

Development and Optimization of Intermediate Lock Position Camshaft Phaser System

2010-01-1192

Published
04/12/2010

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ABSTRACT

Intake camshaft retard beyond that necessary for reliable cold start-ability is shown to improve part-load fuel economy. By retarding the intake camshaft timing, engine pumping losses can be reduced and fuel economy significantly improved. At high engine speeds, additional intake cam retard may also improve full-load torque and power.

To achieve these benefits, an intake camshaft phaser with intermediate lock pin position (ILP) and increased phaser authority was developed. ILP is necessary to reliably start at the intermediate phase position for cold temperatures, while providing increased phaser retard under warm conditions. The phaser also provides sufficient intake advance to maximize low-speed torque and provides good scavenging for boosted engine applications.

Design and development of the intermediate locking phaser system is described. The pros and cons of various methods of accomplishing locking and unlocking a phaser are illustrated. An AMESim model of the phaser was developed and Robust Engineering methods were applied.

Engine simulation and dynamometer testing was performed to determine system benefits. Control algorithms were developed and an enhanced engine management system was demonstrated in a vehicle.

INTRODUCTION

Cam phaser technology has been fundamental to the advancement of SI gasoline engines, with demonstrated benefits in fuel economy, torque, and emissions. Since their introduction in the early 1980s [1], cam phasers have evolved from primitive hydraulically-actuated 2-step spline devices with limited phasing authority, to continuously-variable vane-

type phasers with compact packaging and wide authority (Figure 1). Cam phaser systems are cost effective and have been applied to a range of SI engine types and applications. Recently, electric cam phasers [2] have become available, but their higher cost has, to date, limited them to advanced or niche applications.

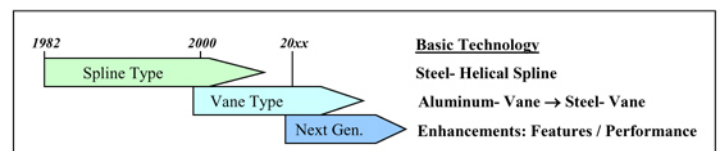


Figure 1. Progression of hydraulic cam phaser technology

Typical cam phasers are oil-pressure-actuated (OPA). At engine startup and subsequent first idle, there is insufficient oil pressure for cam phaser control. During this time, the phaser must be operated in locked position at the phaser “end stop” or default position. For double-over-head-cam (DOHC) engines with dual independent cam phasing (DICP), typically the default position for the intake phaser is fully retarded, and the default position for the exhaust phaser is fully advanced. However, the intake phaser default position can not exceed a certain maximum retard, which is determined by the ability to cold start the engine at altitude with high-drivability index (DI) fuels. Intake cam timing retard reduces effective compression ratio, which degrades ignitability for cold start conditions.

At part load, the intake and exhaust phasers are calibrated for best fuel economy within combustion dilute limits and knock limits. Optimum part-load fuel economy generally requires retarding the intake cam significantly beyond the intake default position [3,4]. This late-intake-valve-closing (LIVC) strategy is well known for reducing pumping losses of SI

engines [5]. However, since the ability to retard the phaser is limited by the default position for good cold starts, optimum fuel economy can not be achieved with current “end-stop” cam phasers. An oil-pressure-actuated phaser with intermediate lock pin capability and increased retard authority is needed to realize improved fuel economy from LIVC, while satisfying phaser requirements for cold start and full-load conditions. Toyota [2] demonstrated improved fuel economy and output using an electric phaser for this purpose.

Figure 2 shows an intake cam timing diagram for an advanced intake cam phaser system with intermediate lock pin (ILP) capability. This diagram shows approximate intake valve opening times in crank angle degrees. For cold start, the intake phaser is positioned at intermediate timing for good effective compression ratio with some valve overlap for rapid heating by residual gases [3]. For optimum fuel economy under warm conditions, the phaser is significantly retarded to reduce pumping losses. For full load at low speed, the phaser is advanced to improve volumetric efficiency and torque. For boosted engines, additional intake advance is important to scavenge burned gases from the cylinder for increased low-speed torque [6]. Conversely, at high speed, the phaser is retarded to achieve maximum volumetric efficiency and peak power. Collectively, intake cam phaser systems with intermediate lock pin capability provide the additional operational flexibility and authority for improved system benefits

