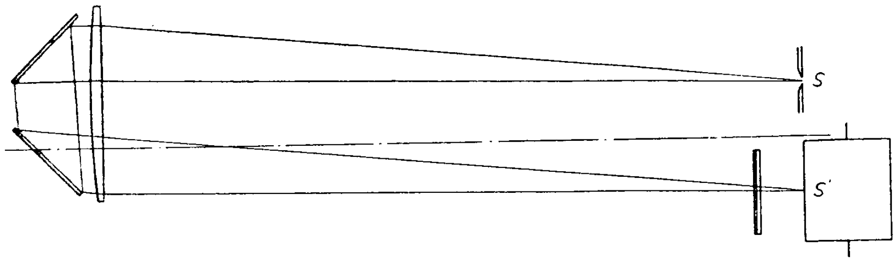

Fig. 2 (a).

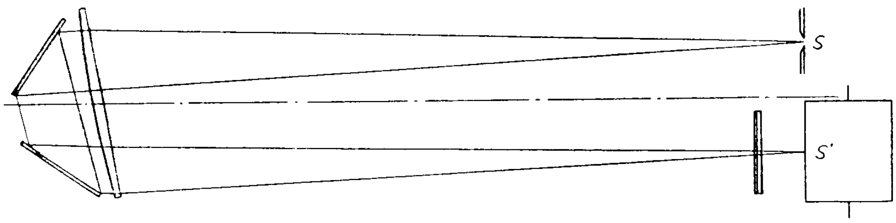

Fig. 2 (b).

Let us now investigate the effect of each kind of vibration, assuming that we shall take the atmospheric line by closing the indicator cock. Fig. 2-a shows a vertical vibration. When the engine is running, the indicator body vibrates with the engine cylinder. But as this vibration is not so rapid as the natural frequency of the moving part of the indicator, the mirrors M_1 and M_2 can follow the motion of the indicator body, hence it may be concluded that the angle between the mirrors is not altered by the engine vibration. And, as shown in the figure, so long as the angle remains unaltered the image will not move at all.

When the vibrations are perpendicular to the plane of the figure, the image of the slit will move also in the same direction, but as the light-beam is made to converge to a point by a cylindrical lens of short focal length, the motion of the light spot is practically negligible.

When the vibrations are parallel to the direction of the light-beam, theoretically, a blurring of the image should occur, but the amplitude of the engine vibration is so small compared with the focal length of the lens L that the blurring is absolutely negligible.

Let us consider next the rotary vibrations about an axis perpendicular to the plane of the figure as shown in Fig. 2-b. In ordinary optical indicators the worst effect is from vibrations of this kind. But, as shown in the figure, the image does not move at all in this arrangement so long as the angle between the mirrors remains unaltered.

As for the rotary vibrations about the other two axes, we can easily see that these correspond to the displacements of the image in a direction perpendicular to the plane of the figure. But as the light beam is converged by a cylindrical lens, the position of the light spot is not altered at all by vibrations of this kind.

We thus see that the vibrations have no effect and a perfectly straight atmospheric line is obtained. Fig. 3-a shows the vibrations of a certain motor cycle engine, taken by affixing a mirror to the cylinder. The indicator of the authors was then mounted on the same engine and an atmospheric line taken. The position of the recording apparatus was the same as before. In Fig. 3-b, which shows this atmospheric line, no vibration is visible.

Let us now investigate the effect of the vibrations, assuming that indicator diagrams are to be taken by opening the cock. The angle between mirrors M_1 and M_2 will change in proportion to the pressure, and image S' move accordingly. Here the length of the optical lever will be changed by the vibrations that are parallel to the direction of the light beam, resulting in change of sensitivity. But the amplitudes of the vibrations are of the order of 1 mm and the length of the optical lever 3～4 m; consequently the amplitudes of the vibrations are so small

Fig. 3 (a).

Fig. 3 (b).

compared with the length of the optical lever that its effect is negligible, considering the accuracy of the indicator. Thus vibrations of whatsoever nature have practically no effect on the indication of pressure.

The arrangement shown in Fig. 1 is only one example. Many other arrangements could be devised; for example those shown in Figs. 4 and 5. In Fig. 4, S is a slit, L a lens, M_1 and M_2 mirrors of the indicator, C a cylindrical lens and S' the image of S. The angle between the mirrors is slightly changed by the pressure. In this case the distance between M_1 and M_2 must be small compared with that between M_2 and

S'. In Fig. 5, M_1 and M_2 are mirrors, and L is a lens fixed to the indicator body.

