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Measuring tappet rotation in a valvetrain rig when lubricated in a fully formulated oil containing MoDTC-type friction modifier

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Abstract

In a direct acting valve train configuration, tappet rotation plays a key role in improving lubrication, reducing wear and friction. However, to the best of the authors' knowledge, no studies were found to investigate the rotation of tappet under the effect of different coatings, thicknesses of tappets and formulations with Molybdenum Dialkyl Dithiocarbamate (MoDTC) which has been recently reported to be detrimental to Diamond-Like Carbon (DLC) wear. In this work, a new technique of measuring tappet rotation has been developed. A giant magnetoresistance (GMR) sensor coupled with a split pole ferrite disk magnet was used. The sensor was installed very close to the tappet/bucket while the magnet was mounted into the underside of the tappet. Experiments were performed using standard production steel tappets coated with Mn-phosphate ($MnPO_4$) and diamond-like carbon (DLC) coatings. In general, results showed that the tappet rotation is strongly dependant on oil formulation, clearance, speed/temperature, and surface roughness of the coating. MoDTC promoted the rotation of the tappet under both coatings. In addition, DLC inserts showed an increase in tappet rotation as compared to $MnPO_4$ inserts. Nevertheless, regardless of the type of coating, the thickest tappets showed the highest rotation.

Keywords: Tappet rotation, Valvetrain, MoDTC, DLC.

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1. Introduction

To meet the challenge of emissions legislation, concerns in vehicle fuel economy have increased dramatically in the last few years. It is mainly accepted that there is a direct correlation between fuel economy and friction losses (i.e. reducing friction losses lead to increasing automotive engine fuel efficiency). In an internal combustion engine, significant frictional losses come from three main tribological components: piston assembly, bearings and valvetrain. The frictional loss from the valvetrain is generally found to be lower than piston assembly and engine bearings, but at low engine speeds, mainly under boundary lubrication regime, its relative importance is much greater. The valvetrain is responsible for 6-10% of the total frictional loss in an engine, depending on the design. In terms of wear, the valvetrain, design and lubrication, has proven to be the most difficult of all the tribological components. Cams and followers are considered the most important and interesting tribological components of the automobile valvetrain. They are responsible for 85-90% of the total friction losses in engine valvetrains. In terms of wear, camlobes and followers are considered as critical areas that suffer wear and the wear increases rapidly with time. Therefore, for improved engine efficiency and durability with minimum emissions, research into this tribopair (i.e. cam/follower) is crucial.

Nowadays, a wide range of valvetrain configurations are used. Each has its own features, advantages and disadvantages. The direct acting valvetrain configuration is one of the most commonly used in internal combustion engines. In this configuration, the camlobe is moved to provide an offset to tappet bore so as to facilitate tappet rotation for friction reduction. Tappet rotation is consider to have a unique effect on the durability of components (i.e. the rotation reduces wear caused by the contact with the camlobe, improves lubrication and then increases the lifecycle of the components) [1-6].

In the literature [5, 7, 8], limited models have been developed to investigate the influence of tappet rotation. However, the validation of such models (i.e. mathematical modelling and simulation) is still a challenge due to lack of experimental techniques and the complex mechanism of cam/follower tribopair. The mechanism of this particular tribopair is complicated due to sliding/rolling motion, large contact pressure variations, changing film thickness, different lubrication regimes, and high acceleration speeds. Various experimental techniques have been used to evaluate the effect of tappet rotation [2, 6, 9-15]. Monteil *et al.* [9] used radioactive markers in the tappet surface while other investigators [10-12] used an optical fibre and a phototransistor situated under the tappet. In recently published work, Mufti *et al.* [1] used a miniature magnetometer chip and showed that the tappet rotational speed generally increased with increase in camshaft speed and oil temperature. In addition, they reported that the rotation of all tappets in the engine may not behave similarly at the same speed under certain operating conditions. Dyson *et al.* [16] showed that during one cam revolution, the tappet rotational speed was not constant and will vary with the change of cam angle.

