2005-01-0764

A Camshaft Torque Actuated Vane Style VCT Phaser

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ABSTRACT

BorgWarner has developed a continuously variable vane style VCT camshaft phaser that, differing from the oil pressure actuated phasers in production, utilizes camshaft torque energy, not oil pump flow, to actuate. This VCT phaser has several distinct advantages, low oil flow requirements and fast response rates even at low RPM. The low oil flow requirement, allows this Cam Phaser to easily adapt to existing engine platforms without major engine modifications or increases in oil pump size. For new engine designs a smaller oil pump can be selected and thereby improve overall engine efficiency. Since the phaser responds to camshaft torque energy and actuates independent of oil pressure, fast response rates are available from idle on up through the engine operating range, allowing the engine calibrator to adopt a more aggressive approach to camshaft timing. Low oil flow requirements, fast response rates at all RPM and minimal engine modifications are all advantages of this new VCT cam Phaser.

INTRODUCTION

In recent years Variable Camshaft Timing has become mainstream technology in engine design. Borg Warner has developed a Variable Camshaft Timing (VCT) phaser that differentiates itself from the current VCT technology in several aspects. See Fig 1. Two unique features of this VCT device are that it uses camshaft torque energy to actuate and it circulates oil internal to the VCT during actuation [1]. The end result is a camshaft-phasing device that operates faster, more efficiently, and with significantly lower oil flow requirements than other VCT devices being used today. This paper reviews the current VCT technology, offers a brief explanation of the origin of camshaft torque, describes BorgWarner's Camshaft Torque Actuated (CTA) VCT phaser and presents test data of the CTA VCT phaser. Comparisons to the existing oil pressure actuated VCT phasers are made throughout the paper.

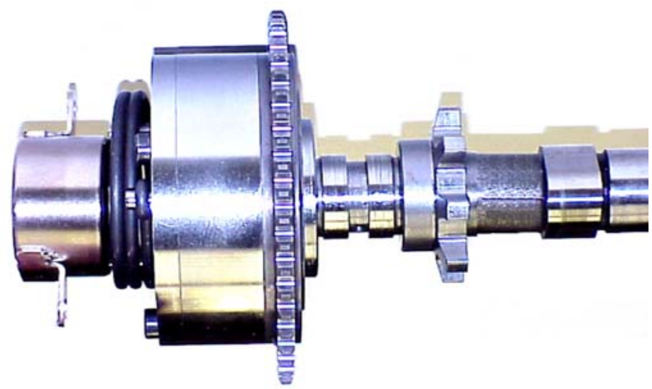

Fig 1. *BorgWarner's Camshaft Torque Actuated VCT with front mounted Variable Force Solenoid and center mounted hydraulic controls.*

BACKGROUND

In order to gain full appreciation of the unique features found in the Camshaft Torque Actuated (CTA) VCT phaser, it is worthwhile to review the status of current VCT technology. The most common device used for phasing a camshaft is a simple hydraulic rotary vane actuator attached to the end of the camshaft [2]. The camshaft sprocket attaches to a hydraulic housing and a rotor with radially projecting vanes attached to the camshaft. The camshaft is moved relative to the sprocket by selectively applying engine oil pressure (and oil flow) to one side of the vane while simultaneously exhausting oil from the other side of the vane. The response rate is limited by the oil pump capacity [3]. A four-way valve located remotely in the cylinder head, cylinder block or front cover can be used to control the oil flow to and from the VCT phaser. The primary advantage of oil pressure actuated phasers is that they are relatively simple mechanisms. They are, however, difficult to adapt to existing engines because they require significant changes to the head, block, camshaft and oil pump in order to route high pressure oil from the oil pump, through the control valve, to the VCT phaser [4]. In addition, they are limited in performance by the oil pump capacity and are inefficient in operation, requiring excess oil pump capacity in order to function at low speeds [5].

CAMSHAFT TORQUE ENERGY

Before describing the BorgWarner Camshaft Torque Actuated (CTA) VCT phaser, a brief explanation of camshaft torque energy is necessary. The typical internal combustion engine has a tulip style poppet valve to control the airflow into and out of the combustion chamber. These valves are spring loaded to the closed position. There are many different styles of valve train mechanisms to open the valves, but the basic function can be easily explained by placing a simple cam mechanism directly above the valve. See figures 2 & 3. As the camshaft rotates clockwise the cam lobe starts to push down on the valve to open it. The valve spring force, imposes a resistive force that, when coupled with the cam lobe geometry, produces a resistive torque on the camshaft. For this paper any torque that resists the rotation of the camshaft is considered a positive camshaft torque. The second force that resists camshaft rotation (i.e. creates a positive camshaft torque) is the inertia of the poppet valve and any other valvetrain mechanism that has to be accelerated by the cam lobe. The inertia forces become more prominent at higher engine RPM where acceleration values are higher. The third force that resists camshaft rotation is any friction in the poppet valve, valve train or camshaft. When the cam lobe reaches its apex the force from the valve acts directly though the center of the camshaft reducing the camshaft torque to zero (except for the positive torque bias caused by friction in the system). As the cam lobe continues to move past the apex, the compressed spring imposes a force that, when coupled with the cam lobe geometry, produces a torque in the same direction as the camshaft rotation. By definition this is a negative camshaft torque.