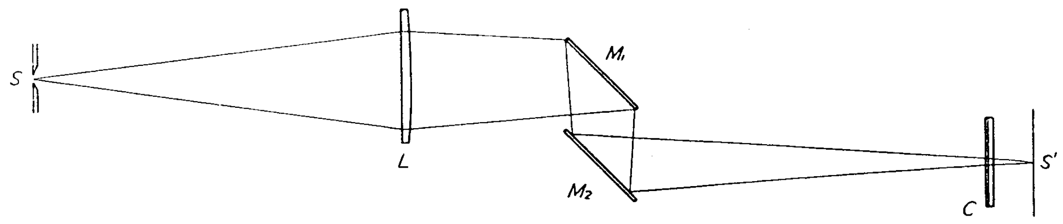

Fig. 4.

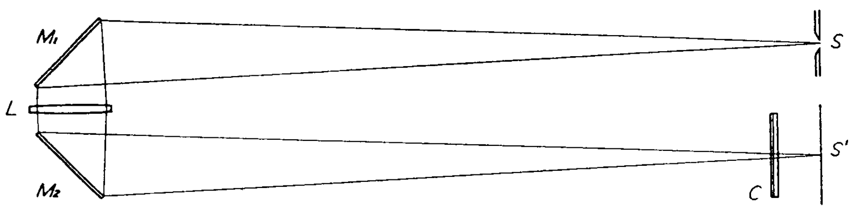

Fig. 5.

3. Construction of the Indicator.

As the motion of the moving parts is very small, any clearance or back lash in the mechanism for moving the mirrors must be avoided at all costs. Hence the moving parts were designed so that all their motions shall be elastic deformations. They were of course made as light as possible.

Fig. 6 shows the indicator. B is a beam spring, the ends of which are tightly fixed to the indicator body. The pressure acts on diaphragm D, while the force which is transmitted through rod R to the beam spring, makes it bend slightly. Mirrors M_1 and M_2 are fixed to the beam spring at points of maximum inclination. In this method the variation in angle between the mirrors is very small, but it will be safer than other methods that permit larger variations by means of delicate and complicated mechanism. L is the lens. The path of the light beam is exactly as shown in Fig. 1. Through *C* passes cool air for the diaphragm and the body.

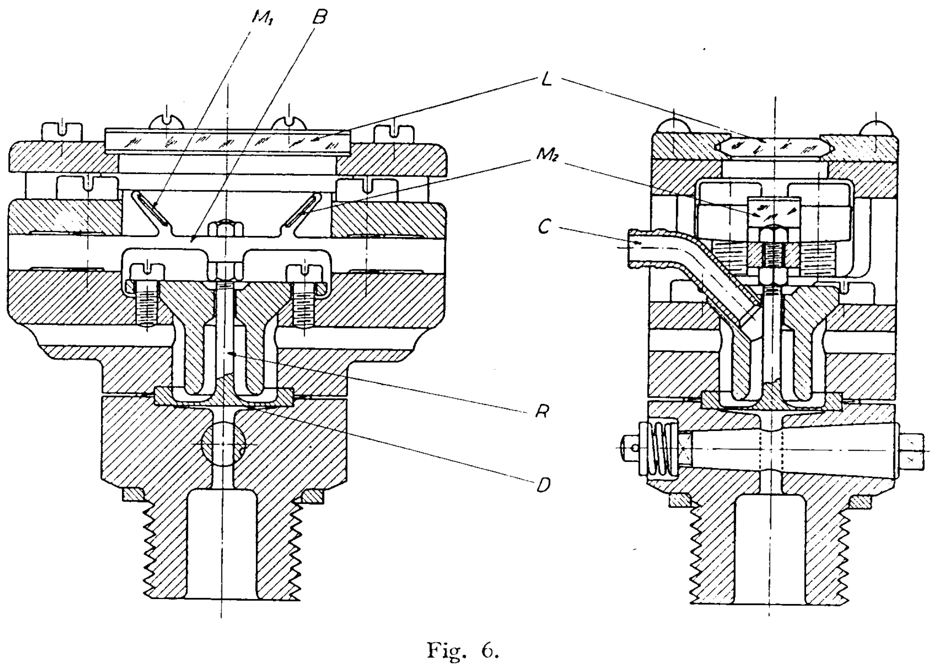

Fig. 6.

