DESIGN AND CRANK TRAIN DYNAMICS OF VARIOUS APPROACHES TO CYLINDER DEACTIVATION SYSTEM FOR SPARK-IGNITION ENGINES

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ABSTRACT

Due to the fact that emission reduction has become an important topic and due to the upcoming EURO 7 standard, the automotive industry is focusing on reducing the carbon footprint. One of the ways to do so is enhancing the efficiency of internal combustion engines by technologies such as cylinder deactivation. This technology offers fuel economy benefit, therefore, also CO_2 emission reduction. However, implementing cylinder deactivation to modern engines with lower cylinder count can be challenging. The implementation requires numerous design modifications and some negative consequences like higher torsional vibration are associated with the technology. This paper focuses on investigating these constraints of cylinder deactivation.

KEYWORDS

Selective cylinder deactivation, rolling cylinder deactivation, torsional vibration, switchable pivot element, movable cam sections

1 INTRODUCTION

The first implementation of cylinder deactivation (CDA) dates back to the turn of nineteenth and twentieth century and many car manufacturers have attempted to incorporate the technology to their cars [Wilcutts 2013]. However, the systems were not reliable enough, therefore, the technology has not been widely used and investigated for many years. Engines with CDA deactivate some of the cylinders in part-load operation by closing the intake and exhaust valves and deactivating fuel injectors and spark plugs of chosen cylinders. Remaining cylinders operate at higher load and lower brake specific fuel consumption [Baykara 2017] caused also by lower cylinder-wall heat loss and reduced pumping losses [Zhao 2018, Rimar 2022]. There are also negative consequences of implementing CDA that must be taken into consideration. The most important negative effects include worse NVH [Archer 2018], higher frictional losses [Morris 2018], uneven wear [Turnbull 2021], increased temperature of components [Bech 2016] and higher engine oil consumption [Ma 2010]. This paper deals with part of the NVH issue, specifically with increased torsional vibration of the crankshaft [Smeringaiova 2021].

CDA can be divided according to the confined gas in deactivated cylinders [Faust 2016, Kuznetsov 2020]. The most usual ways are trapping exhaust gas or fresh air. The last option is the low-pressure technique that uses the state near vacuum inside the cylinder. However, there are many constraints to this approach, such as high oil consumption through the piston rings [Drapal 2016], therefore, it has never been used in mass production. Even though there are studies focusing on introducing CDA to compression-ignition engines [Joshi 2018], the technology shows the greatest fuel economy benefit for spark-ignition engines [Fridrichova 2021]. The CDA system can also be combined with other measures to increase engine efficiency [Drapal 2018].

There are two possible approaches to CDA. The first one is called selective CDA. With this approach, the engine is capable of deactivating only some of the cylinders that are specified during the design process, and these cylinders are equipped with switchable elements. In comparison, rolling CDA changes the number of firing cylinders on cycle-to-cycle basis. All of the cylinders need to have switchable elements and the number of active cylinders can be adjusted according to the actual load of the engine. This method could even substitute throttling. Rolling CDA offers wider range of firing sequences, and therefore, the engine works with lower fuel consumption and the NVH caused by CDA can be partially mitigated [Scheidt 2015]. The difference between those two methods is explained graphically in Figure 1. The presented firing patterns are used in this study to compare these two methods for spark-ignition engine with firing order 1-3-4-2.

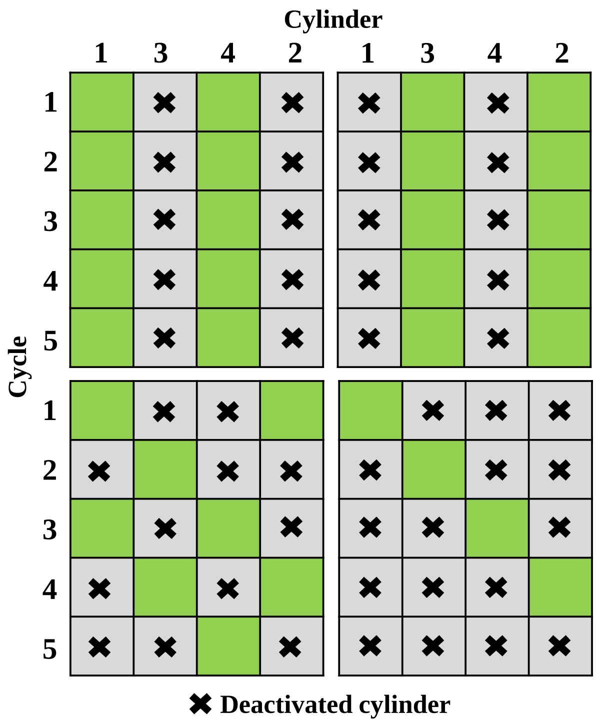

Figure 1. Comparison of firing patterns for selective (upper) and rolling (lower) CDA