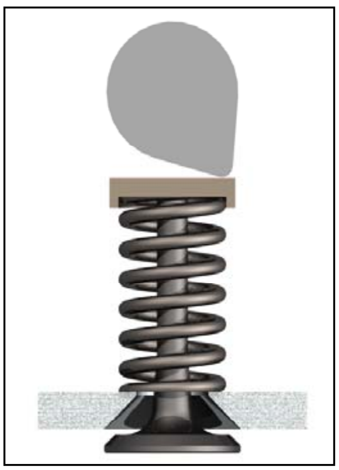

Fig 2. *Camshaft lobe profile and rotation combine with valve spring force to create resistive torque on the camshaft.*

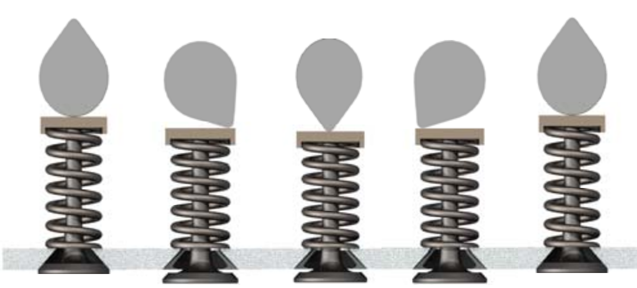

Fig 3. *Camshaft lobe rotation through a single valve event*

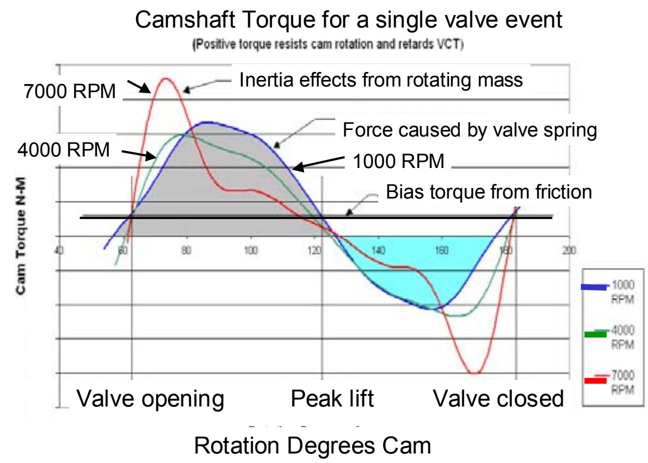

Fig 4. *Camshaft torque for a single valve event on an OHC Roller Finger Follower valve train V6 engine.*

Figure 4 is a plot of camshaft torque versus camshaft angle of rotation. Since torque over time or distance represents energy, and since we have energy available in the positive and negative direction, it's logical to apply this available energy to actuate a VCT mechanism in both the advanced and retarded timing directions.

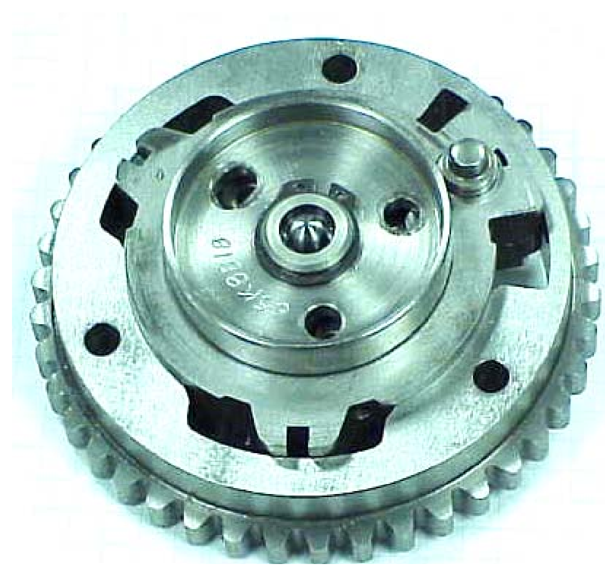

Fig 5. *BorgWarner's hydraulic vane-style Cam Torque Actuated VCT Phaser.*

CAMSHAFT TORQUE VCT DESCRIPTION

Figure 5 is an example of the camshaft torque actuated VCT Phaser. It is a traditional vane style hydraulic actuator. Two vanes are the working chamber used to actuate the VCT while the third vane provides the mechanical limits in rotation as well as a mounting place for the locking pin. The hydraulic controls, which consist of a spool valve, an inlet checkvalve, and two recirculation checkvalves, are located in the rotor [1].

Figure 6 is a simple hydraulic schematic of the Cam Torque Actuated vane type VCT that is subjected to positive and negative camshaft torque. By definition, the chambers are labeled such that filling the chamber determines the VCT direction of motion. So filling the advance chamber causes the VCT rotor and camshaft to move toward the advanced timing position and vice versa for the retard chamber.