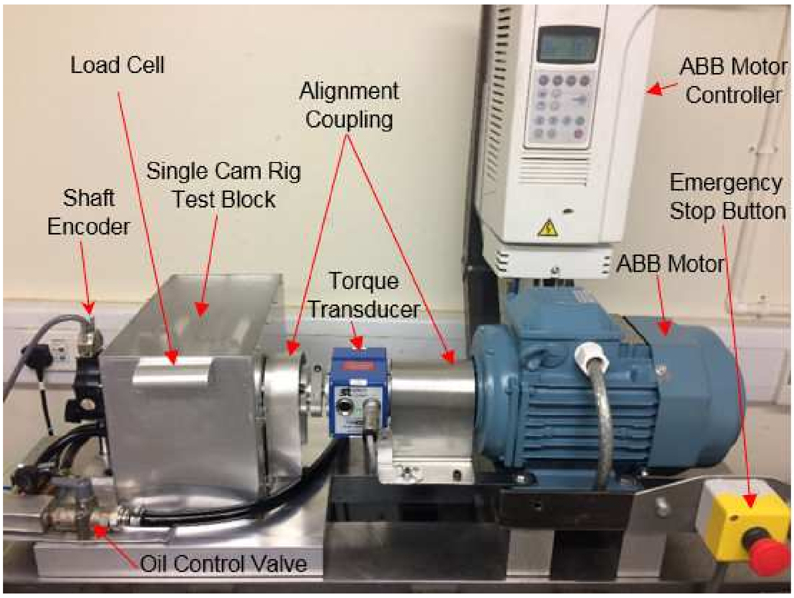
Researchers have mainly focused on understanding the link between tappet rotation, cam angle, oil temperature and camshaft speed. Very limited studies can be found focusing on the behaviour of tappet rotation under different oil formulations [2, 15]. Also, no work has been reported on the performance of tappet rotation under the effect of different coatings, thicknesses of tappets and formulations with Molybdenum Dialkyl Dithiocarbamate (MoDTC) which has been found to be problematic to DLC wear [17-22]. To fill the gap, a simple and effective technique has been employed in the Single Cam Rig (SCR) taken from a Ford engine used in this study. This technique does not require any changes or modifications on the SCR [1] while almost all the previous techniques are inapplicable as they required extensive modifications. According to [1], mounting the sensor and the magnet was a challenge due to lack of space on the single cam rig. Therefore, a new technique was developed as well as new positions for the sensor and the magnet were applied to overcome the limitations of the single cam rig employed.

This work outlines the procedure for the adaption of a single cam rig for the study of tappet rotation. The other aspect of this paper is to link the rotation of different thicknesses/coatings of tappets to the tribological characteristics of cam/follower interface when lubricated in a fully formulated oil containing MoDTC.

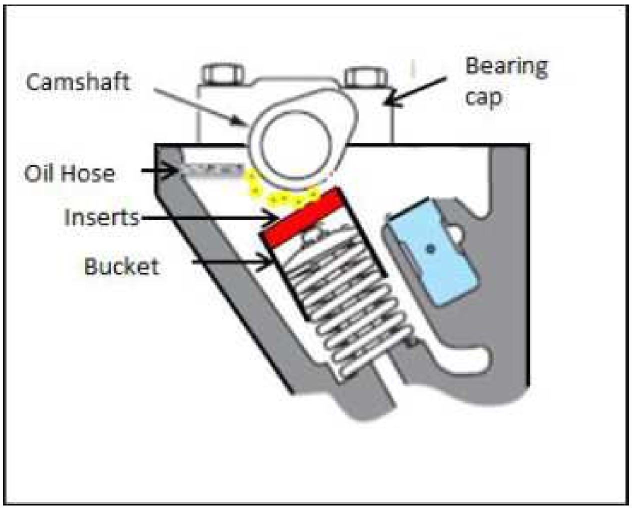
2. Experimental details

2.1. Single Cam Rig (SCR)

Tests were carried out using the Single Cam Rig (SCR), as shown in Fig. 1. The rig was constructed from a cut down 1.25L ford Fiesta Zetec-SE engine with a double overhead camshaft (DOHC) and flat faced removable inserts/tappets in bucket arrangement. The development and calibration of the direct acting SCR tribometer have been described in detail previously [23]. However, the camshaft was driven through a mechanical coupling by a 2.2 kW ABB motor (i.e. non-fired mode). The system was able to operate at high speed (up to 3000 rpm) with limited noise and vibration. A high sensitivity torque transducer (RWT 421) was connected to the camshaft by means of flexible coupling to obtain speed and torque measurements. A Hohner shaft encoder with a 720 pulse wheel of 25.4 mm diameter was affixed at the end of the 20 mm camshaft for cam angle triggering. The SCR was equipped with a heating system (HAAKE DC200) to simulate the temperature close to real engine operating conditions. The lubricant bath consists of a 5 L reservoir which was filled with the set amount of the lubricant for the test. The flow rate of the lubricant was controlled by check valves connected to a 6 mm hose. The clearance/gap between the followers and base circle of the camlobes was maintained around 0.11-0.58 mm. This was achieved by using standard production inserts with different thicknesses (i.e. 2.275, 2.575 and 2.75 mm). The centre of the tappet was slightly offset from the centre of the camlobe to facilitate rotation of tappet/bucket for friction torque reduction.



(a)



(b)

Fig. 1. The motored single cam rig: (a) photograph of the rig (b) 2D-schematic diagram of direct acting mechanical type of valvetrain [24]

2.2. Tappet rotation measurement

A range of GMR sensors against magnets were investigated for sensing rotation of the tappet. Initially, a simple test rig (see Fig. 2) was designed (by ReSolve, UK) to help validate and tune the sensor-magnet setup. The test rig was used to evaluate the different sensor board-magnet combinations across varied geometric conditions. The relative orientation of the sensor and magnet was investigated to determine the best signal response while considering the machining and geometric constraints of the cam housing and tappet respectively. The sensor signal was monitored using a data acquisition device (NI myDAQ, National Instruments, USA) while the speed of the motor (918D15112/1, Como Drills, UK) was varied from 0-400 rpm. For a vertical mounted sensor with the magnet configuration shown, a stable pulse train was generated across the entire speed range. This configuration was therefore selected for integration into the cam housing.

