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Improvement of Full-Load Performance of an Automotive Engine Using Adaptive Valve Lift and Timing Mechanism

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Abstract

This paper describes an improvement of full-load performance of an internal combustion engine using Adaptive Valve Lift And Timing Mechanism (AVLT). AVLT enables engine power improvement by increasing valve timing and lift at high engine speed and load operating regions. It utilizes engine fluids pressure difference with respect to engine speed to actuate the AVLT mechanism which will make the valve lift higher and longer duration at higher engine speed and loads. Since engine speed and load can be linearly correlated to these pressures, a mechanical sliding arm valve actuation mechanism is constructed based on their transient behavior. Therefore, a continuously dynamic valve lift profile with respect to engine speed can be achieved to increase brake power of the engine. Dynamics analysis performed using MSC Adam software showed that tappet translation increased by 32% from 9.09 mm to 12.01 mm by varying translational skate position between 0° and 10°. The results from this simulation are then set as intake valve profile in Lotus Engineering software simulation. With AVLT, brake power at speed between 5000 and 6500 rpm increased between 2% to 7%. Maximum torque improvement was realized at 7000 rpm while BSFC was reduced by up to 2% at 7000 rpm. The increased in brake power and torque are direct results from volumetric efficiency linear improvement between 1.5 and 6% at speed range of 5000 to 7000 rpm.

Keywords: Variable valve timing; Charge formation; Volumetric efficiency; Brake power; BSFC

Introduction

Direct fuel injection has been used in internal combustion engines to improve volumetric efficiency of internal combustion engines which results in increased heating value of cylinder charge for specific power improvement. It also enables charge stratification and unthrottled operation which are favourable for improved thermal efficiency. Compressed natural gas spark ignition engine can significantly benefit from direct fuel injection due to the problem with displaced air in the intake manifold that reduces output power in port fuel injection system. Compressed Natural Gas Direct Injection (CNDGI) engine is fuel-efficient, environmentally friendly and offers low overall vehicle ownership cost [1]. By understanding the behaviour of CNGDI engine, changes can be made in order to improve thermal efficiency and performance including optimization of compression ratio, valve lift-timing profile, as well as design of exhaust and intake manifolds.

One of the major aspect in improving engine performance lies on the optimization of valve lift and timing of an intake valve [2]. The intake (as well as exhaust) valve profile determine the quantity and quality of air-fuel mixture in the combustion chamber, which affects the power produced. In spark ignition engines, intake valves close during the initial part of compression stroke and the spark plug ignites the air-fuel mixture at the end of the stroke, creating a force that eventually propels the car forward. Most engine have intake and exhaust valves at the top of the cylinder. Other engines, however, may put the valves on the sides. The valves can also be in a combination with one valve on the top of the cylinder and the other located on the side [3].

In internal combustion engines, Variable Valve Timing, often abbreviated to VVT, is a generic term for an automobile piston engine technology. VVT allows the lift, duration or timing of the intake or exhaust valves to be changed while the engine is in operation. The advantage of varying the valve lift and timing is useful either for slow driving or fast driving [4]. The mechanism of VVT varies from retarding, forwarding and even makes the valve lift higher and longer duration. Variable valve timing available at present are Variable Valve Timing-intelligent (VVT-i), Variable Valve Timing and Lift Electronic Control (VTEC), Cam Profile Switching system (Campro CPS), Mitsubishi Innovative Valve-timing-and-lift Electronic Control (MIVEC) and Variable Nockenwellen Steuerung (Vanos). These systems adjust the cam profile with respect to speeds and load conditions either for power, emissions or thermal efficiency improvements.

VVT-i and Vanos have similar operating mechanism where the cam profile is forward and retarded at low and high engine speed. VVT-i adjusts valve lift timing to make the valve open later in smooth idle speed and open earlier in medium speed. Vanos adjusts valve lift timing to make the valve open later in low speed, valve open earlier in medium speed, and opened later in high speed [5,6]. VTEC and Campro CPS have similar operating system where they use trilobe cam for every valve. Cam profiles changed by switching lobe profile for the valve. VTEC Uses engine oil pressure to push rocker arm pin when switching from low profile to high profile. However, Campro CPS Have Variable Intake Manifold (VIM) to switch between a long intake manifold at low engine speeds and a short intake manifold at higher engine speeds and uses electronically controlled tappets to change from low to high profile cam. MIVEC Switching cam lobe profile from

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low lift and duration valve lift to high lift and duration as the engine speeds up it uses engine oil pressure to push a piston to lock T-lever upon activating high cam profile. Profile changes of MIVEC system depending on engine oil pressure which activating high cam profile at certain value of engine oil pressure.