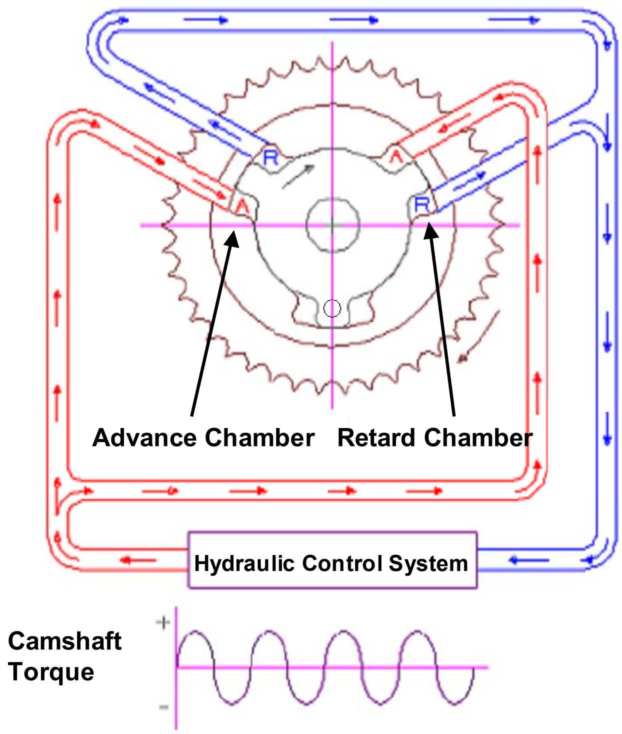

Fig 6. A simple hydraulic schematic of the Cam Torque Actuated vane-type VCT with oil recirculation.

The positive camshaft torque, generated during the valve-opening event, is applied to and pressurizes the advance chamber. Negative camshaft torque, generated during the valve-closing event, is applied to and pressurizes the retard chamber. Since the oil is alternately pressurized in each chamber, a hydraulic control system can be developed to selectively direct that oil from one chamber to the other through the control system and thus control the actuation of the VCT in either the advance or retard timing direction.

Figure 7 shows the hydraulic controls for the CTA VCT. Since the working fluid in this VCT is engine oil, a single oil source is necessary to initially fill the VCT. This single oil source line passes though a single inlet check valve. This check valve prevents pressure spikes within the VCT from going back to the engine oil supply. This safeguards the operation of other hydraulic devices such as hydraulic lifters, etc. The inlet oil enters the VCT at the center or "common" passage of the spool valve. In this figure the spool valve is shown in the centered or "null" position. Oil travels from the common passage and flows through the advance check valve to fill the advance chamber, and through the retard check valve to fill the retard chamber. Once filled with oil, the VCT retains and circulates the oil within the VCT during actuation. Therefore the source oil is only used for the initial filling of the VCT and to make up for the small amount of oil that leaks from the VCT during normal operation. When alternating torque is applied to the VCT the advance chambers and retard chambers are alternately pressurized. However, the VCT maintains its position because the spool valve lands and the check valves block the fluid from exiting the chambers.

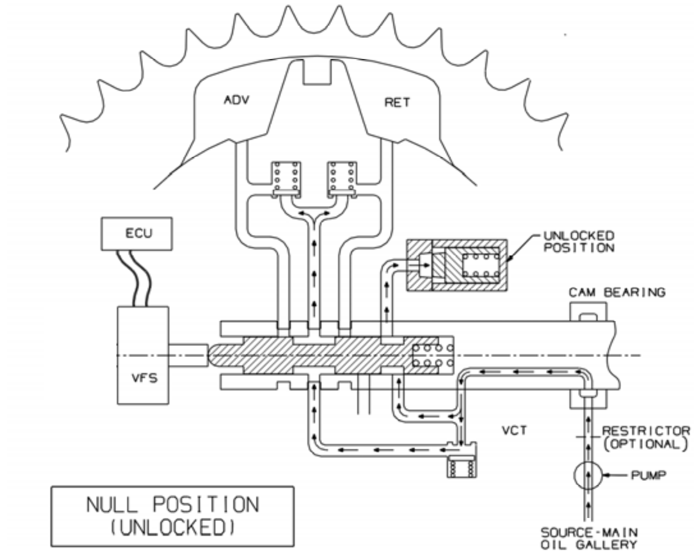

Fig 7. Hydraulic controls schematic for the CTA VCT with the spool at null position.