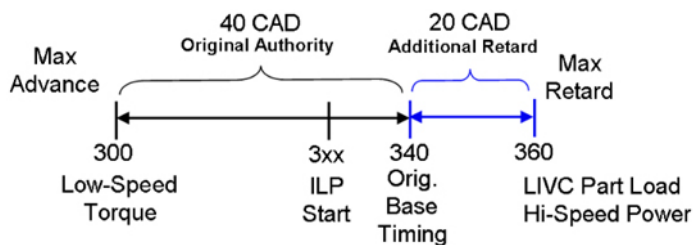


Figure 2. Progression of hydraulic cam phaser technology

SIMULATION RESULTS

To estimate the benefits realizable from phasers with ILP, engine simulations were performed for a naturally aspirated engine using GT Power [7]. For part-load operating conditions at 1200 rpm and 300 kPa IMEP, results shown in Figure 3 indicate that net specific fuel consumption may be reduced about 1.5 percent for 10 CAD of intake retard provided the exhaust phaser is also retarded. This is consistent with expectations for LIVC strategy [3]. The red line in Figure 3 represents dilute combustion limits.

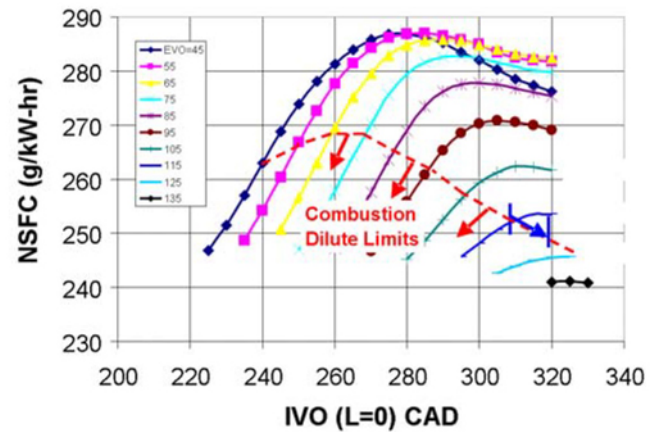


Figure 3. Simulated net specific fuel consumption at 1200rpm and 3 bar IMEP

Engine simulations were also performed under cold conditions at full load to determine if engine cold launch torque could be improved by using intermediate lock pin positions (for the intake phaser). The exhaust phaser was in the fully advanced default positions for these simulations. Results in Figure 4 show significant 5 percent increased torque by advancing the phaser 20 CAD relative to base timing. This is consistent with BMW findings on a L4 SULEV application in which spline phasers were used to start the engine at intermediate phaser positions [8].

Peak power at rated speed can also be increased by further intake retard depending on the application.

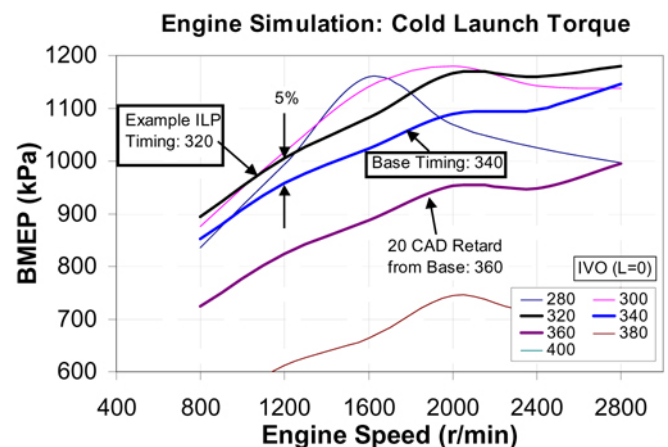


Figure 4. Simulated cold launch BMEP at low engine speeds as a function of intake phaser timing

Additional full-load simulations were conducted under warm conditions to estimate the benefit of additional intake retard on high-speed rated power of an engine. For these simulations, the exhaust phaser was fully advanced. Results shown in Figure 5 indicates that 20 CAD of additional intake

retard can increase peak power by 2 or 3 percent depending on rated speed of the engine. This benefit is expected to be application dependent and will vary with intake tuning and breathing characteristics.