Although there are many VVT mechanisms available in standard production cars, they mainly applied to petrol spark ignition engine and valve profile changes are actuated at a certain predetermined value. There are some challenges to overcome including power drop at high speed operations caused by multiple factors including decreasing volumetric efficiency. This challenge can be more serious with gaseous fuel. This paper explains a development of an adaptive variable valve and timing mechanism for a CNGDI engine and the performance improvements at high speed and load operations. AVLT mechanism is designed with the aim to maintain engine volumetric efficiency at high speed and high load by making the valve lift higher and longer at those conditions.

Analysis of Adaptive Valve Lift and Timing

Analysis of adaptive valve lift and timing were made to determine the improvement of high end performance using Adaptive Valve Lift and Timing (AVLT). It includes mechanism modeling, dimension analysis and engine simulation test with chosen engine specifications. The mechanism was designed so that it can possibly be mounted on the engine head and improves valve lift and duration upon actuation. The valve lift, duration and timing were varied to determine the improvement of using AVLT.

Engine specifications

A 1.6-liter Proton Campro engine with dual overhead camshaft (DOHC), multiport fuel injection (MPI) was used in this work. This engine is design for gasoline operation and later converted to CNG operation in this study. The specifications of the engine, intake valve and exhaust valve are listed in Tables 1-3.

AVLT mechanism

The VVT system that is presented in this paper is a pressure differential Adaptive Valve Lift and Timing (AVLT) mechanism. With some modification on cylinder head, this mechanism is integrated with the existing cam system with some retrofitting. As seen in (Figure 1), it is a push-rod/rocker type mechanism that able to adjust the intake valve lift consisting oscillating follower and a translational skate [7,8]. The position of translational skate is adjusted by a control lever and a connecting rod so that every valve lift can be achieved continuously between minimum and maximum value during operation. The position of the control lever is given by a hydraulic cylinder that is controlled in respond with lubricant oil pressure. The oil pressure needed to set the hydraulic cylinders piston displacement, thus the intake valve lift is controlled. Since the lubrication oil and cooling water pressure increases linearly with engine speed, output from lubricant oil pressure can be used to set the skater's position where low engine speed will place the skater at the minimum valve lift position illustrated in Figure 2, and continuously adjusts the skater position towards maximum valve lift position to make the valve lift higher and longer duration.

Parameters	Units	Specifications
Number of cylinders	-	4
Displacement	cc	1597
Firing order	-	1-3-4-2
Bore	mm	76
Stroke	mm	88
Bore spacing	mm	82
Connecting rod length	mm	131
Piston compression height	mm	26
Compression ratio	-	10:1
Valve centre distance	mm	34
Intake valve inclination	degree	21.5
Intake valve diameter	mm	30
Exhaust valve inclination	degree	20.5
Exhaust valve diameter	mm	25
Hyd. Tappet diameter	mm	32
Maximum torque	Nm @ rpm	148 @ 4000
Maximum power	kW @ rpm	82 @ 6000

Table 1: Engine specifications.

Parameters	Unit	Specifications
Maximum lift	mm	8.10
Length	mm	115.11
Diameter	mm	31
Camshaft/bore offset	mm	66.60
Valve open	°	12 BTDC
Valve close	°	48 ABDC
Lift duration	°	240

Table 2: Intake valve specifications.

Parameters	Unit	Specifications
Maximum lift	mm	7.50
Length	mm	113.31
Diameter	mm	26.75
Camshaft/bore offset	mm	65.20
Valve open	°	45 BTDC
Valve Close	°	10 ATDC
Lift duration	°	240

Table 3: Exhaust valve specifications.

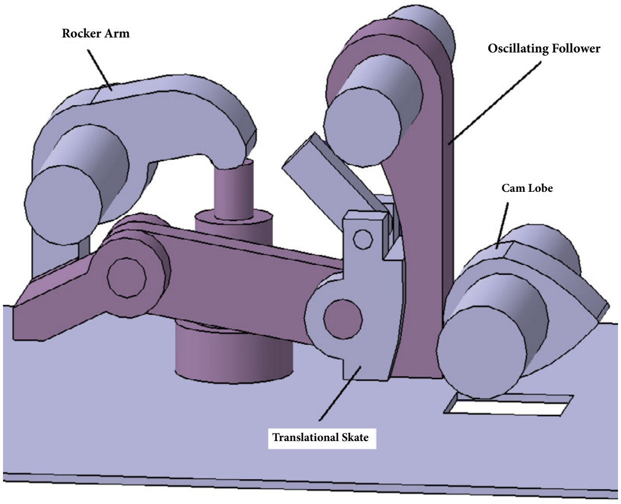

Figure 1: AVLT mechanism.