The deflection of the beam spring is about 0.02 mm for maximum pressure, while the natural frequency of the moving parts is 7,000~10,000 per sec., which of course varies according to the sensitivity. The deformations, being very small, are elastic and the calibration curve is perfectly straight. Fig. 7 shows a calibration curve.

The temperature rise of the beam spring is so small as to be negligible, while the change in elasticity of the diaphragm due to its temperature rise, if any, has practically no effect since the beam spring is very stiff compared with the diaphragm.

At first we used pistons, but there was some friction with a tight piston and leakage with a loose one. We are now using air-cooled diaphragms with satisfactory results. Its material is stainless steel of about 0.1 mm thickness.

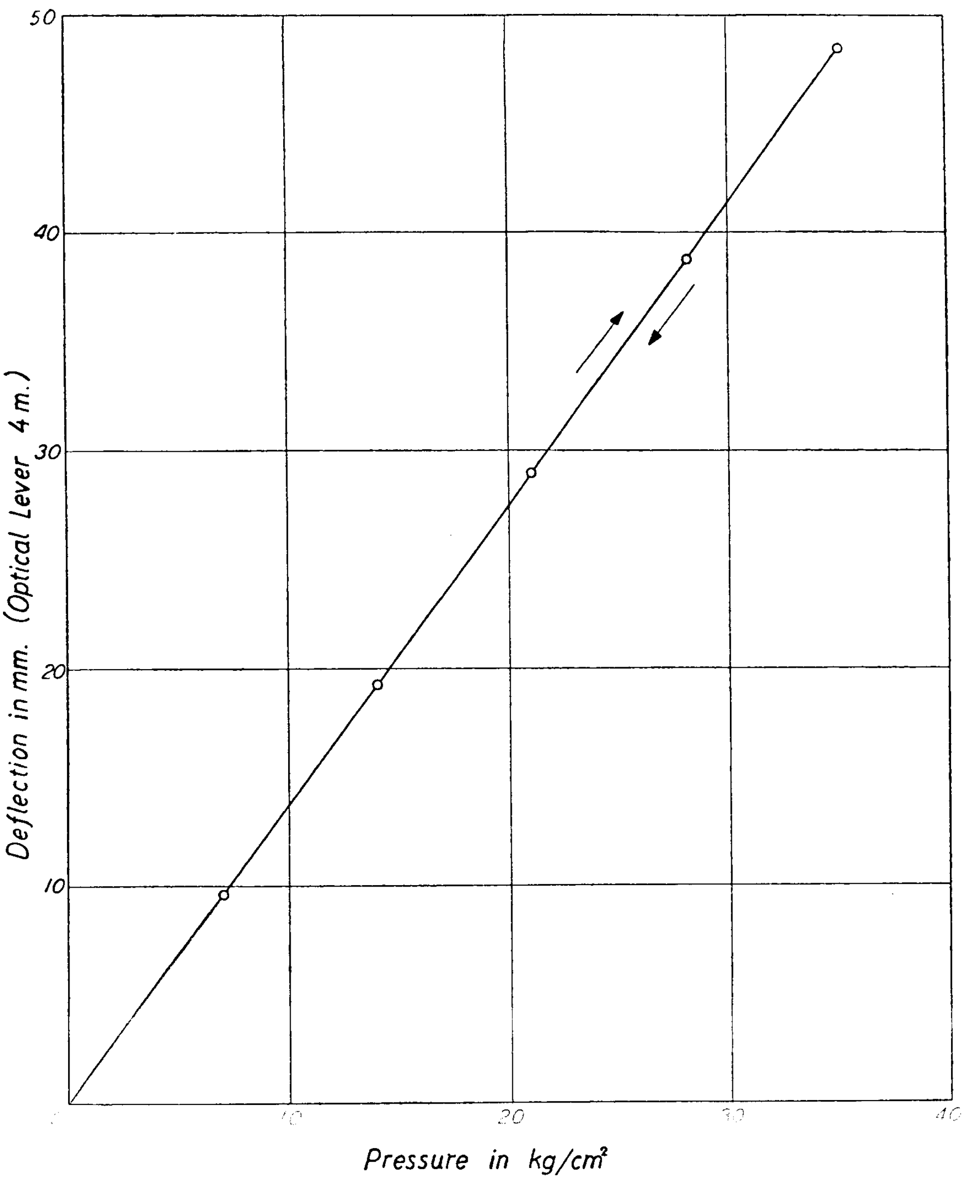

Fig. 7.