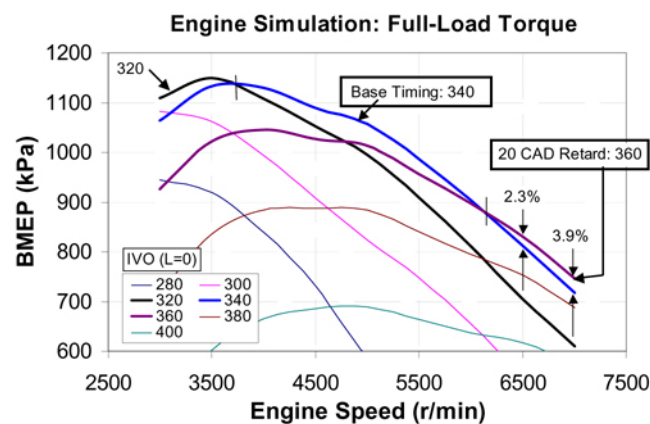


Figure 5. Simulated full-load output as a function of engine speed for various intake timings of an engine

Thus there is need for phaser systems that provide intermediate positions for good start-ability and launch torque and increased retard capability for part-load fuel economy and peak power. This phaser system provides sufficient advance for low-speed volumetric efficiency for naturally aspirated engines, and scavenging for boosted engines.

Table 1 - Summary of system benefits for intermediate lock pin phasers shows a summary of expected system benefits from an ILP phaser for various operating conditions. Additional benefits are expected for flex-fuel applications where the cold start is also challenged. Further advancing the intake cam for E85 cold starts can provide compression heating.

Table 1. Summary of system benefits for intermediate lock pin phasers

Operating Mode	ICP Position	Effect on Engine	System Benefit
Cold Start	Intermediate	Good ECR, some valve overlap for residual heating	Reduced HC, improved cold launch torque
Cold Start E85	Advanced intermediate	Compression heating	Improved starts
Part Load	Increased ICP retard	LIVC and reduced pumping loss	Improved fuel economy
Low-speed full load	Advance	Increased VE	Increased torque
Low-speed full load (boosted)	Additional advance	Improved scavenging & VE	Increased torque
High-speed full load	Increased ICP retard	Increased VE	Increased peak power

FUEL ECONOMY / DYNAMOMETER TESTING

Dynamometer tests were conducted on a V6 engine equipped with DICP. Special phasers with additional retard authority were utilized. Test conditions were selected using speed / load points commonly seen during the FTP city and highway driving schedules, as shown in Figure 6 and Figure 7. The measured fuel consumption and engine out emissions were compared to baseline camshaft timing values.

To determine the best intake camshaft timing, phase angle was swept from baseline timing up to twenty crank degrees retarded (late intake closing). Spark timing was varied to determine MBT spark timing and throttle position was adjusted to maintain engine load. In order to maintain internal dilution, exhaust camshaft timing was also retarded from baseline position by the same increments as the intake camshaft timing (dual equal camshaft timing). Optimum camshaft timing corresponded to COV of IMEP less than 1.5 percent. Data for COV of IMEP, MAP, PMEP, BSFC, BSHC, BSCO, BSNOX were recorded and plotted as a function of camshaft timing change. Data is presented in Figure 8 and Figure 9.

