INDICATING OF HIGH SPEED DIESEL ENGINES.

An important problem that engaged early attention at the Admiralty Engineering Laboratory in the course of experimental work on internal combustion engines running at high speeds of revolution, was that of obtaining consistently accurate indicator diagrams. The fundamental importance of this matter in experimental work need scarcely be emphasised, as it is from the indicator diagram, the purpose of which is to give an accurate reproduction of the pressure variations in the cylinder during the cycle of operations, both in respect to extent and time, that the effect of many essential variables can be ascertained. Unless the diagrams are consistent, much of the information so deduced may be to some indeterminate extent misleading.

The general type of errors to which indicators are liable are, of course, well known to engineers, and the main effects on the diagram of inertia of the piston and pencil mechanism, including their vibrational effects, friction in the piston and joints and of the pencil on the drum have been generally appreciated in the course of steam engine developments. Consideration has been given to all such effects by the makers of indicators, which instruments are in general proprietary articles, and improvements have been made from time to time, and especially as speeds of engines have increased, to eliminate or reduce errors due to the above causes. In the main these have operated in the direction of maintaining the mechanism, including the piston, as light as possible, although at the same time so designing the parts that sufficient rigidity is ensured. By careful workmanship in the pin joints, coupled with the provision of ample bearing surface at these positions, errors due to inertia, vibration, friction and backlash may be reduced and at the same time reliability of the indicator ensured over a considerable period.

It may be as well to state at this stage, however, that in spite of all possible improvements and with the best of workmanship and attention in use, the inherent defects in the ordinary mechanical indicator cannot be eliminated when used for engines running, say, above 500 r.p.m., and the accuracy of diagrams from engines running at higher speeds must be open to suspicion in an increasing degree as the speed is increased. For engines well above this speed, as are common in motor-car and air-craft practice, special optical or electrical indicators are necessary, unless, as in the form of what is known as the micro-indicator, very small diagrams can be accepted. These diagrams, however, require magnification for their examination, it being recognised that a reasonable size of diagram for easy examination should be 2 to 3 inches long and 1½ to 2 inches high at the position of maximum recorded pressure. A continuously recorded set of micro-cards is useful in some class of work for noting changes as conditions are varied, but the fact of having to use magnification introduces errors which entails absolute data from an individual card being treated cautiously. Optical diagrams also, it should be noted, are magnified cards and contain sources of error, but are practically the only type of diagram that can be obtained from very high-speed engines. It is not proposed to discuss these special indicators in the article as they form a suitable subject to be treated apart.

Although well-adapted to meet all ordinary requirements of modern steam practice, it is found that the standard instruments when used on gas and oil engines do not by any means give equally satisfactory results, the sudden shock which the mechanism receives at the instant of attainment of maximum pressure, and which is transmitted to the levers of the pencil movement, not infrequently leading to their being strained and distorted to a serious extent. This has led to the introduction of special instruments for indicating internal combustion engines, in which the links, pins and levers are of more substantial construction. As a consequence, it is usual to work with stiffer springs and smaller movements in this class of work and to suppress the height of the diagram at its maximum point to about $1\frac{1}{2}$ inches.

The chief special sources of error arising with mechanical indicators in internal combustion engine work are :—

(1) *Friction of the Piston.*—To attain the best results in high-speed work, the indicator must be close to the cylinder, the connection being short and direct, otherwise the pressure transmitted to the indicator may be incorrectly recorded owing to what are known as " bore waves " being set up in the connecting pipe by the explosion. Due, however, to this close proximity, the internal part of the indicator forms, in effect, a part of the combustion space and is exposed to carbonisation effects, in common with other surfaces, if only intermittently. It has been demonstrated from experience that to ensure consistently accurate results the piston and cylinder should be cleaned after every few diagrams, and considering the simplicity with which the modern indicator can be dismantled, this operation can be quickly carried out. It is the practice at the laboratory to clean the piston and cylinder after every diagram with a greasy rag or pad. Further, thorough cleaning with petrol is also advisable at intervals. The piston which, in the best form of mechanical indicators, is made of a special alloy steel with a low co-efficient of expansion, is carefully ground to size and is constructed so as to present a minimum rubbing surface to the cylinder consistent with maintaining its alignment and reasonable gas-tightness.