If the path from the cylinder wall to the diaphragm is long and narrow, the pressure will be damped, whereas if it is long and wide a vibration of gas will be set up in it. But in the present indicator, the effect of the path is practically negligible, as it is very short as shown in the figure.

There are, however, some engines to which the cock shown in the figure cannot be attached. In such cases new cocks will have to be made to fit each individual engine. Fig. 8 is an example. It is a combination of plug and cock, the screw thread being 18 mm standard. Here the path becomes somewhat longer, but the use of such a cock is necessary when the cylinder has no holes other than those for the plugs.

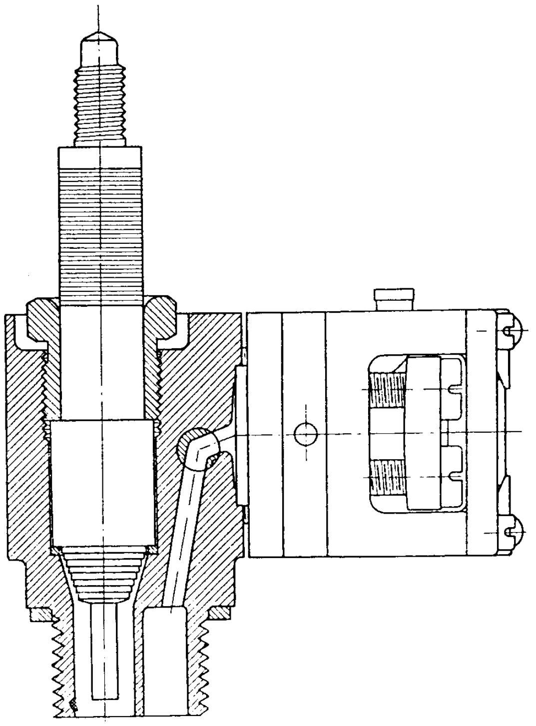

Fig. 8.

4. The Recording Camera.

An ordinary rotating drum may be used as the recording apparatus, but it is not convenient for the engine testing laboratory. We are now using a recording camera, shown diagramatically in Fig. 9. *S* is a shutter. *M* is a rotating mirror which can be rotated at any speed. *F* is a photographic film stretched on tne arc with center M. The film being an ordinary roll film, there is no need of a dark room for loading. As the mirrors of the indicator are very large compared with those of the oscillographs, we get a bright image on the film. Therefore, to take indicator diagrams, we need neither a dark room nor a light-tight pipe between the camera and the indicator. Most of the unnecessary rays can be intercepted by placing a short pipe P before the camera.

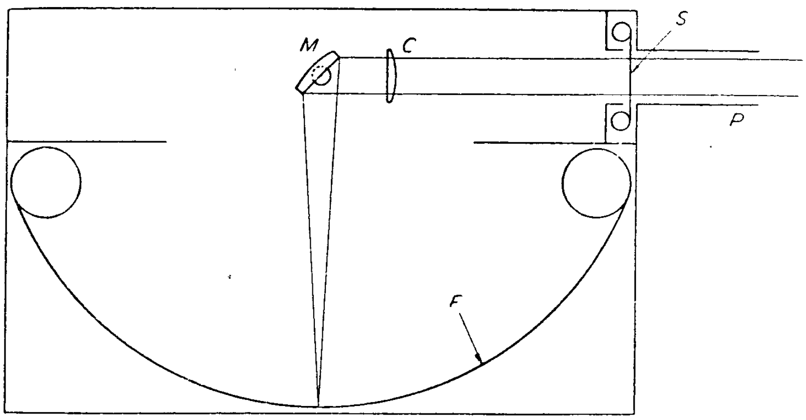

Fig. 9.

To indicate the piston position the simplest way is to cut the light beam at a definite position of the crank, as shown in Figs. 10 and 11. An alternate way is to cut another light beam, which is reflected into the camera, by a small mirror affixed to the indicator. See Figs. 12 and 13.

5. Examples of Indicator Diagrams.

Figs. 10 and 11 are indicator diagrams of a certain motor cycle engine. Fig. 10 shows a diagram, taken when the engine was running at 2,000 r.p.m., and Fig. 11 when it was motored at 1,500 r.p.m. in the throttled condition.