The ADV001-00E north-south latching bipolar digital switch sensor (RHOPOINT components, UK) was found to give the highest sensitivity to the magnet/tappet magnetic field within a suitable form factor for integration into the tappet housing. The ADV001-00E was configured with a 5 V supply (myDAQ, National Instruments, Texas, USA) and a pull up resistor to generate a latch low (0 V) signal upon approach with a sufficient magnetic field and high reset (5 V) on presence of an opposing field. As shown in Fig. 3-a, the sensor was installed very close to the tappet/bucket and the wires (from the sensor) were routed out of the rig from the side. Different sizes of magnets (see Fig. 3-b) were initially tested in order to select the right size magnet which has the ability to maintain a strong magnetic field at high temperatures. Therefore, the sensor was coupled with a split pole ferrite disc magnet (12249, RHOPOINT components, UK) which was machined eccentrically into the underside of the tappet (see Fig. 3-c). A material from the tappet was extracted and the magnet (with thickness 0.7 mm) was force fitted onto the tappet. Magnet information (i.e. dimensions and its position on the tappet) are shown in Fig. 3-d. The mass of tappet was checked with and without the magnet and the difference was negligible. Likewise, magnet position did not modify the normal rotation of the tappet. Latching behaviour of the sensor generated a robust pulse train with one cycle per revolution of the tappet allowing rotation count and speed determination. Measurements of tappet rotation were obtained using a data acquisition device and bespoke software (LabVIEW, National Instruments).