The upper part of the figure shows the selective CDA method, the usual approach used in mass production is deactivation of inner cylinders, however, this study investigates also the effects of deactivating outer cylinders. The lower part of the figure shows two firing patterns used for rolling CDA.

2 EXPERIMENTAL CONDITIONS

There are many possibilities of implementing CDA. The most common ones are switchable roller finger followers [Hoffman 2009], switchable hydraulic valve tappets [Maehara 2010], switchable rocker arms [Kreuter 2001], switchable pivot elements with hydraulic lash adjusters [Ihlemann 2014] and movable cam sections [Middendorf 2012]. The last two are the chosen design options for implementation of CDA in this paper. Implementing rolling CDA can be challenging because each cylinder needs to be equipped with the switchable elements. The investigated engine is a four-cylinder spark-ignition engine used in passenger vehicles. The aim is to redesign the engine with selective CDA to accommodate rolling CDA.

2.1 Switchable pivot elements

Switchable pivot elements with hydraulic lash adjusters used for CDA are bigger than the usual lash adjusters. They are controlled by solenoids adjusting the oil pressure in the system. The size of the lash adjusters and the necessity of redesigning the oil gallery led to the concept where a part of the engine head must be removed and replaced by an insert. The pressure oil is distributed via the solenoid to a set of grooves in the cylinder head cover, camshaft caps and the camshaft. Each camshaft cap has two grooves. The oil from the solenoid goes from the first groove to the second one via the groove in the camshaft. The oil from the second groove is then fed through the galleries in the head cover and the engine head into the switchable pivot element of the cylinder that should be deactivated. This system is shown in Figure 2 and the design is carried out using state-of-the-art computer methods [Kasparek 2017].

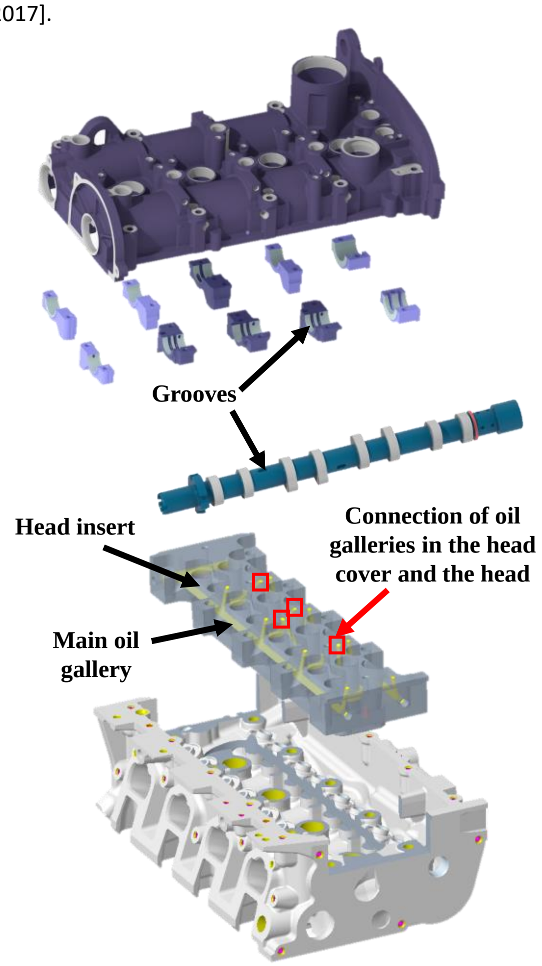

Figure 2. Design modifications of system with switchable pivot elements

The switchable pivot element consists of two parts, the inner and the outer part. Higher oil pressure disengages these two parts, and the inner part moves freely in the outer part, absorbing the whole cam lift instead of the valve placed on the second side of the roller finger follower. The cylinder is reactivated when the oil pressure drops. The whole engine head assembly can be seen in Figure 3.