(2) *Friction, Inertia and Wear of the Pencil Mechanism.*—As previously stated, this portion of the indicator is of robust design to withstand the shocks to which it is exposed. By careful

attention to the design of such parts the makers of indicators have succeeded in producing instruments in which these effects are reduced to a minimum and which instruments with due precautions in their attention and upkeep can be relied upon for accurate work over long periods as regards giving a faithful reproduction of the pressure changes in the cylinder of the type of engines being considered. Periodic overhaul by the makers of the instruments is, however, found necessary by the laboratory, chiefly owing to development of slackness in the pin joints.

(3) *Error of the Pressure Spring.*—Owing to the high pressures obtained, especially in Diesel engine work, where 600 lbs. is normally exceeded, and due, as mentioned previously, to the necessity of keeping the motion of the pencil drum to about $1\frac{1}{2}$ inches (that is six times the stroke of the piston in one particular make of mechanical indicator which is found very satisfactory for this class of work), the "rate" of the spring, even with the reduced size of the cylinder, viz., $\frac{1}{8}$ sq. inch in area, is comparatively high. The "rate" must be constant over the active range of compression of the spring, and it has been found after some time in service that this rate may alter definitely or become a variable quantity, and so give inaccuracies in the diagram. In all high-class indicators for internal combustion engine work the spring is arranged outside the cylinder and is therefore subject only to atmospheric temperatures. The temperature of the gases in the indicator cylinder reaches a very high figure, and if the pressure spring were exposed to this, its accuracy would be impaired and reliable results would be quite impossible.

(4) *Drum Motion.*—So far, only the pressure-measuring portion of the instrument has been considered, but it need hardly be said that, in all engines, accuracy of motion of the paper-carrying drum, which should be an exact reproduction (although on a reduced scale) of the motion of the engine piston, is essential. Particularly is it so in Diesel engine work, where the diagrams are not so "full" as those normally met with in steam practice and where, therefore, it can be appreciated, an error in reproduction of the piston phase in the high-pressure region of the diagrams may lead to serious errors and incorrect diagnoses.

In the ordinary arrangement of indicator rig, the drum is actuated by means of a cord, the end of which is connected to a mechanism which gives a small-scale reproduction of the piston motion. Assuming this reproduction is faithfully obtained, its transference to the indicator drum may be accompanied by errors due to the inertia and friction of the drum, and varying tension of the drum spring. These effects cause the tension and length of cord to vary. It may be noted at this stage that in any particular indicator the tension of the drum spring requires to be higher if used for a high speed as compared with a slow or moderate speed of engine revolution in order to control the effect of inertia of the drum which would otherwise overrun the spring and cause the length of the diagram to exceed that of the reduced motion. Errors due to stretching of the indicator cord may, therefore, be expected in high-speed engines in spite of all reasonable precautions that can be taken with such type of rig, especially if associated with a comparatively long length of string, as is usually unavoidable. It is in this important particular, which it may be noted is outside the sphere of the indicator maker, that special attention has been found necessary in order that reasonably accurate results could be obtained and correct deductions made.

If the practical difficulties connected with actuating the indicator drum directly from the piston or crosshead without the interposition of link gear with its pin joints and possible mechanical errors could be overcome, such a method is obviously preferable as the indicator rig is freed from the inevitable errors attending any intermediate link motion. A simple arrangement of the type meeting this requirement is given by the assembly of steel tapes and pulleys shown in Fig. 1. One end of a steel tape is connected to the piston or crosshead and passes downwards and outwards, the necessary change in direction being effected over a pulley running on ball-bearings and suitably mounted on the engine framing. It is then led to and envelops the circumference of a comparatively large pulley and to which its other end is rigidly attached. On the same axis, and attached to the large pulley, is a smaller pulley which is enveloped by a second tape and the free end of which is led towards the indicator. Obviously the end of the second tape will move a reduced distance as compared with the first tape in the proportion of the two pulley diameters. A spring has necessarily to be provided in the system to control the inertia effects and ensure the return motion on the return stroke of the piston. From the end of the second tape the connection to the cord actuating the drum of the indicator can be made, this cord being kept the minimum possible length. If steel tapes of suitable dimensions and flexibility be used, it is found they are, for all practical purposes, inextensible under the tensions to which they need be subjected. The pulleys must be kept as light as possible, and are therefore, preferably of aluminium or a light alloy and should run on ball-bearings. The pressure on the bearing journals which arises from the tensions in the tapes is always in the same direction, and hence backlash effects do not arise, and if the tension in the tapes is always maintained, the reducing motion is evidently a true one. The indicator drum spring still requires to be of sufficient tension to neutralise its own inertia and frictional effects, but, due to the indicator cord being so very short, its change of length is also practically negligible.