Figure 8 shows the spool valve moved all the way to the left. In this configuration the oil that is pressurized in the advance chamber during the valve-opening event is free to flow from the advance chamber to the common center

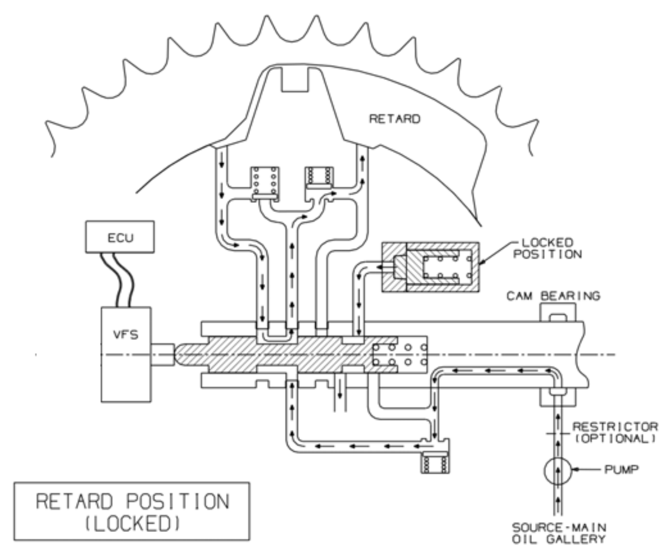

Fig 8. Hydraulic controls schematic for the CTA VCT with the spool at the retard position

of the spool valve. From there it flows through the retard check valve and fills the retard chamber. The VCT is exhausting oil from the advance chamber and using that same oil to fill the retard chamber. Therefore the rotor and camshaft move toward the retard timing position with each valve-opening event. When the retard chamber is pressurized during a valve-closing event, the oil is blocked from leaving the retard chamber by the retard check valve and by the land on the spool valve. The VCT maintains its retard position during each valve-closing event that creates a negative camshaft torque.

Figure 9 shows the spool valve moved all the way to the right. This reverses the operation described in the previous paragraph. In this configuration the oil that is pressurized in the retard chamber during the valve closing event is free to flow from the retard chamber to the common center of the spool valve.

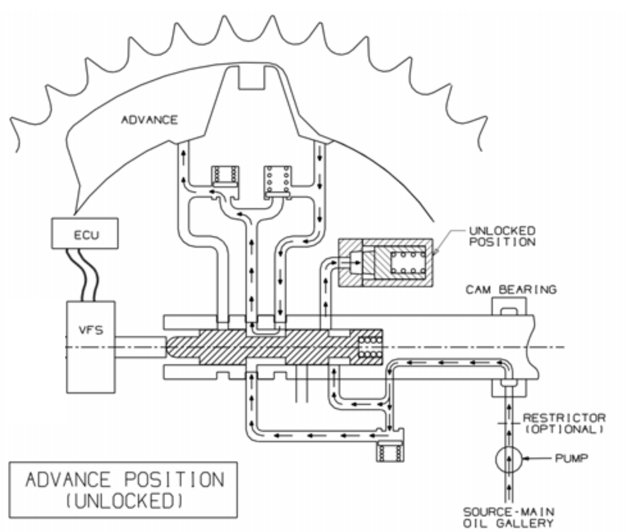

Fig 9. Hydraulic controls schematic for the CTA VCT with the spool at the advance position

From there it flows through the advance check valve and fills the advance chamber. At this point the VCT is exhausting oil from the retard chamber and using that same oil to fill the advance chamber. Therefore the rotor and camshaft move toward the advance timing position with each valve-closing event. When the advance chamber is pressurized during a valve-opening event, the oil is blocked from leaving the advance chamber by the advance check valve and the land on the spool valve. The VCT maintains its advance position during each valve-opening event that creates a positive camshaft torque.

It may be helpful to think of this mechanism as a hydraulic ratchet or one-way clutch with the cam torque energy supplying the power to move the device and the check valves creating the one-way ratcheting type mechanism. The fact that we have torque energy in both directions and check valves and flow paths that can be selected via a spool valve allows us to direct the VCT in either the advance or retard direction. The spool valve is infinitely variable in position so it can be used to select both the direction and rate of actuation.

LOCK PIN FUNCTION

The final explanation of the basic CTA VCT function involves the function of the locking pin. Engine designers have identified certain cam timing positions that are optimum for engine starting and idle conditions. These positions are significant for both smooth engine operation as well as their effects on emissions. Given this requirement it is desirable to have the VCT return to the ideal start condition and mechanically lock in that position before the engine shuts down [5].

The function of the locking pin can best be described by referring to the hydraulic schematic in figure 9 once again [6]. Note that the same source oil that fills the VCT device through the inlet check also communicates with a separate land on the spool valve. This land on the spool is used to control the pressurized oil to the locking pin. In figure 8 the spool valve is shown in the “default” full left position. When the VFS Variable Force Solenoid duty cycle is zero, the spring behind the spool valve pushes the spool “out” or, as illustrated in this schematic, to the left. As previously discussed, when the spool valve is moved to the left the rotor is commanded in a certain direction, which according to this figure is toward the retard valve timing position. (By reversing the hydraulics in the rotor the default “spool out” position can be the fully advanced timing position.) When the rotor reaches the fully retarded position the locking pin is aligned with a receiver in one of the endplates. Simultaneously, the land on the right hand side of the spool valve blocks source oil from reaching the locking pin. In addition, the spool valve opens the locking pin oil passage to a vent back to sump. This allows the oil to evacuate from the locking pin chamber and allows the spring-loaded locking pin to engage the receiver. The VCT is now locked in the optimum start position. Using the CTA VCT technology, the event just described can occur in less than 300 milliseconds at idle speeds. Therefore, at “key off”, the VCT can be commanded to go to the default locked position before the engine turns off.