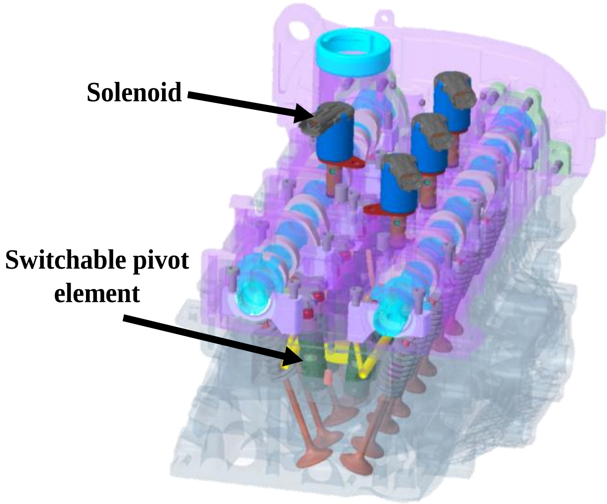

Figure 3. Engine head with incorporated CDA system

2.2 Movable cam sections

The second option was using the movable cam sections introduced by VW Group. The most important advantage of this approach is the fact that only the cylinder head cover must be adjusted to incorporate all the necessary design changes. The engine head remains the same as for engine without CDA. The technology is widely used for selective CDA. Adjusting the concept for rolling CDA is challenging due to the limited design space. The system for selective CDA incorporates four actuators. However, there is not enough space to add more actuators, therefore, all the cylinders for rolling CDA must be deactivated and reactivated using the same number of actuators. The system is shown in Figure 4.

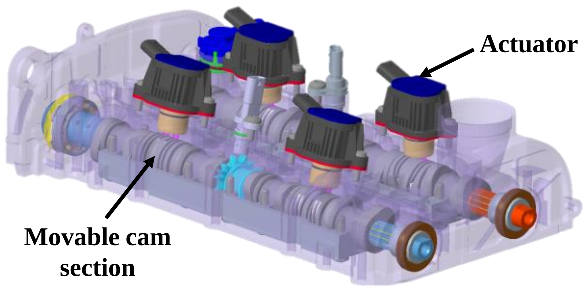

Figure 4. Engine head cover with implemented movable cam sections

Movable cam sections consist of a cylindrical part with grooves and cams, where one of these cams is a zero-lift cam. This approach uses electromagnetically actuated pins that extend to the groove on the movable cam section. This cam section is forced to move axially positioning the zero-lift cam into the contact with roller finger follower instead of the full-profile cam. For implementing rolling CDA, twice as many pins and grooves had to be used. Each actuator has to be able to deactivate not only one of the cylinders but two, one at each side during one revolution of the crankshaft. The cam part is divided into three sections. One of them is a zero-lift cam and the remaining two are full-profile cams. The mechanism is explained in Figure 5. The brown objects are roller finger followers that are in contact with the cam.

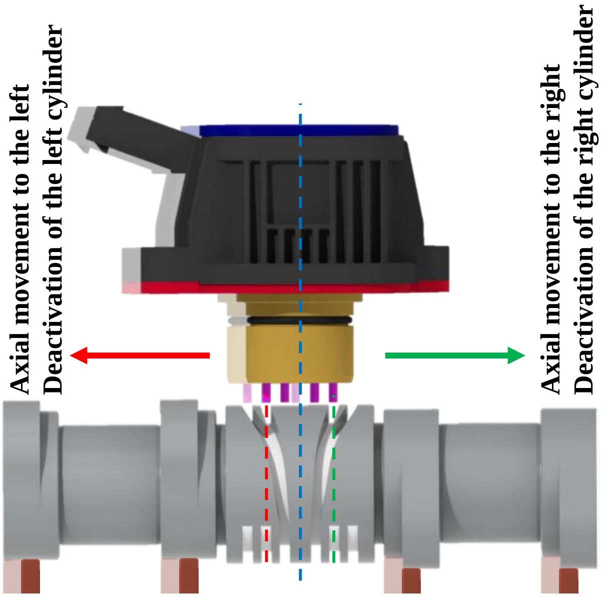

Figure 5. Possibilities of axial movement of cam section

In the position that is shown in the Figure 5, the mechanism can extend the pin into two possible grooves and cause the deactivation of each of the neighbouring cylinders. The semi-transparent part of the Figure 5 shows the position of the mechanism if the movement marked with green arrow would be done. It is important to note that the cam section is the part that moves. The actuator and the roller finger followers are still in the same place. Figure 5 is only showing the relative position of these parts to each other in those two situations. In the semi-transparent position, the mechanism could go back to the initial position or deactivate the left cylinder by extending the pin that is the most on the left into the groove. The second of these two cylinders would be deactivated right in the next cycle, which is not possible in the selective cylinder deactivation design of movable cam sections. However, it is clear that this concept is not suitable for rolling CDA. Firstly, the pins are inadequately sized to withstand the load. Secondly, this design does not enable deactivating both neighbouring cylinders at once.