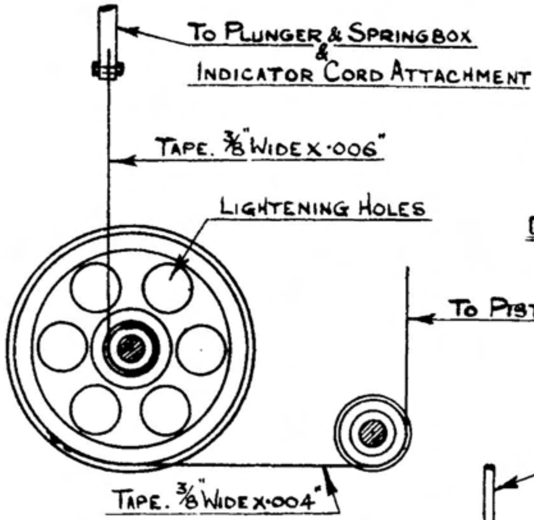
This type of rig has been found to be fully satisfactory for normal speed engines, but when used on engines of very high piston speed shortcomings are revealed. It will be evident that the large pulley must have a circumference at least greater than the piston stroke, and experience shows that the minimum diameter of the smaller pulley is settled by the permissible flexure stress in the tape, in conjunction with its speed. In consequence, to obtain the desired ratio of transmission, the size of the large pulley will be such as to give rise to considerably greater inertia effects at the higher piston speeds, and a stiffer spring will be required in the circuit which leads to increased tension in the tapes. If the width of the tapes be increased, the width and inertia of the pulleys are increased *pro rata,* whilst the use of thicker tapes means increased flexure stresses. A design of the type shown in Fig. 1 using tapes $\frac{3}{8}$-inch wide and ·006 inch thick was fairly satisfactory for an engine of 15 inches stroke running at 380 r.p.m., but when fitted to an engine of greater stroke, it was found to be insufficiently reliable at piston speeds exceeding about 1,000 f.m., and consideration had accordingly to be given to other forms of reducing device. The difficulty arose from the very short life of the tapes, and here it will be noted that in all types of rig using tape drive from the piston, repair cannot be effected without stopping the engine. Such types are, therefore, not suitable for general service other than for investigational purposes.

In the other forms of reducing device developed, the type of indicator rig is based upon the well-known method of speed reduction employed in multiple pulley-blocks. Two types are shown in Figs. 2 and 3. That shown in Fig. 2 has been in use for a considerable period on an engine of 12 inches stroke running at 375 r.p.m. If the lead of the tapes be studied it will be seen that the speed reduction is 6 to 1, and the pulleys can be kept comparatively small and light consistent with limiting excessive bending of the tape. Moreover, the spring tension required to maintain the system taut and to control the inertia is shared by the two leads of the second tape. A few failures of tapes have occurred from time to time, but these have been generally attributable to damage incurred during the overhaul or examination of the engine rather than to running conditions. With the greatest of care and where during the course of experimental work frequent dismantling takes place, it is not possible to avoid damage to these relatively delicate parts.

In the type shown in Fig. 3, all the pulleys can be kept small and the tension in the tape is much reduced owing to the spring tension being shared by several leads. Such a rig has been found very satisfactory in large fast-running engines, the length of card being approximately $2\frac{1}{2}$ inches. In smaller fast-running engines of 15 inches stroke, 6 pulley blocks are used, giving a 6 to 1 reduction ratio. It has also been found more satisfactory in this case to carry the spring external to the tube to prevent possible contact with tapes and pulleys.