Upon engine start, or some time shortly thereafter, it is required to release the VCT from the locked position and function under closed loop control. Referring the schematic in figure 9, as the spool valve moves to the right, the following sequence of events occurs. The initial motion of the spool valve to the right blocks the vent passage from the lock pin. The next part of the spool motion allows the source oil to pressurize the locking pin, causing it to release. (This is the only function in the CTA VCT that is affected by source pressure. Higher oil pressure will cause the locking pin to respond quicker to this command.) As the spool continues to move to the right, it passes beyond the center, or null, position and begins to command the VCT to move in the opposite direction, away from the default locked position. For example, if this were an intake VCT device, the VCT would move off the retard stop toward the advance position. The position of the spool valve land that controls the locking pin function is such that as the spool valve travels from left to right the locking pin is released *before* the VCT is commanded to move. This prevents the VCT movement from side-loading the locking pin and making it more difficult to release.

FUNCTION SUMMARY

To summarize the basic function of the CTA VCT, these specific items are worth reviewing. The source oil is only used to initially fill the VCT and to supply a small amount of oil to make up for leakage. Any air in the oil that enters into the phaser is purged through the clearance between the spool and sleeve. The oil flow to actuate the CTA VCT is from chamber to chamber, internal to the CTA VCT. The energy used to move the oil from chamber to chamber is provided by the energy created by opening and closing poppet valves via a camshaft system. The spool valve controls the flow direction and rate of flow from chamber to chamber. The check valves internal to the VCT are used to resist the reversals in camshaft torque. The inlet check valve is used to isolate the CTA VCT oil pressure from the engine oil supply system. Since energy consumed in a hydraulic device is directly proportional to oil flow, the only time a CTA VCT uses energy is during a phase shift. To help optimize the phaser, each engine application must be analyzed for the cam torsionals. By using the camshaft torque as the energy source, this VCT can be thought of as a device with a built-in "on demand" energy source. The oil pressure actuated VCT has an oil pump that runs all the time and therefore wastes the energy of pumping oil that is only occasionally used to move the VCT. This difference alone represents a significant overall efficiency increase in the engine design.

CTA PERFORMANCE

For improved engine performance a cam phaser should be able to actuate quickly, be stable, and have low flow requirements over the entire engine speed operating range. Because the CTA phaser uses cam torsional energy to move rather then engine oil pressure, the CTA phaser can advance or retard during engine cranking and when the engine is running, from idle to full speed. The CTA phaser also has low oil flow requirements because the oil recirculates from chamber to chamber. Control of the cam phaser is important to the engine calibrator to optimize the operation of the engine under all operating conditions.

A production DOHC RFF (Roller Finger Follower) valvetrain V6 engine was modified by adding two intake and two exhaust CTA phasers. New cam covers and a front cover were fitted to the engine as well. See Fig 10.

Each phaser requires a single oil feed passage. For this application we used oil from the #1 cam journal bearing. The CTA equipped engine uses the original oil pump and heads without any modification. To control the phaser's position a Variable Force Solenoid is used to move a spool valve mounted centrally in the phaser [7] [8]. See Fig 10

The solenoids' signal can come from either a Morse

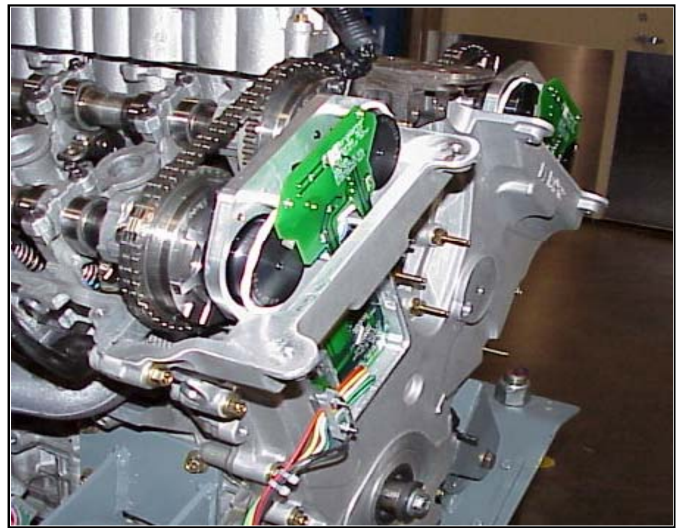

Fig 10. *A new front cover with Variable Force Solenoids to control the CTA cam phasers on a DOHC V6 engine.*

VCT Electronic Interface Module (EIM) or an engine controller. The feedback signals to the control module come from Variable Reluctance sensors, which are used to measure each camshaft position and the crankshaft position. The desired cam phase angle set point can come from either the engine controller or it can be generated by the EIM. Each cam is equipped with an 8-tooth pulse wheel for fast updates to the EIM for improved control at low engine speeds. 720 pulse encoders were also added on each cam and the crankshaft for use with an in house designed Phase Angle Measurement System (PAMS). This is used to measure in real time the camshaft phase angle accurately during engine cranking speeds.