2.3 Multi-body model

The next step of the study was to evaluate seective and rolling cylinder deactivation in terms of torsional vibration. A multi-body model of the engine is used for this purpose. The model incorporates also flexible crankshaft and flexible engine block (including cylinder liners, main bearings, bolts and main bearing caps). These flexible parts have to be meshed and undergo modal reduction using the Craig-Bampton method [Cacko 2014].

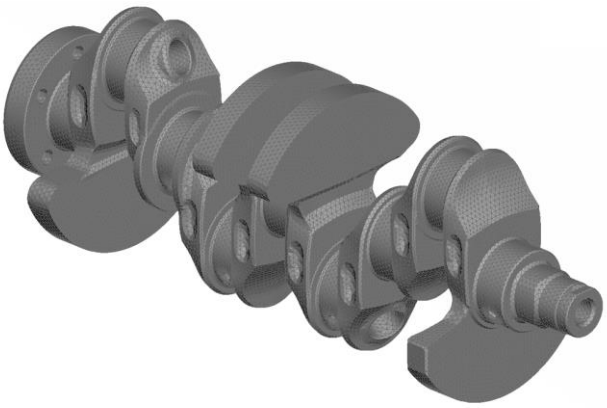

Figure 6. Meshed crankshaft prepared for modal reduction

Modally reduced bodies are then implemented into the model. An example of the mesh can be seen in Figure 6. The model of the crankshaft is meshed using tetrahedrons.
The meshing is done using ANSA software, the modal reduction is carried out in ANSYS and the model is built in Virtual Dynamics. The flexible bodies are connected to the system via interface nodes. These interface nodes are connected to the structure via rigid beam elements. It is important to check excessive stiffening of the flexible body caused by added beam elements. The modal analysis is performed to verify the issue. The whole model including flexible parts is shown in Figure 7. Engine oil specification is 5W-40. The torsional vibrations are evaluated on the crankshaft pulley, therefore, it is important to mention that the model uses torsional vibration damper with loss angle of 5.7°. The engine is connected to a virtual dynamometer [Drapal 2020]. Simulations are performed in the time domain [Kasparek 2015].

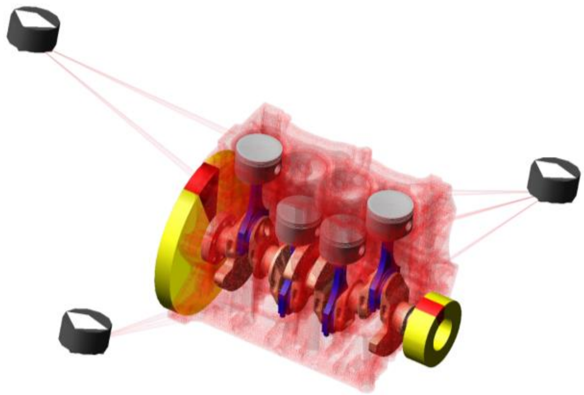

Figure 7. Multi-body model of investigated engine

The most important input needed for simulating engine with CDA is pressure in the combustion chamber. The pressure is obtained by indication of the engine on the test stand. The results from 200 cycles are processed with synchronous filtration. The setup of the measurement is shown in Figure 8.