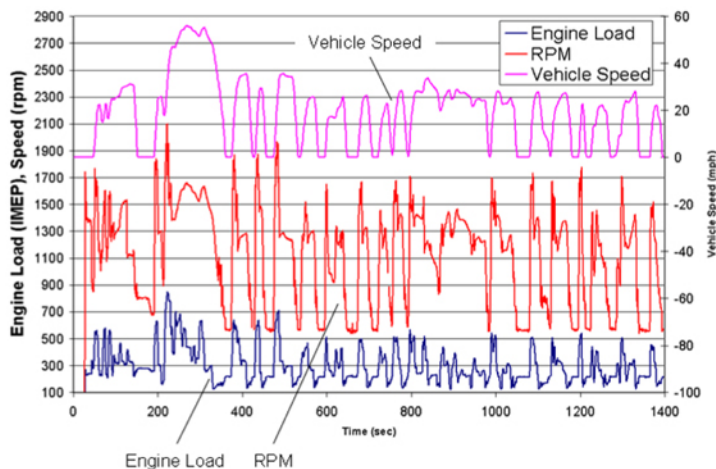


Figure 6. Plot of engine speed and load seen during FTP for emissions

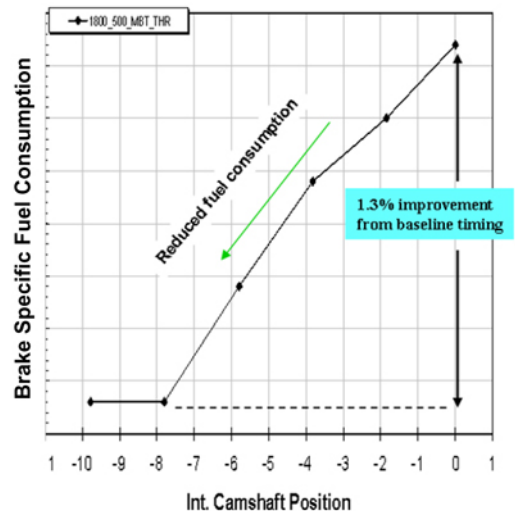


Figure 8. Fuel consumption measurements at 1800 rpm, 500 IMEP load

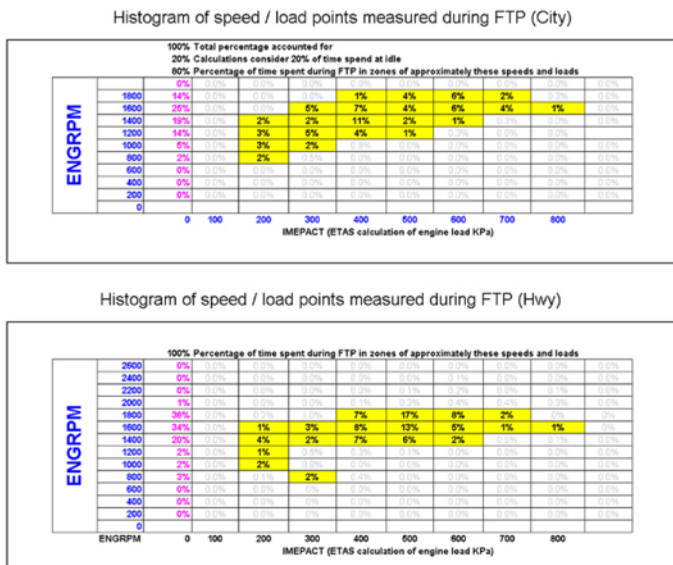


Figure 7. Table of percentage of time spent during FTP city and highway test schedules at various speed-load points

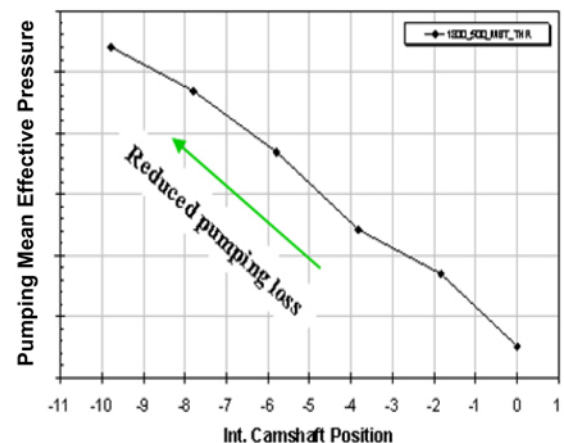


Figure 9. Observed reduction in pumping losses with late intake valve closing

To estimate vehicle level benefits, dynamometer result at speed-load points where beneficial results were measured, were weighted (for percentage of time spent during FTP drive schedule) and summed. A table of these results is seen in Figure 10. The projected benefit of around 1% was comparable to that predicted with GT Power simulations.