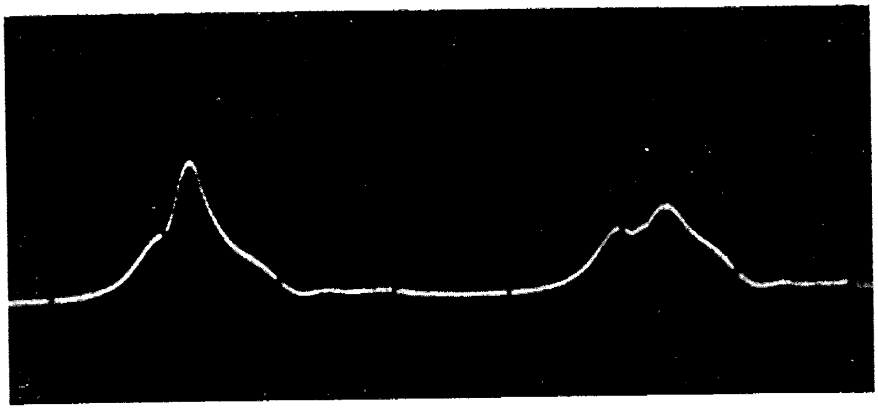

Fig. 10.

Fig. 11.

Fig. 12.

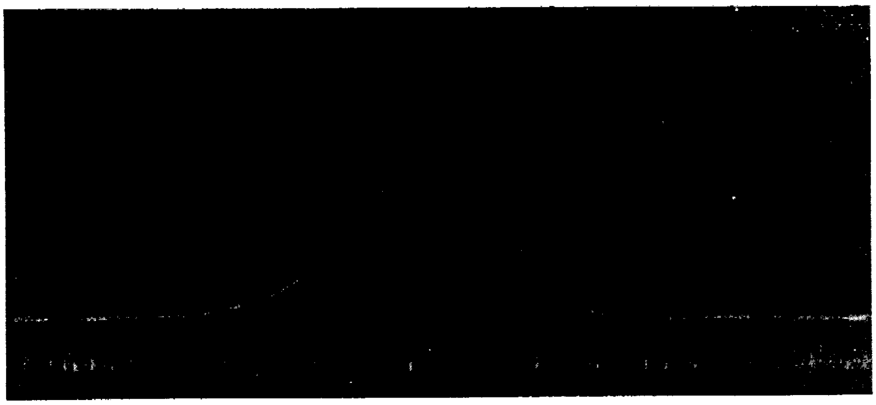

Fig. 13.

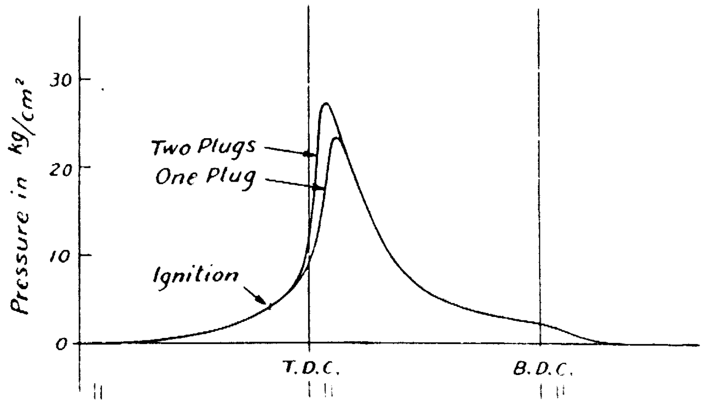

Fig. 14.

Figs. 12 and 13 are indicator diagrams of a Benz 160 H.P. engine. Fig. 12 shows a diagram taken when the engine was running normally, and Fig. 13 when one of the plugs was earthed. The engine speeds in both cases were 1,400 r.p.m. The vibrations of small amplitude that are seen near the maximum pressure of the indicator card are due to the rather long length of the path from the cylinder wall to the diaphragm, which in this case was about 38 mm.

Tôkyô, July, 1932.