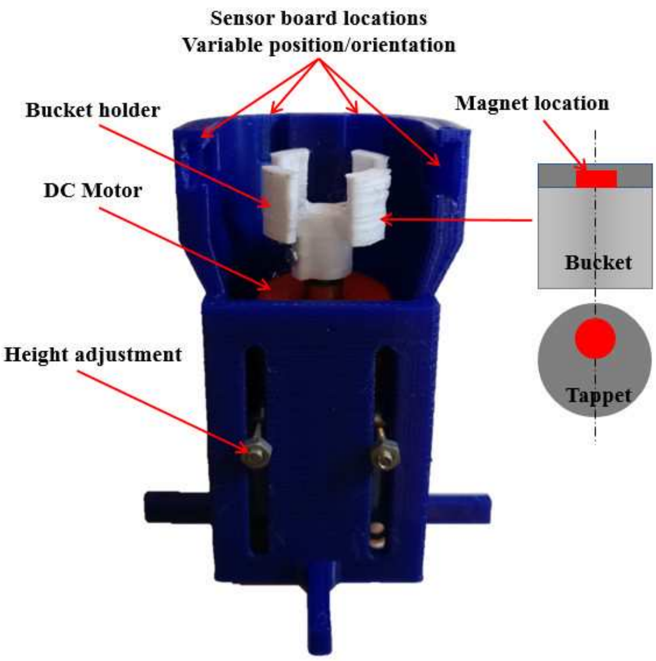


Fig. 2. Tappet rotation test rig

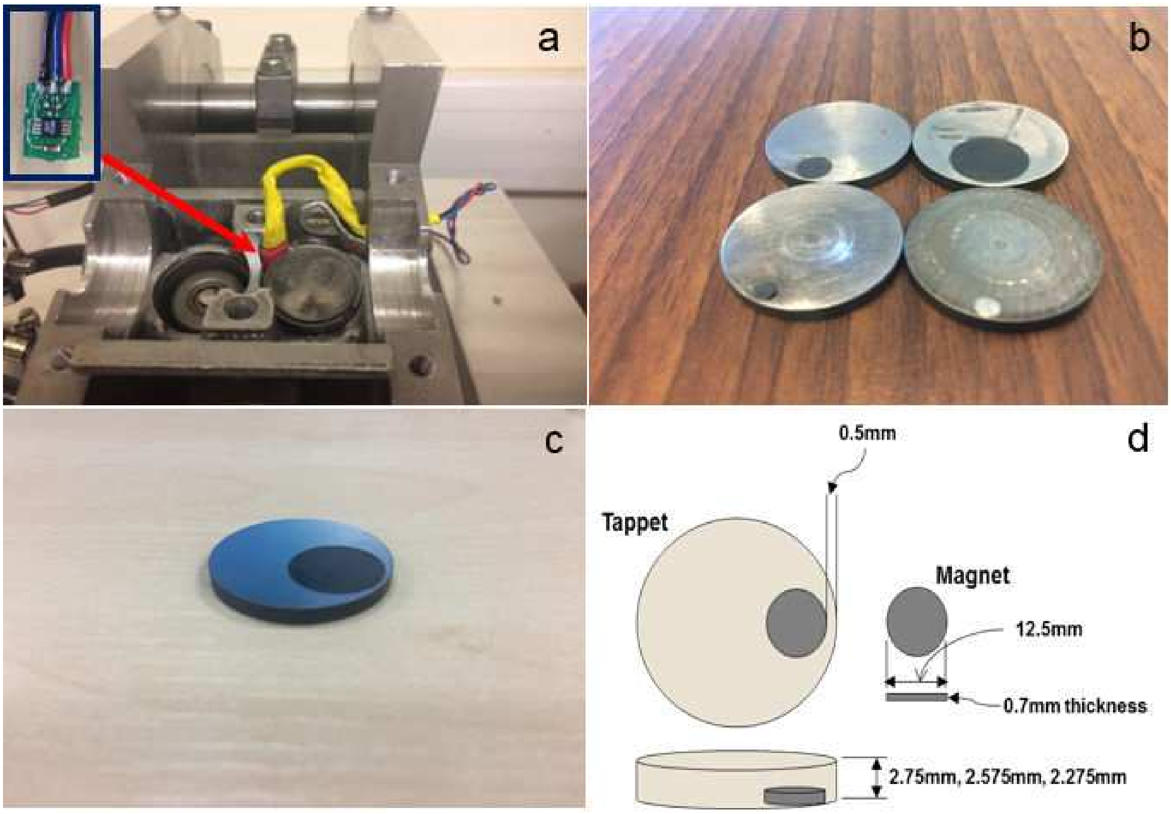


Fig. 3. Sensor and magnet information: (a) sensor position on the single cam rig, (b) different sizes of magnets were initially tested, (c) a magnet force fitted onto the underside of a shim (d) magnet dimensions and position

2.3. Materials

Tests were performed using standard production inserts made of 16MnCr5 steel. The inserts were coated with Mn-phosphate coating ($MnPO_4$) with thickness of 0.5-2.0 µm. On the other hand, diamond-like carbon coating (DLC) with thickness of 1.5-5.5 µm was also evaluated in the motored single cam rig. The surface roughness was 0.25 and 0.02 µm for the Mn-phosphate and DLC coating respectively. The camshaft is a standard production made from chromium chilled cast iron with R_a 0.15 µm. Two lubricants (SAE 5W30) were used in the experiments and both of them were containing 1wt% of Zinc DialkyIDithioPhosphate (ZDDP). However, one lubricant was blended with 1 wt% of Molybdenum Dialkyl Dithiocarbamate (MoDTC). This friction modifier is more effective when used together with the ZDDP and the combination of both offered friction and wear reduction [25-28]. Overall, MoDTC offers low friction, mainly in the boundary lubrication regime, at the tribological contacts due to formation of MoS_2 low friction sheets. It is worthwhile to mention that the lubricants used in this study were commercial and supplied by Total. Therefore, the detailed chemistry of the lubricant cannot be shown due to confidentiality.

2.4. Test procedure

The test procedure has been described in detail previously [23]. However, for durability purposes and wear evaluation, the tests were run for 80 hrs. Tappet inserts of three different thicknesses were used in this study (2.275, 2.575 and 2.75 mm). The samples (camlobes and followers) were cleaned prior to the start of the test using acetone. The oil temperature was maintained at 100 °C and 130 °C, as different test conditions. The lubricant was initially pumped to the single cam rig to heat up the entire setup. The average friction torque was recorded at camshaft speeds of 300, 600, 1000, 1200, 1500, 1800 and 2100 rpm. The average friction torque was obtained by taking an average of the 200 data points obtained for each camshaft cycle (i.e. this corresponds to approximately 1 data point for every 1.8°of cam shaft rotation). The test cycle included two sections: the running-in stage and the steady state stage, as shown in Fig. 4. A whole test contains six cycles (i.e. each cycle takes 12.5 hrs and the total time for each test is 75 hrs, without the running-in time). Tappet rotation was recorded using an advanced data acquisition system. Accordingly, from the LabVIEW software, the rotation was obtained by calculating the number of counts (i.e. pulse counts) per second.