The phaser performance was characterized for response rate and oscillation both under open loop and closed loop control. The engine speed ranges were from idle to full engine speed at 240°F (116°C) and also tested for response time at –19°F (–28°C). These tests were performed on both a firing engine and a motorized engine rig that was set up in our dynamometer facility in Ithaca, New York.

The open loop testing consists of commanding the exhaust phaser to move from the advance stop to the retard stop, and then back to the advance stop. The closed loop testing consists of commanding the phaser from one position to another position that is away from both end stops.

The open loop tests were conducted from 500 RPM to 5700 RPM at 240°F (116°C). The oil pressure was measured at the front bearing cap and varied from a low of 5 PSI (0.34bar) at 500 rpm to a high of 29 PSI (2bar) at 5700 rpm. The response rate was 170°/sec at 500

RPM and 230°/sec or greater from 1000 RPM to 6700 RPM. See fig 11.

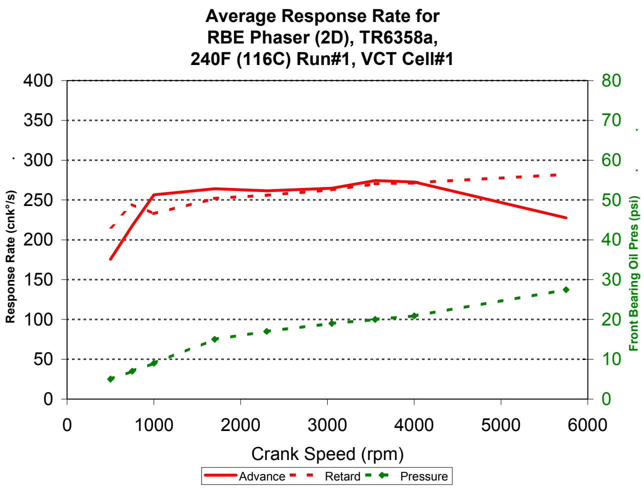

Fig 11. *Average open loop response rate in crank°/sec for the right bank exhaust phaser at 240F (116C) from 5 PSI (0.34 bar) to 90 PSI (2 bar).*

During the closed loop test, the exhaust phaser was shifted from 5 degrees to 35 degrees, then back to 5 degrees. The response rate was 170°/sec at 500 -1000 RPM and 200°/sec or greater from 1700 RPM to 6700 RPM. See fig. 12.

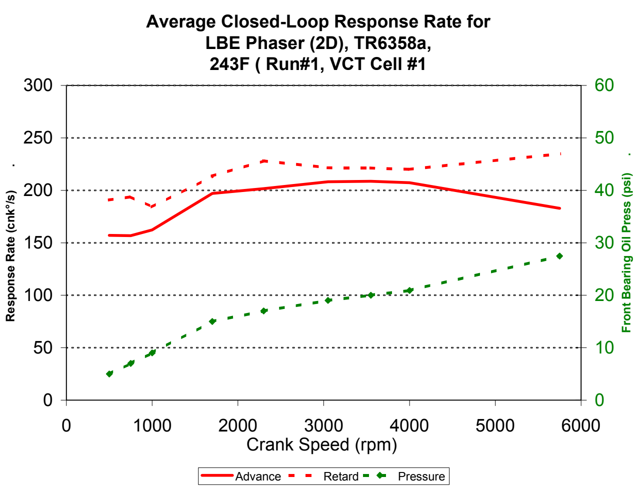

Fig 12. *Average closed loop response rate in crank°/sec for a left bank exhaust phaser at 243°F (116°C) from 5 PSI (0.34 bar) to 30 PSI (2bar).*

Fig 13 shows the variation in oscillation of the camshaft with the phaser under closed loop control from 500 RPM to 6700 rpm, when the oil temperature is at 240F (116°C). As encoders were mounted on the crankshaft and camshaft, this data includes the variation from both the timing drive and cam phaser. The total peak-to-peak oscillation is +/- 2.2 degrees at 500 RPM and less than +/- 1.2 degrees from 1000 rpm to 6700 rpm.

The next test shows the CTA phaser's ability to return to the base timing during engine cranking after an abnormal engine shutdown. Figures 14 and 15 show that the intake and exhaust phasers can move back to the base timing during engine cranking even at –22°F (-28°C).