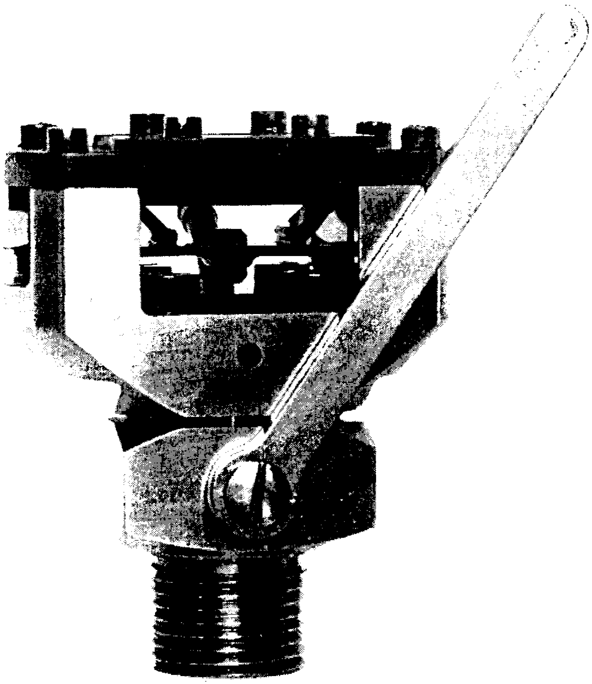

Fig. 15.

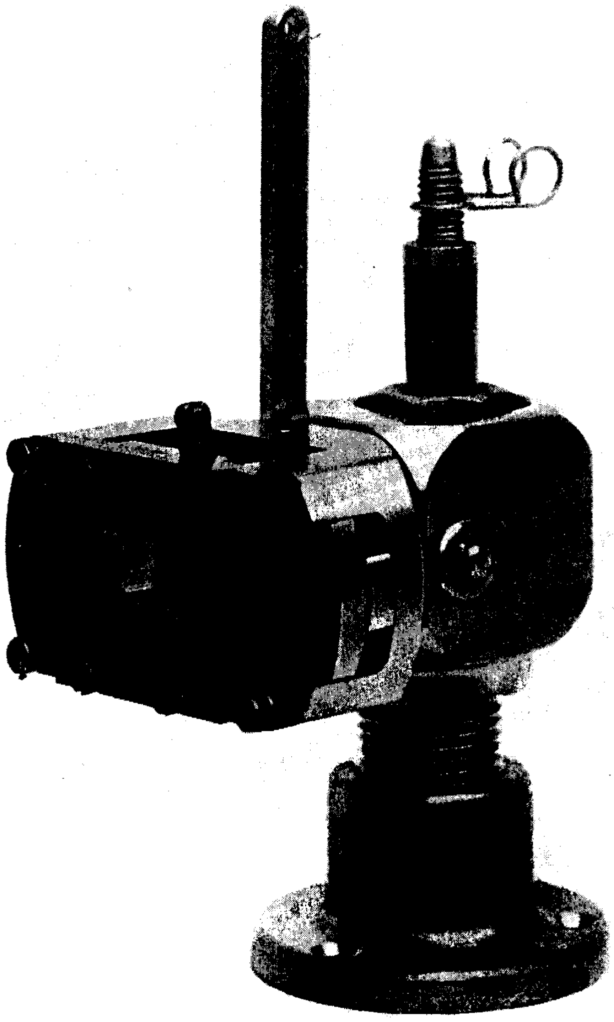

Fig. 16.

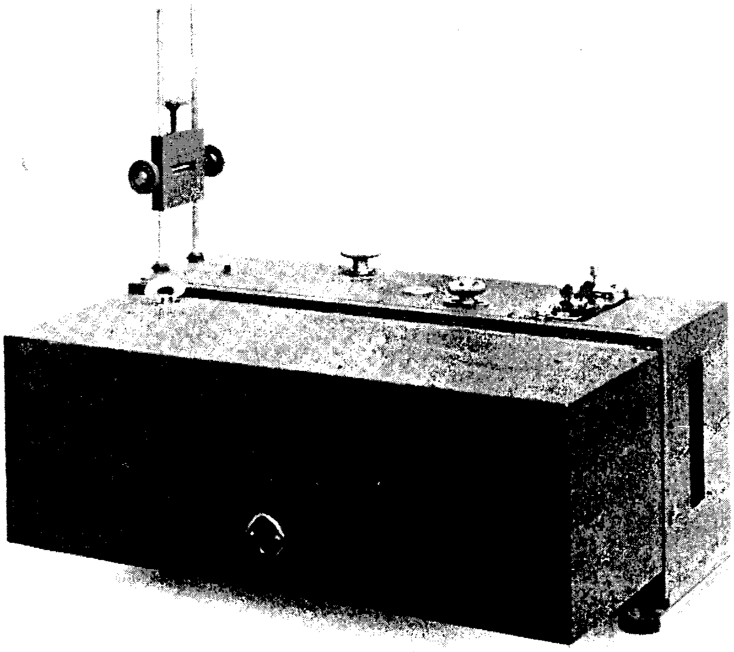

Fig. 17.