Engine Condition		Time During FTP		Fuel Economy
Speed (rpm)	Load (IMEP kPa)	City	Highway	BSFC
1800	600	6.0%	8.5%	-1.1%
1800	500	4.3%	17.0%	-1.3%
1600	700	3.8%	1.3%	-0.8%
1600	600	5.7%	5.5%	-1.6%
1600	500	3.5%	13.1%	-1.3%
1600	400	6.8%	8.2%	0.0%
1600	300	4.6%	3.4%	0.0%
1400	500	2.4%	5.5%	-2.3%
1400	400	10.6%	6.5%	-1.8%
1200	300	4.6%	0.5%	-1.5%
600	150	20.0%	0.0%	0.0%
Total percentage of time =		72.3%	69.4%	
Estimated FTP Effect (City)				0.83%
Estimated FTP Effect (Highway)				-1.20%
Negative = improvement				

Figure 10. Chart of dynamometer speed/load points, results and predicted vehicle level benefits

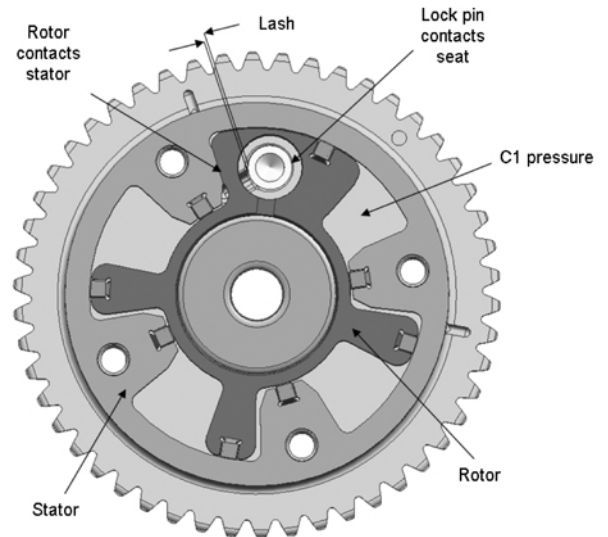


Figure 11. Cross-section view of production phaser in locked position

iVCP DESIGN CONSIDERATIONS

Torque transmitted through vane type camshaft phasers inherently drives the phase angle to the maximum retard direction mechanical limit, in the absence of hydraulic pressure. Intake phasers normally lock at their maximum retard position. For an iVCP, the locking position is no longer at the mechanical limit position. This makes the phaser system design more complicated to accomplish the functional requirement of relocking either during the engine shut down or subsequent restart.

On Delphi's standard phaser design the rotor physically contacts the stator at the default, locked position. During engine shut down the phase angle control oil control valve is de-energized. This maximizes the retarding control pressure C1 pressure and minimizes the advancing oil pressure. C1 pressure, along with camshaft friction, causes the phase angle to move to the retard limit position. A cross-section view of design is shown in Figure 11. When the rotor contacts the stator, the lock pin and seat align with (moments of) no rotational motion. As engine oil pressure decays, and as speed drops, C1 pressure falls below the lock pin retraction pressure. With the next positive cam torque the lock pin is able to drop into its seat.

Measured data of phase angle, C1 and C2 pressures along with the lock pin axial position, from an instrumented intake phaser during an engine shutdown, are seen in Figure 12.

With this design, the rotor contacts the stator when reacting positive cam torque and when cam torque is negative, the lock pin contact its set to react the torque. A tapered pin and seat locks the phaser lash with no lash. Cam torque load applied to the tapered faces produces a force vector in the direction of lock pin retraction. When this axial force exceeds frictional force the lock pin can self retract, undesirably. Single direction loading removes this tendency. To avoid this phenomena an intermediate lock position phaser requires a straight lock pin and seat design.

At an intermediate lock position phaser contact between the rotor and stator no longer assist alignment of the pin and seat for relocking.