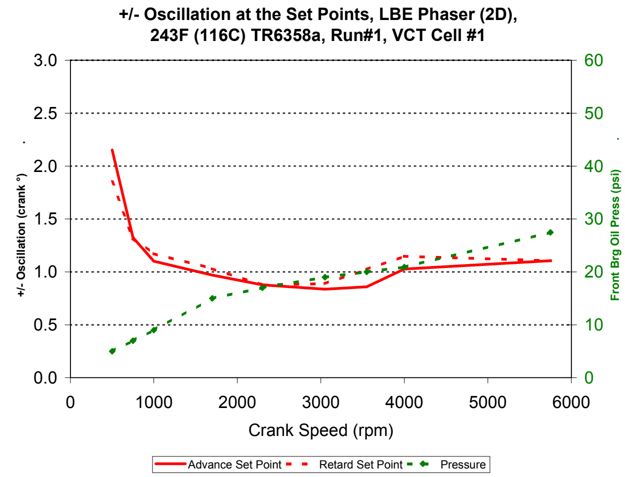

Fig 13. *+/- Oscillation in crank degrees at the closed loop set points on the left bank exhaust phaser described in Fig 12.*

We used modified phasers for this test that allowed the lock pin to be released manually when the engine was stopped. In preparation for the cold cranking test we ran the engine at normal operating temperatures, then let the engine idle before shutting it off. When the engine was turned off, the intake phaser was at full retard and the exhaust phaser was at full advance.

To test the exhaust phaser the lock pin was released and the engine was rotated by hand until the exhaust phaser was at the full retard position. The engine was

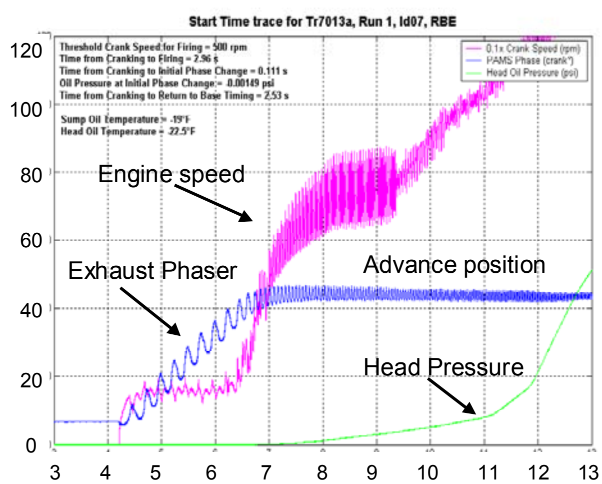

Fig 14. *Right bank exhaust phaser moves back to the full advance position at –28°C during cold engine start-up during a failsafe test.*

then cooled to -8°F (-22°C) and soaked overnight. The engine was then cranked over until it started. The exhaust phaser position is plotted vs. time, along with engine speed and oil pressure. See fig 14.

The exhaust phaser was able to move back to full advance within 2.5 seconds, before there was any oil pressure at the head.

For the intake phaser a similar procedure was followed,

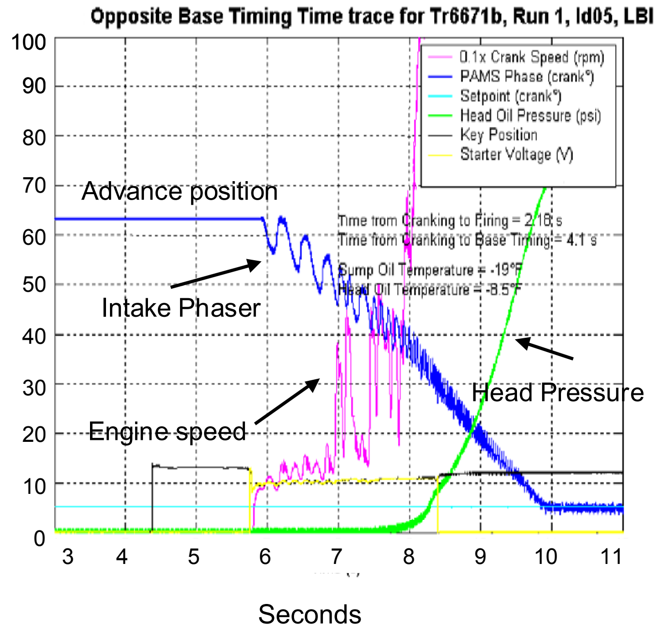

Fig 15. Left bank intake phaser moves back to the full retard position during cold engine start-up during a failsafe test

except that the intake phaser was moved to full advance for the cold test. The intake phaser moved back to full retard in 4 seconds. See fig 15.

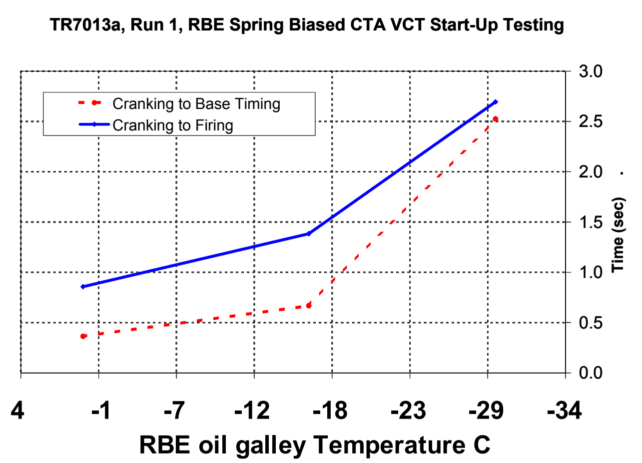

Fig 16. Time required for the right bank exhaust phaser to return to base timing at different temperatures during cold start-up failsafe test.