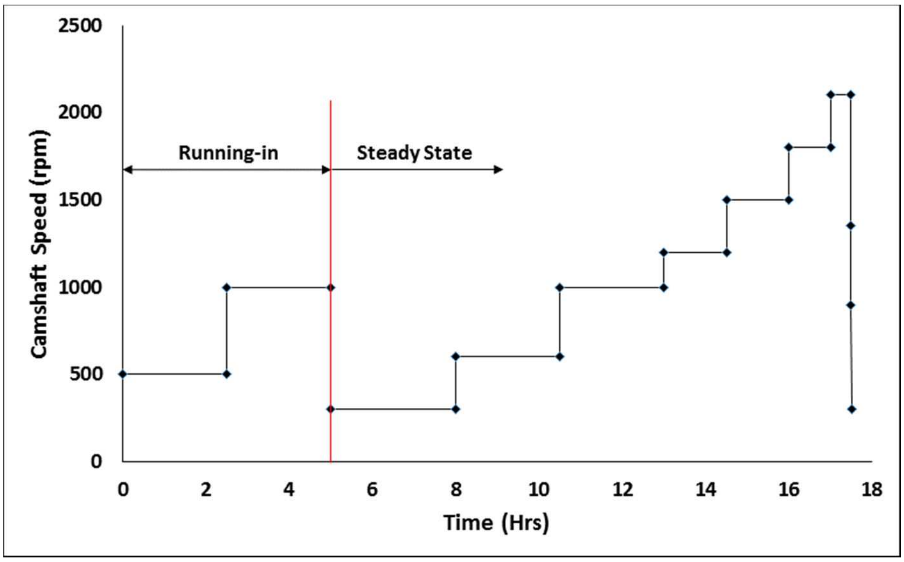


Fig. 4. Single cam rig test cycle

3. Results and discussion

3.1. Effect of test duration on tappet rotation

Initially, the repeatability of the tappet rotation during an 80 hr test was investigated. Fig. 5 compares the number of counts/rotations (per second) at the end of the time for each cycle. In general, it can be seen that the number of counts, for all speeds, gradually increases with increase in the number of test cycles (i.e. longer test duration). This believed to be due to running-in which suggests that the surface of the tappet becomes smoother over time which could potentially lead to a better conformity of the two surfaces in contact. This in return promotes the rotation of the tappet over time. To have a better picture of the effect of test duration on tappet rotation, a representative set of data at 1200 rpm over six test cycles is shown in Fig. 6. A considerable increase of the tappet rotation was observed at the first four cycles. However, tappet rotational speed became fairly stable and comparable for the last three cycles. Therefore, the average tappet speed was generally calculated based on the last three cycles (i.e. steady state rotation).

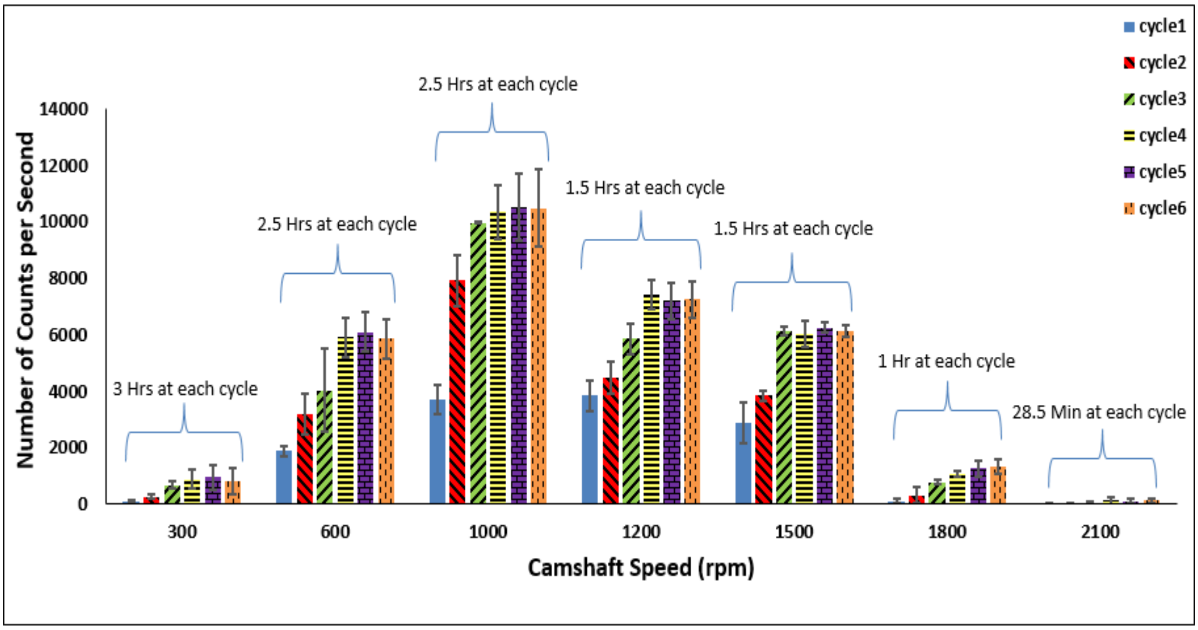


Fig. 5. Number of counts for $MnPO_4$ insert with thickness of 2.75mm during an 80 hour test