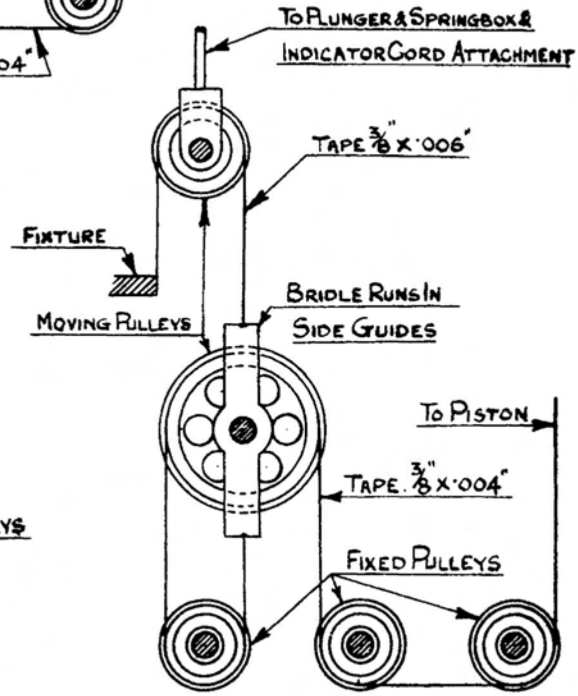
An obvious question that will occur to an interested reader is, " How can the accuracy of these rigs at high speeds be verified ? " They are tested as follows :—

The engine is barred round by hand and at equal intervals in the piston stroke, the indicator pencil is run up the card,



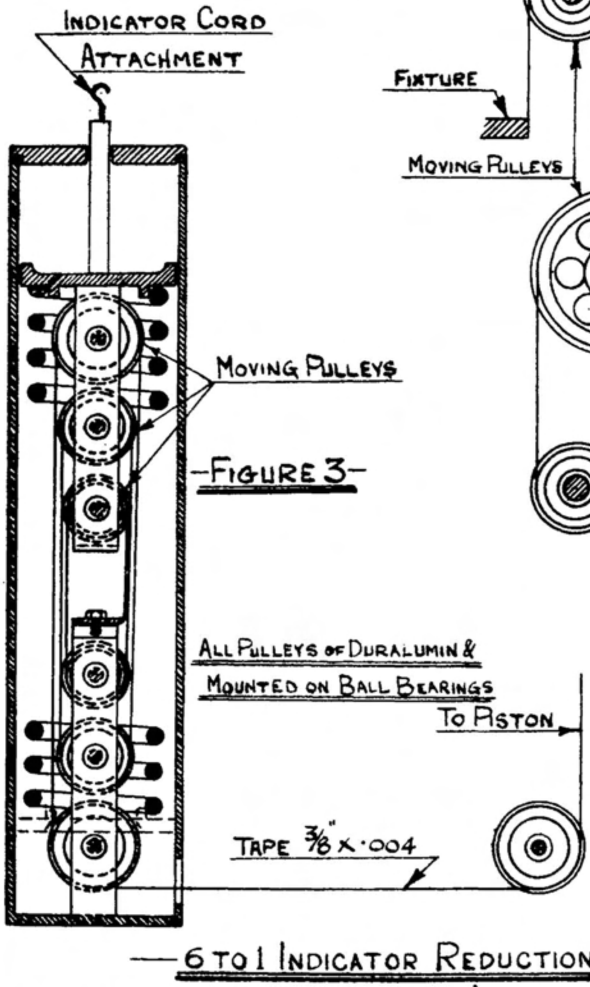
—Figure 1—

Duralumin Pulleys Mounted on Ball Bearings



—Figure 2—

Duralumin Pulleys Mounted on Ball Bearings



—Figure 3—

—6 to 1 Indicator Reduction Devices—

Diagrammatic Arrangements

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tracing a vertical line. All such vertical lines should be equidistant, and those on the down-stroke should coincide with those on the up-stroke. This certifies the correctness of reproduction of the piston motion on a reduced scale and that there is no appreciable stretch or backlash in the transmitting mechanism. Such a procedure cannot, of course, be adopted with the engine running, but if now the engine be run at various speeds and on the same card the pencil be permitted to trace horizontal lines by being moved up to successive positions at different speeds, then if these lines be all the same length and be truly one above the other, *i.e.*, are bounded by the same extreme vertical lines, it is safe to assume that the piston motion is being as correctly reproduced at all speeds as when the engine was barred round by hand. Such results, which are realised by the mechanisms described, are not possible with the ordinary rigs.

When testing as described above, the tensions in the drum and tape springs are adjusted to a minimum value consistent with the desired result being obtained. It is found if the tensions are too small that the series of lines will be of varying lengths, and may show at the same time a displacement as a whole. Too great a tension leads to greater stresses on the details than are necessary and should be avoided for the sake of reliability and freedom from wear of running parts.