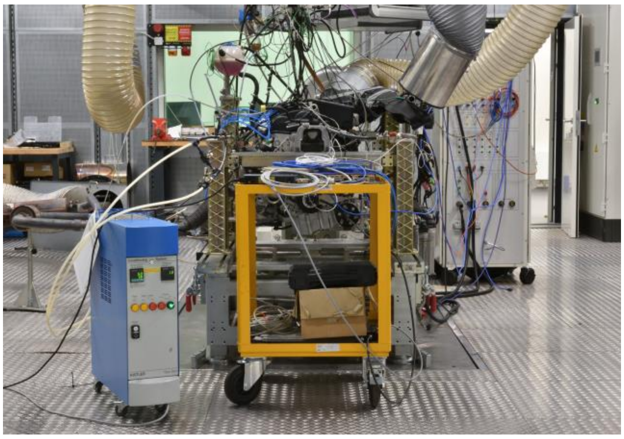

Figure 8. Measurement setup on dynamometer

This study compares different approaches to CDA with the situation where all cylinders are active in part-load operation. The selected engine load is 40% and 20%. There is only compression and expansion of the air in the deactivated cylinders. Selective CDA deactivates inner or outer cylinders. The pressure in active cylinders for selective CDA at 40% load is similar to all-cylinder operation at 80% engine load. Likewise, the pressure in active cylinders at 20% load is similar to all-cylinder operation at 40% of engine load. The pressure in active cylinders for rolling CDA equals to the pressure at full load. The percentage of engine load is equal to the number of active cylinders. The comparison of the pressures for 40% load is in Figure 9.

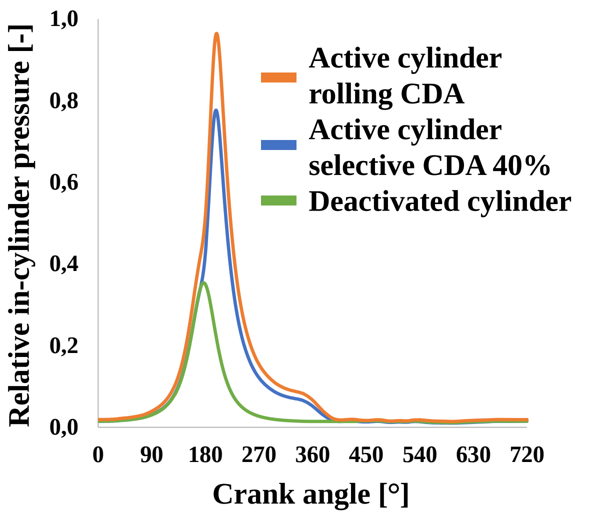

Figure 9. Comparison of relative in-cylinder pressure used for simulation

3 RESULTS AND DISCUSSION

The main aim of the study is to compare different approaches to CDA in terms of torsional vibration. The simulations of all-cylinder mode at 40% and 20% load are also carried out for better comparison. The crankshaft pulley angular displacement incorporates crank train speed oscillations as well as torsional deformation of the crankshaft [Mascenik 2020]. Figure 10 shows the relative crankshaft pulley angular displacement for different CDA configurations. The worst results are obtained by deactivating outer cylinders.

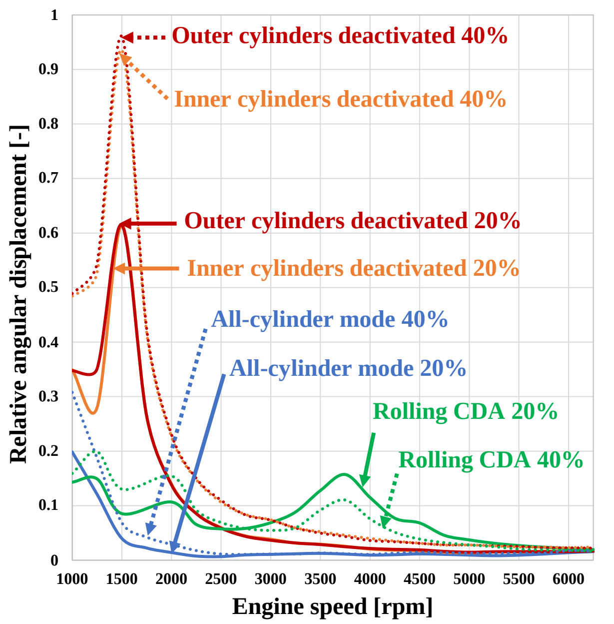

Figure 10. ½ peak-to-peak value of relative crankshaft pulley angular displacement for different CDA approaches

CDA decreases the firing density. This leads to higher irregularities on the crankshaft. Selective CDA deactivates two out of four cylinders, which notably increases the pulley angular displacement in low engine speed. The increase is caused mostly by the 1st harmonic component. This component takes a big share on crank train torsional vibration during its resonance at 1500 rpm. Cylinder deactivation changes the dominant orders of harmonic components, therefore, a harmonic analysis has to be performed. The results of harmonic analysis for selective cylinder deactivation of inner cylinders with 40% engine load are shown in Figure 11. The results for deactivation of outer cylinders and 20% load followed the same trend. The peak at 1500 rpm is always caused by the 1st harmonic component.