Dimension Analysis

Dimension analysis were carried out using MSC Adams to analyze the translation of tappet. Translational skate positions were varied to determine the differences in tappet translation. The position of translational skate is set so that the minimum translation position is matching with the default valve lift and timing of the cam profile would have do and is set to the maximum translation of tappet the mechanism can do. Figure 3 shows the maximum translation of skater position and is set as reference angle for this analysis.

Test result were varied for 0° (maximum), 5° and 10° (minimum) of translational skate position [9]. Test were carried to determine the differences between the tappet translation that directly moved by cam and the tappet translation made by mounting the mechanism. Figures 4 and 5a and 5b show the example of tappet translation analysis in MSC Adams for maximum translation of skater position.

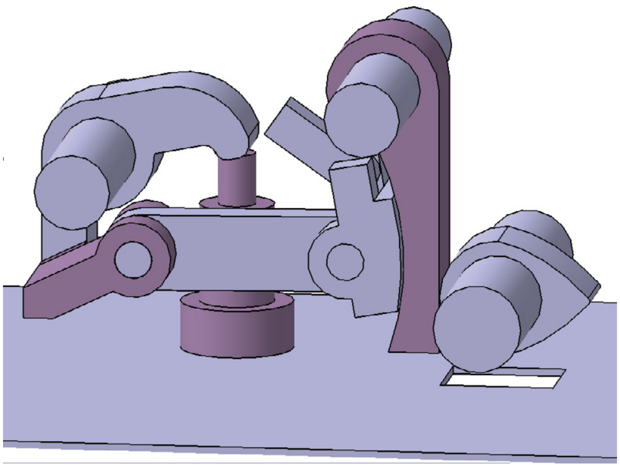

Figure 2: Minimum skater position of AVLT mechanism.

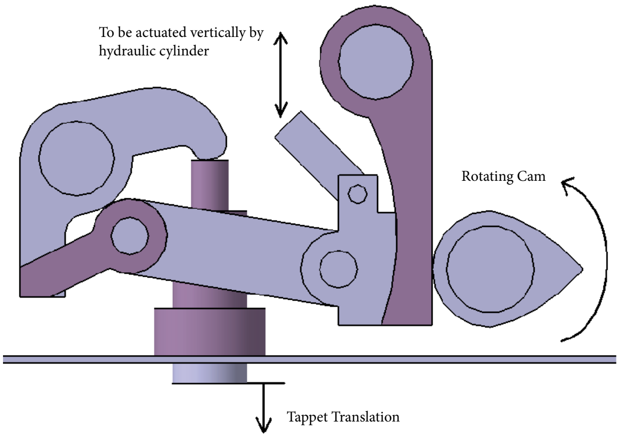

Figure 3: Maximum translation of skater position.

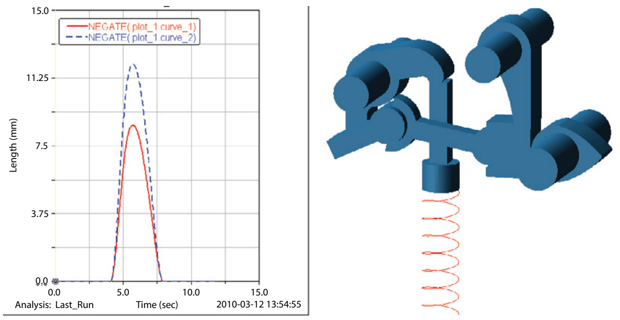

Figure 4: Simulation in MSC Adams for maximum tappet translation of skater position before started.