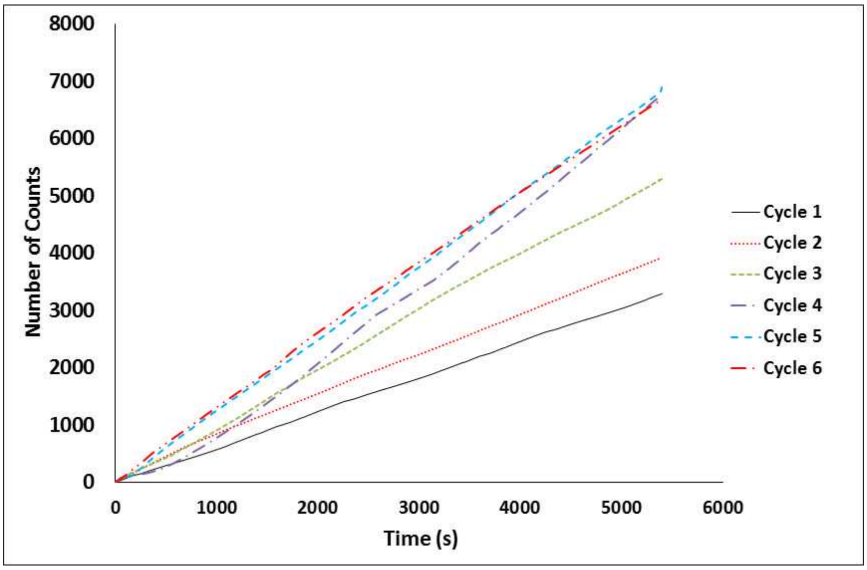


Fig. 6. Repeatability of tappet rotation for $MnPO_4$ insert with thickness of 2.75mm at 1200 rpm

3.2. Effect of tappet thickness and camshaft speed on tappet rotation

For the tappets coated with Mn-phosphate, the effect of tappet thickness and camshaft speed on the average tappet rotation is shown in Fig. 7. In general, tappets with higher thickness showed higher rotation. This could be due to an enhanced interaction between the cam/follower interface when reducing the clearance between the follower and base circle of the camlobe (i.e. increasing the tappet thickness). In addition, based on the configuration of the SCR, the valve lift typically occurs at 112° revolution (i.e. the action angle of cam half period is 56°). Changing the thickness changes the relative point of contact on the camlobe (see Fig. 8). This relative point of contact obviously varies with different variation of the tappet thickness. Therefore, the highest thickness of tappet offers the maximum relative point on contact, which in turn provides longer contact area between the camlobe and the follower. This would lead to a higher tappet rotation with the thicker tappet. From Fig. 7-a, the highest rotation of 2.75 mm insert was observed at 1200 rpm. For this thickness, the tappet speed is directly related to the camshaft speeds of up to 1200 rpm. For speeds more than 1200 rpm, the tappet rotation was decreased gradually and the lowest rotation was at 2100 rpm. Similar results were reported in the literature [1, 9]; they found less rotation in some tappets for camshaft speeds more than 1050 rpm [1] or 2000 rpm [9]. A potential reason for this particular behaviour could be an increase in slip at the cam/follower interface with increase of the camshaft speed. For 2.575 mm thickness, the tappet speed was also increased and the highest rotation was at 1000 rpm. However, the rotation was negligible at camshaft speeds between 1500 and 2100 rpm. For 2.275 mm, there was no rotation at 300 rpm while the highest rotation was at 1200 rpm. Comparing all thicknesses, it is interesting to note that the rotation of tappet was considerable at 2100 rpm when using tappet with the thickness of 2.275 mm. This suggests that a lower slip rate (at the tribocontact) can be achieved with a higher clearance between the cam/follower tribopair.