The tests show that, if needed, both the intake and exhaust phaser can move back to their respective base timing, even at –22°F (-28°C). This could be useful for times when the engine is running with the phasers are away from their base timing, the engine is stalled, not restarted, and then cooled down. When the engine is cranked over, the phasers would rapidly move back to the base timing, allowing the engine to start.

Fig 17 shows a comparison between a production Oil Pressure Actuated (OPA) phaser mounted on the intake cam and the BorgWarner CTA phaser mounted on the exhaust cam. Both phasers are commanded to shift 60

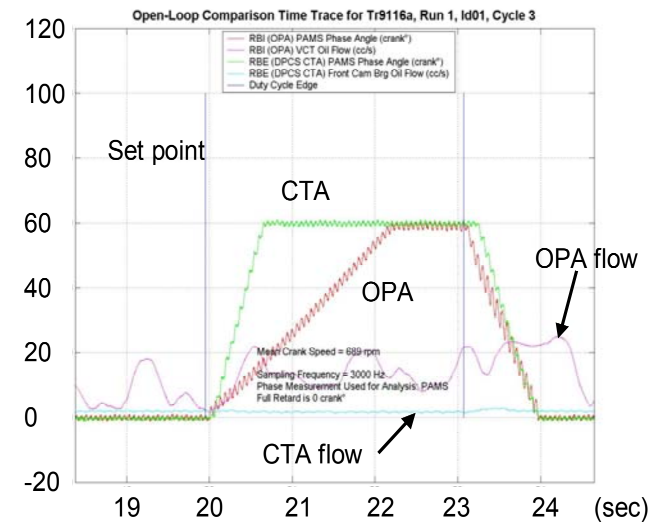

Fig 17. Comparison of an OPA (Oil Pressure Actuated) phaser and a CTA phaser mounted on a DOHC V6 engine.

degrees with an engine speed of 689 rpm and the oil temp at 98°F (37°C). The CTA has a constant oil flow of 2cc/sec, while the OPA oil flow peaks at 23cc/sec even though it has a much slower response rate.

Another feature of the CTA phaser is the low oil flow requirements. Because the oil moves from one chamber to the other, the oil demand from the engine oil circuit is low during a phase shift and during steady state operation.

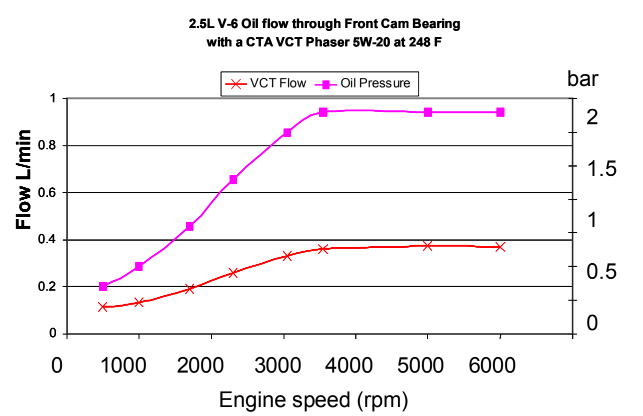

Fig 18. Oil flow versus engine speed for a CTA phaser at 248°F (120°C) with an oil pressure of 5 PSI (0.34 bar) at 500 RPM to 30 PSI (2 bar) at 6000 RPM

Fig 18 shows the oil flow vs. engine speed for a CTA phaser measured on a motorized engine with 5w-20 oil heated to 248°F (120°C) during phase shifts. At 500 RPM the measured oil flow to the CTA phaser was 0.1L/min, and it increased up to 0.4L/min at 6000 RPM. The increase in oil flow with engine speed is primarily from the increase in oil pressure as the engine speed increases.

CONCLUSION

The BorgWarner Camshaft Torque Actuated VCT distinguishes itself from existing VCT technology in several key areas. Response during engine cranking, faster response rate at low RPM, lower oil flow, response and control independent of oil pressure and minimal engine modification requirements are all desirable features of this technology heretofore not offered to the engine designer through any other VCT technology. The device has been designed, built, tested, and proven ready for the commercial marketplace.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CTA	Cam Torque Actuated
DOHC	Dual Over Head Cam
ECU	Electronic Control Unit
EIM	Electronic Interface Module
LBE	Left Bank Exhaust
LBI	Left Bank Intake
OPA	Oil Pressure Actuated
PAMS	Phase Angle Measurement System
RBI	Right Back Intake
RBE	Right Bank Exhaust
RFF	Roller Finger Follower
VCT	Variable Cam Timing
VFS	Variable Force Solenoid