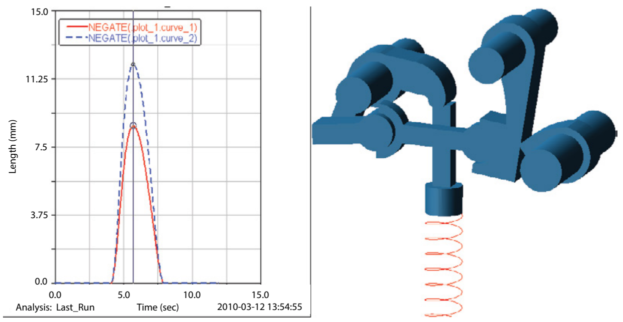

Figure 5a: Simulation in MSC Adams for maximum tappet translation of skater position in maximum lift.

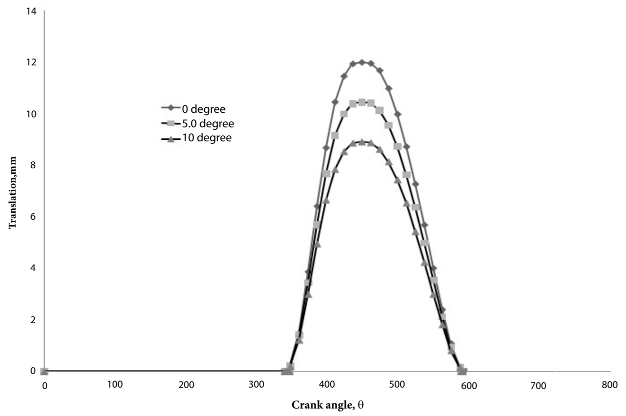

Figure 5b: Tappet translation against crank angle at various skater position.

By using the AVLT mechanism, the tappet translation of normal cam can be improved considerably high. By varying the skater position, translation range can be set from minimum value to a maximum value when the AVLT mechanism actuated. Figure 5a and 5b illustrates the results from simulation of tappet translation from variable position of skater.

Result from the simulation shows that the maximum value of tappet translation is 12.01 mm in 0° of skater position and improves default tappet translation by 2.92 mm. By varying the skater position, the values of tappet translation were increasing from the minimum position (10°) towards the maximum position (0°). This proves that by varying the skater position in the mechanism can vary the intake valve lift corresponded to engine speed.

Engine simulation test

In order to determine the effect of AVLT to the engine performance, engine test simulation was done by using Lotus Engineering Software. With this software, engine parameters can be input to the engine map in various conditions. By using the results from dimension analysis, valve lift and duration data were inserted to the valve specifications thus the performance result on power, torque, mean effective pressure, specific fuel consumption and volumetric efficiency can be acquired. Figure 6 shows the engine map constructed in Lotus Engineering Software with Campro 1.6 engine specifications [9,10].

Simulation were carried by 4 phases, first is the performance of modifying the valve lift from AVLT of the engine, second is by making the valve lift earlier (forwarded) and modified valve lift, third by making the valve close later (retarded) and modified valve lift, and lastly a combination of retarded, forwarded and modified valve