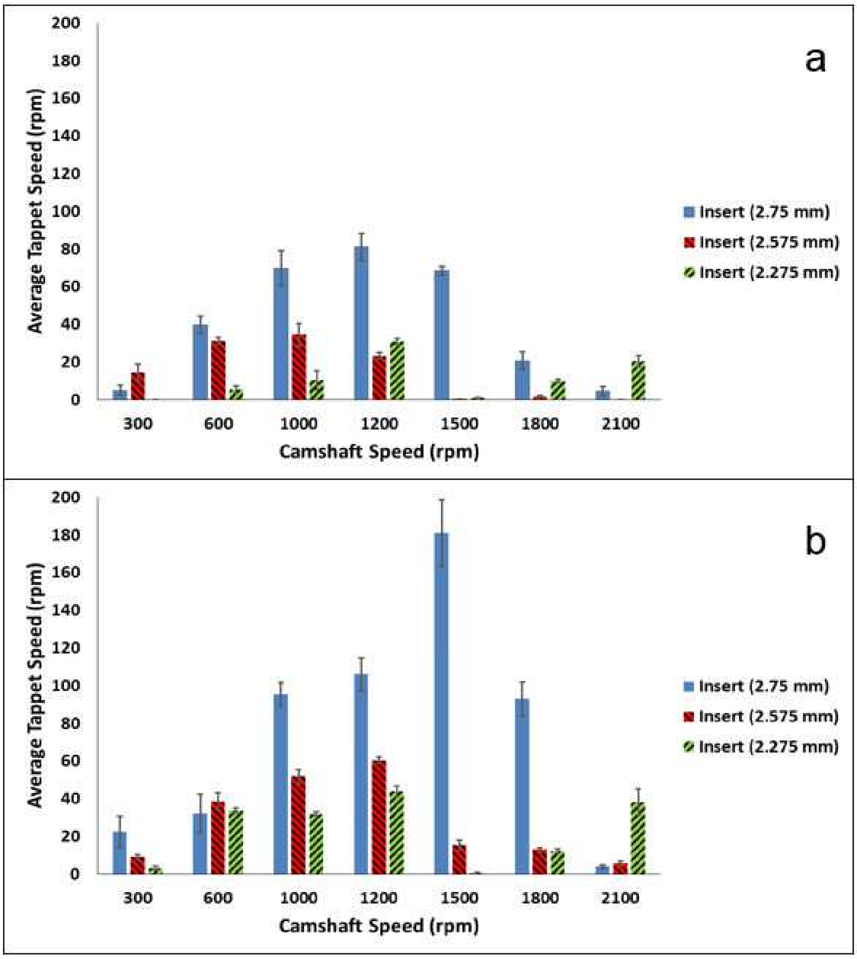


Fig. 7. Average tappet rotation versus camshaft speed for $MnPO_4$ inserts: (a) at 100 °C, (b) at 130 °C

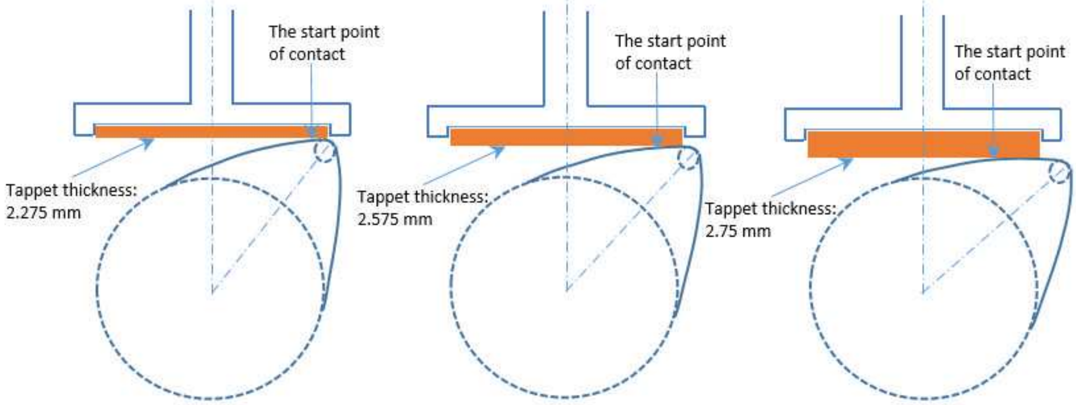


Fig. 8. The start point of contact on the camlobe under different tappet thicknesses

3.3. Effect of temperature on tappet rotation

Figure 7 also shows the effect of temperature on the average tappet rotation. From Fig. 7-b, it can be seen that the rise of the oil inlet temperature to 130 °C clearly increases tappet rotation. This is due to decrease in the oil viscosity, resulting in more mixed to boundary interaction, which lead to the increase in friction at the cam/follower interface. This in return promotes the rotation of the tappet. Similar results regarding the effect of temperature on the tappet rotation were reported previously [1, 2, 15]. However, Monteil *et al.* [9] reported that the tappet rotation is slightly dependent on the temperature while oil pressure has the major influence on the tappet rotation.

3.4. Effect of MoDTC and coating on tappet rotation

Figure 9 shows the effect of MoDTC-type friction modifier on tappet rotation. It can be seen that regardless of type of coating, a significant increase in tappet rotation was reported under the presence of MoDTC. This means that the MoDTC additive helped in increasing tappet rotation (i.e. as the MoDTC was reported to form MoS_2 low friction sheets on the tribological contact, these sheets were suggested to provide a better conformity of the two surfaces in contact which in return increases the rotation of the tappet). Regardless of the thickness, a similar behaviour of tappet rotation was seen for all $MnPO_4$ and DLC inserts under the presence of MoDTC additive.