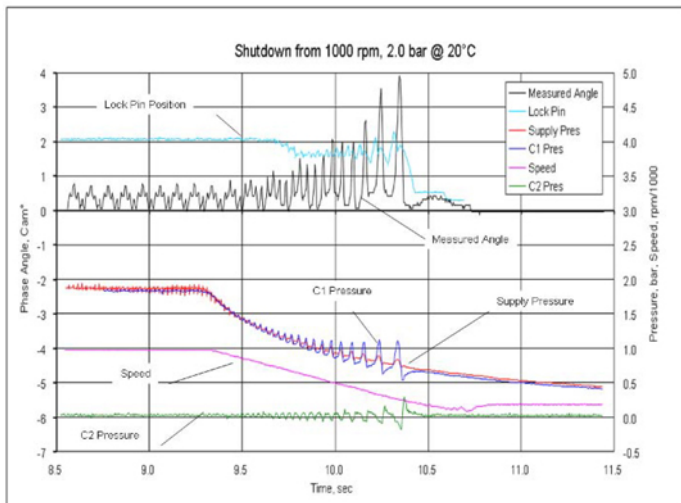


Figure 12. Phaser control pressures and lock pin position during engine shutdown

Some amount of angular velocity will likely be present during relocking. Therefore, time available for lock pin re-engagement is decreased making lock pin acceleration during re-engagement critical. Angular velocity between the pin and seat results in impact forces that must be absorbed during re-engagement.

With intermediate lock position designs, opposing impact loads between the pin and seat result from camshaft torque reversal moving the lock pin relative to its seat the angular distance of their diametrical clearance (lash). This is seen in Figure 13. The end face edges of the lock pin and seat typically have chamfers. It is imperative that the lock pin travel beyond these features during its initial movement - typically a travel of 0.5 mm or more is needed.

Otherwise, the cam torque transmitted through the lock pin may result in the pin being ejected from the seat, causing edge damage and the phaser not relocking when commanded. With the lock pin fully engaged with the seat, camshaft torque reversals cause impact loads on a single lock pin from opposing directions. As mentioned earlier in this document, a tapered pin and seat is considered not viable due to self ejection from opposing impact loads. Therefore, a straight lock pin design is used.

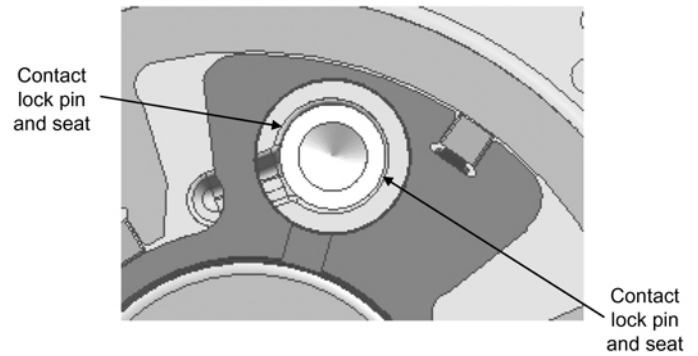


Figure 13. Cross-section view of phaser at an intermediate lock position

The lock pin is retracted with engine oil pressure. Consequentially, oil surrounds the pin, especially the clearances between the pin and the bore it resides in. A volume of oil (active area x travel) is displaced with pin motion. Therefore damping of lock pin motion, especially at low operating temperatures, must be understood. Excessive damping will result in the inability for the lock pin to sufficiently re-engage its seat in the time available for motion during engine shutdown.

Several methods for lock pin control are available. The simplest are "passive" schemes (Figure 14) where phase angle control pressures are used to retract the pin. A double acting (C1 and C2 pressures retracted) lock pin is needed to maintain lock pin retraction in both advancing and retarding directions. Both C1 and C2 pressures must be removed before the lock pin can accelerate toward the seat. Eliminating both phasing pressure signals can be accomplished either with a complicated OCV that simultaneously opens C1 and C2 to vent, or by adding a secondary OCV to vent C1 when the phase angle control OCV is venting C2 (or visa-versa).

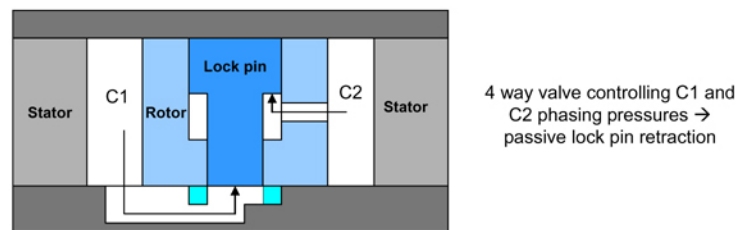


Figure 14. Passive lock pin retraction

But in the absence of C1 or C2 pressures, phase angle position is uncontrolled. Hence, in order to relock, phase angle must be near, preferably advanced from, the locked position prior to engine shut down, thus allowing the lock pin to sweep over the seat for re-engagement at the moment these pressures are removed.