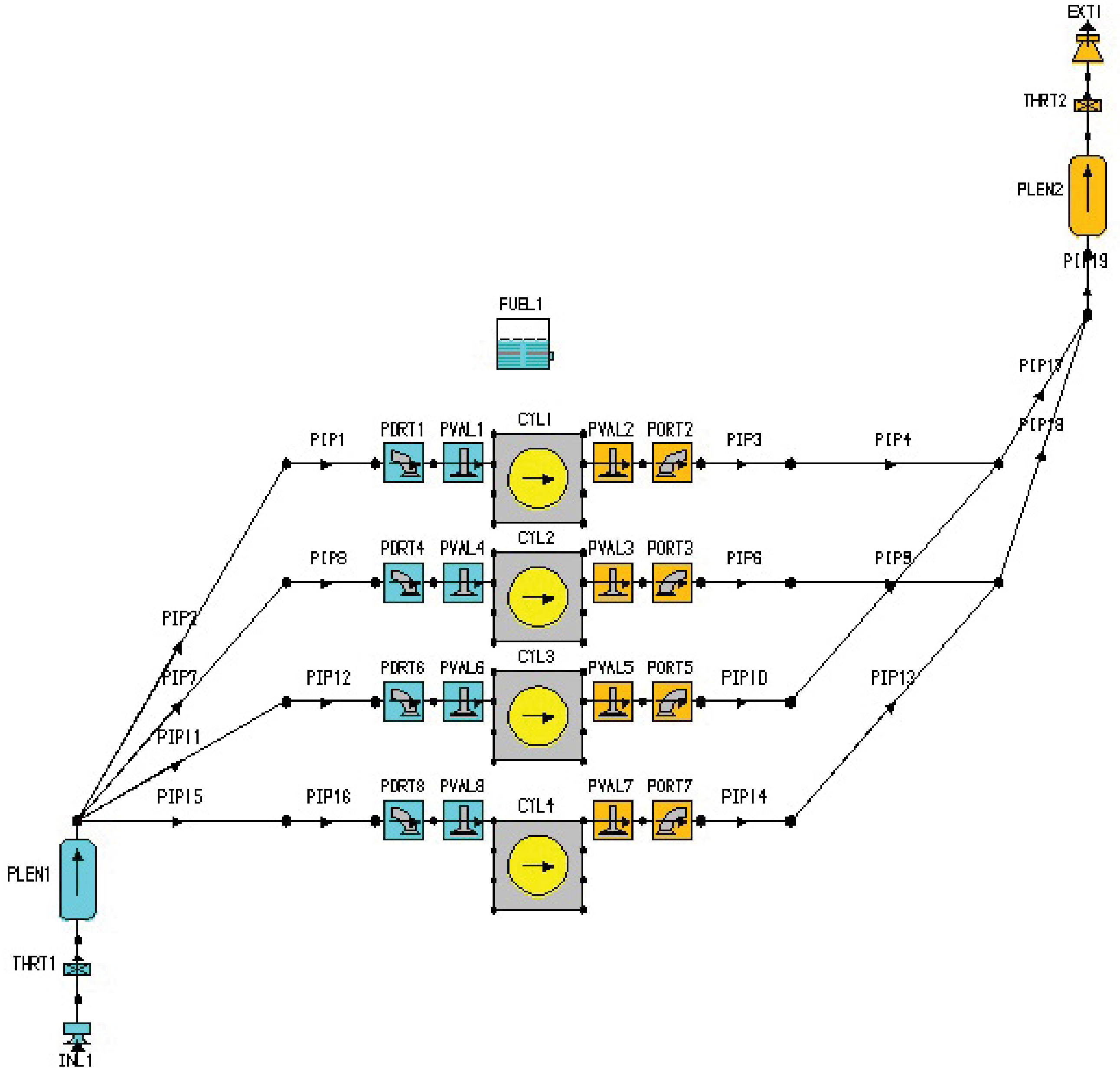

Figure 6: Engine model in Lotus Engineering Software.

lift. Translation values (skater position) were varied from 0° and 10°, forwarded, retarded and both forwarded and retarded values were varied from 0° and 5°. From the simulation of various parameters on the intake valve profile, performance data were acquired. Figures 7-9 show the power, torque, and BSFC output data graph of engine simulation test. All data were plotted from 5000 to 7000 rpm as the improvement of using AVLT only influenced the performance in this area.

As indicated in Figures 7 and 8, power and torque output varies for every parameter. Every condition set by AVLT proven to improve the power and torque output of the engine. In minimum translation condition as standard valve lift, the combination of forwarded and retarded give the highest power and torque output compared to others. However, the value is closed to retarded which make the retarded position is more efficient as the valve lift duration only needed to be delayed 5 degree of camshaft angle rather than opening it and closing it earlier and later. In the other hand, forwarded condition only improves output power and torque by small value and not improving much. These behaviors also showed by maximum translation condition of AVLT, but with higher power and torque output as the valve lift higher than the minimum condition [10].

In terms of BSFC, by making valve lift higher, forwarding and retarding the valve lift duration lowers BSFC of the engine. The data plot behavior is the same either in minimum lift or maximum lift of AVLT where maximum lift of AVLT gives much lower BSFC. The combination of forwarded and retarded valve lift duration gives the lowest BSFC and forwarded lift gives the highest BSFC. This behavior is similar to torque and power where the retarded lift having a close value with the combination of forwarded and retarded.

Figure 10 illustrates the improvement percentage of engine's volumetric efficiency. As shown in figure, forwarded valve lift with minimum lift of AVLT has the lowest improvement and starts after 5000 rpm compared to others that start slightly before 5000 rpm. Forwarded valve lift is not favorable as it does not improve volumetric efficiency much and start later. Compared to the others, retarded valve lift is more efficient as it improves the volumetric efficiency at lower speed through high speed almost linearly and have the highest efficiency at 7000 rpm. However, the combination of forwarded and retarded valve lift at maximum lift of AVLT improves volumetric efficiency better from 5500 to 6500 region.