It is generally proven that coatings have a significant role in reducing wear and friction in a large range of applications. Mn-phosphate ($MnPO_4$) and diamond-like carbon (DLC) coatings are widely used in cam/follower systems. $MnPO_4$ coating has a crystalline, porous, soft and rougher surface finish which provides good oil wettability, absorbance and oil retention characteristics [29]. DLC coatings are considered to be good candidates for reducing friction and improving durability of automotive engines. In particular, tappets coated with DLCs revealed ultra-low friction in boundary lubrication regime even in un-lubricated condition [30]. Thus, investigating the effect of both coatings on tappet rotation was one of the main concerns in this work. Accordingly, the DLC coating was applied for all tappet thicknesses. In both coatings, similar findings were seen regarding the effect of tappet thickness on tappet speed (i.e. tappet with higher thickness generally showed higher rotation). It is apparent that regardless of the type of the coating, the tappet speed is mainly controlled by the tappet thickness. Fig. 9 also shows the effect of both coatings (i.e. DLC and $MnPO_4$) on tappet speed. In general, the tappet speed for DLC insert was also increased gradually with the increase in camshaft speed. For all thicknesses and coatings, the highest tappet rotation was seen to vary with different type of coating and the tappet thickness. Thus, it is fair to conclude that the highest tappet rotation was found to be influenced not only by the camshaft speed but also by the type of coating and the tappet thickness. From Fig. 9, regardless of the effect of lubricant, it is interesting to note that for most camshaft speeds, the tappet rotation for DLC insert was higher than the insert coated with $MnPO_4$. Similar results were generally observed for all thicknesses of the DLC tappets. The higher tappet rotation of DLC coated inserts is most likely one of the main reasons that helped in reducing friction and increasing the antiwear properties of the DLC inserts. Details of this will be published in subsequent work. However, the reason for this behaviour is understood to be mainly due to surface roughness. $MnPO_4$ is rougher than the DLC and the polycrystalline surfaces of $MnPO_4$ resist any motion particularly those due to tappet rotation (i.e. any ridges/grooves on the surface of the insert can directly affect tappet rotation behaviour. Thus, a smoother surface of DLC inserts gave higher tappet rotation than the $MnPO_4$ inserts with a rougher surface). Another important aspect is better running-in properties of DLC surfaces than the Mn-phosphate coating which gives rise to increased tappet rotation at boundary/mixed lubrication regimes.

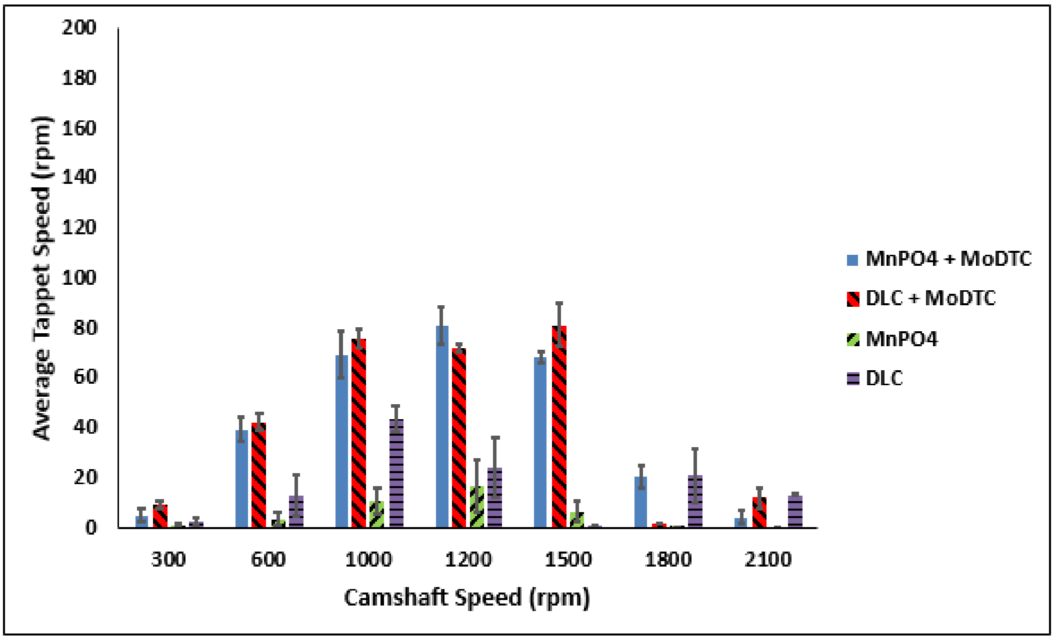


Fig. 9. Effect of MoDTC and coating on the rotation of 2.75mm tappet thickness at 100 °C

4. Conclusions

The following conclusions are drawn based on the adaption of the single cam rig to measure tappet rotation when lubricated in a fully formulated oil containing MoDTC:

- The technique developed in this study facilities evaluation of tappet rotation with good repeatability and high sensitivity to distinguish tappet rotational speed under different temperatures, coatings and thicknesses.
- In both coatings, the thickest tappets showed high rotation, suggesting that the tribological performance is more controlled by the clearance between the follower and the camlobe rather than the type of coating or tappet rotation.
- Regardless of the thickness and coating, a significant increase in tappet rotation was observed when lubricated with fully formulated oil containing MoDTC, suggesting that MoS_2 sheets was led to a better conformity of the cam/follower surfaces which then helped in increasing the rotation of the tappet.

- Based on the findings in this article, we have discovered that tappet rotation is controlled by the following factors in order of impact ;
    - Lubricant formulation (i.e. MoDTC additive).
    - Clearance between the camlobe and the tappet (i.e. coating thickness).
    - Temperature and speed.
    - Surface roughness of the tappet or type of coating.

It is worthwhile to mention that the tribochemistry between the lubricants and coatings was believed to influence the behaviour of tappet rotation.

Further work is underway to link the behaviour of tappet rotation to the tribochemical reactions and the tribofilms formed on $MnPO_4$ and DLC surfaces.

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