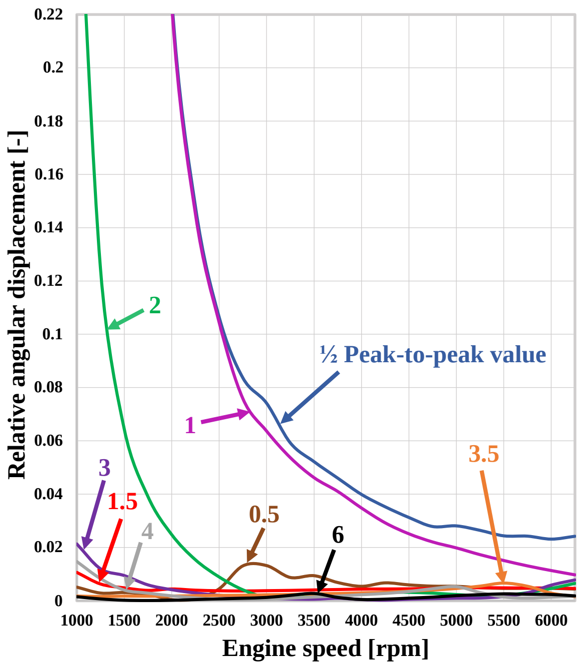

Figure 11. Harmonic analysis of crankshaft pulley angular displacement for selective CDA with deactivation of inner cylinders (40% of engine load)

Rolling cylinder deactivation causes increased pulley angular displacement too. However, the results are more favourable. The harmonic analysis must be carried out for orders of the harmonic components that are multiples of 0.1 due to the fact that the sequence of rolling cylinder deactivation repeats after ten revolutions of the crankshaft. Dominant harmonic orders for rolling CDA with chosen firing pattern for 40% load are 0.4, 0.8 and 1.2 as can be seen in Figure 12. Again, the results for 20% engine load follow the same trend.

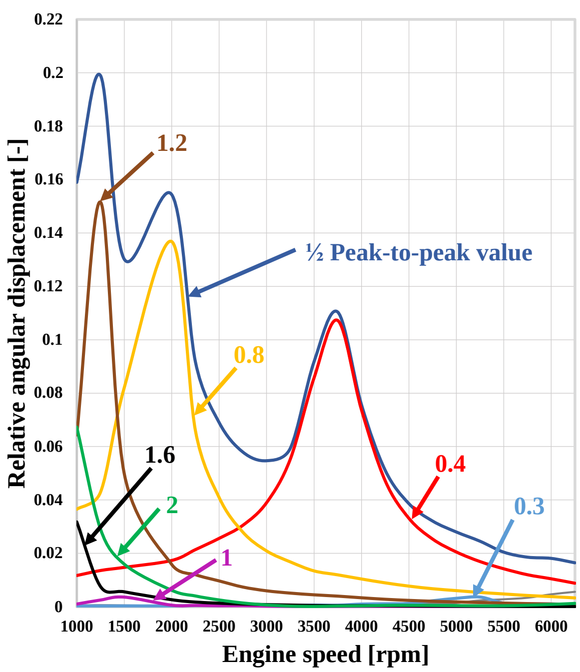

Figure 12. Harmonic analysis of crankshaft pulley angular displacement for rolling CDA (40% of engine load)

4 CONCLUSION

Even though CDA is a technology that has been in production for many years, there are still areas that could be improved and investigated. One of those is rolling cylinder deactivation. Rolling CDA is more complicated and costly for implementation than the selective method. However, it can further decrease the fuel consumption. Selective CDA cannot be used in some of the operating points of the engine due to excessive torsional vibration. Rolling CDA can broaden the operation zone of CDA. Implementing CDA with movable cam sections led to design problems and it would not be suitable for this type of engine. The approach using switchable pivot elements with hydraulic lash adjusters proved to be more appropriate for accommodating rolling CDA. Selective deactivation of two cylinders caused a significant increase in pulley angular displacement caused mostly by the 1st harmonic component. This issue could be partially mitigated by using rolling CDA, where the results are more favourable.

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