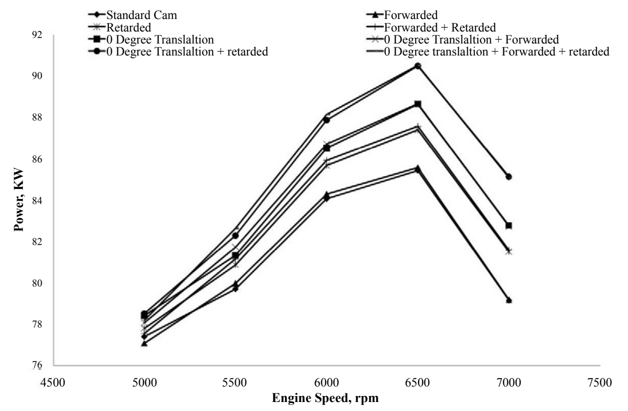

Figure 7: Power output.

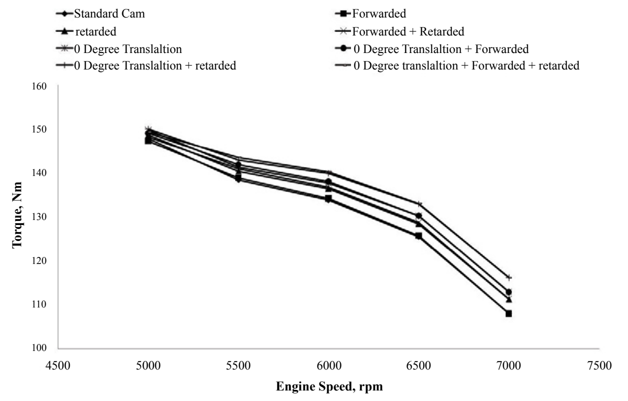

Figure 8: Engine torque.

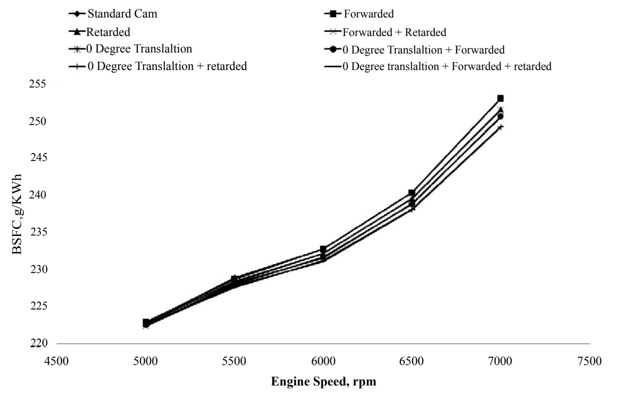

Figure 9: Brake specific fuel consumption.

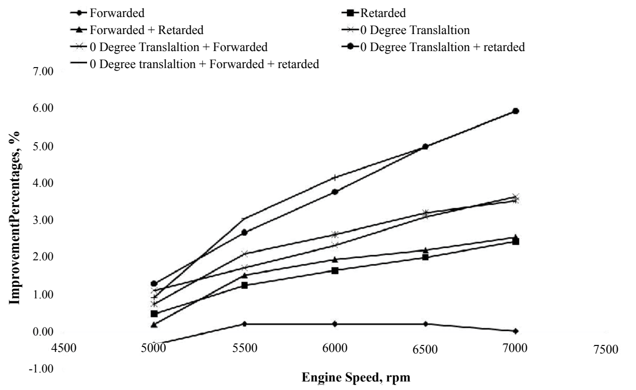

Figure 10: Improvement of volumetric efficiency.

Conclusion

This study has demonstrated that using AVLT mechanism in an engine has a potential to improve high end performance with respect to fuel efficiency, volumetric efficiency and output power. Dynamics analysis performed using MSC Adam software showed that tappet translation increased by 32% from 9.09 mm to 12.01 mm by varying translational skate position between 0° and 10°. The Lotus Engineering software simulation showed that brake power at speed between 5000 and 6500 rpm increased between 2 to 7%. Maximum torque improvement was realized at 7000 rpm while BSFC was reduced by up to 2% at 7000 rpm. The increased in brake power and torque are direct results from volumetric efficiency linear improvement between 1.5 and 6% at speed range of 5000 to 7000 rpm. AVLT mechanism design is flexible where oscillating follower can be shaped so that it can fulfill the desired valve lift and duration which can be applied to any internal combustion engine. The combination of forwarded and retarded in maximum translation of AVLT improves high end performance the most.

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