Contract Number: DE-FC26-05NT42483

Title of Project: Variable Valve Actuation

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1.0 EXECUTIVE SUMMARY:

Many approaches exist to enable advanced mode, low temperature combustion systems for diesel engines – such as premixed charge compression ignition (PCCI), Homogeneous Charge Compression Ignition (HCCI) or other HCCI-like combustion modes. The fuel properties and the quantity, distribution and temperature profile of air, fuel and residual fraction in the cylinder can have a marked effect on the heat release rate and combustion phasing.

Figure 1 shows that a systems approach is required for HCCI-like combustion. While the exact requirements remain unclear (and will vary depending on fuel, engine size and application), some form of substantially variable valve actuation is a likely element in such a system. Variable valve actuation, for both intake and exhaust valve events, is a potent tool for controlling the parameters that are critical to HCCI-like combustion and expanding its operational range. Additionally, VVA can be used to optimize the combustion process as well as exhaust temperatures and impact the after treatment system requirements and its associated cost.

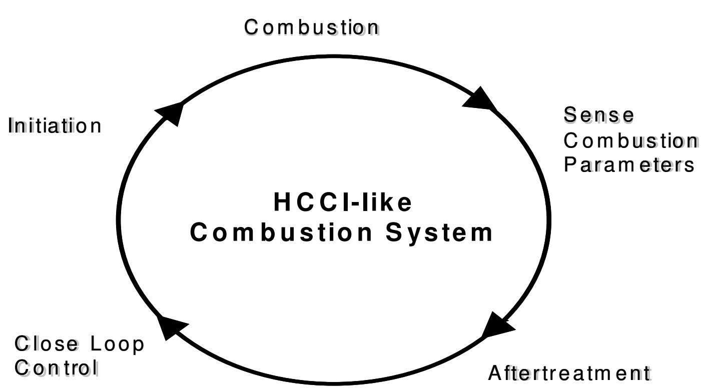


Figure 1: Elements of an HCCI EMS

Delphi Corporation has major manufacturing and product development and applied R&D expertise in the valve train area. Historical R&D experience includes the development of fully variable electro-hydraulic valve train on research engines as well as several generations of mechanical VVA for gasoline systems. This experience has enabled us to evaluate various implementations and determine the strengths and weaknesses of each. While a fully variable electro-hydraulic valve train system might be the “ideal” solution technically for maximum flexibility in the timing and control of the valve events, its complexity, associated costs, and high power consumption make its implementation on low cost high volume applications unlikely. Conversely, a simple mechanical system might be a low cost solution but not deliver the flexibility required for HCCI operation.

After modeling more than 200 variations of the mechanism it was determined that the single cam design did not have enough flexibility to satisfy three critical OEM requirements simultaneously, (maximum valve lift variation, intake valve opening timing and valve closing duration), and a new approach would be necessary.

After numerous internal design reviews including several with the OEM a dual cam design was developed that had the flexibility to meet all motion requirements. The second cam added complexity to the mechanism however the cost was offset by the deletion of the electric motor required in the previous design.

New patent applications including detailed drawings and potential valve motion profiles were generated and alternate two cam designs were proposed and evaluated for function, cost, reliability and durability.

Hardware was designed and built and testing of sample hardware was successfully completed on an engine test stand .

The mechanism developed during the course of this investigation can be applied by Original Equipment Manufacturers, (OEM), to their advanced diesel engines with the ultimate goal of reducing emissions and improving fuel economy.

2.0 GOALS AND OBJECTIVE ATTAINMENT

A detailed task list and timeline was developed at project onset. Monthly review discussions were held with DOE representatives to keep them apprised of progress. Quarterly and yearly reports were prepared and submitted detailing the results and accomplishments during each specified time period.

2.1 Goals and Objectives Summary:

- Develop an optimal, cost effective, variable valve actuation (VVA) system for advanced low temperature diesel combustion processes.
- Design and model alternative mechanical approaches and down-select for optimum design.
- Build and demonstrate a mechanism capable of application on running engines

2.2 Accomplishments Summary

- Confirmed that a single cam design did not have the required control flexibility to meet all OEM design requirement
- Three dual cam design concepts were developed and modeled.
- A dual cam design was selected from concept designs and all dynamic analyses were completed.
- An OEM confirmed that the proposed dual cam design is a cost effective and production feasible design.
- Package size was reduced to require minimal change to OEM engine envelope.
- Advanced VVA math based design process was introduced and design tools are now available for future modeling work.
- All of critical design analyses for high stress subcomponents including spring, bearings, gears and output rocker cam were completed.
- The mechanical actuator (cam phaser) development engineering work was completed and prints prepared.
- Cam phaser controller with PID control capability built and tested
- A single cylinder device was built and installed on a free running lab engine.
- Mechanism was tested on engine test stand and demonstrated the capability of meeting all design requirements.

2.3 Project Timeline and Milestones

Project Milestones were set forth in the Project Milestone Chart Figure 2.3-1. A Milestone Checklist chart was prepared and updated quarterly to indicate the planned and actual completion dates of the various tasks.

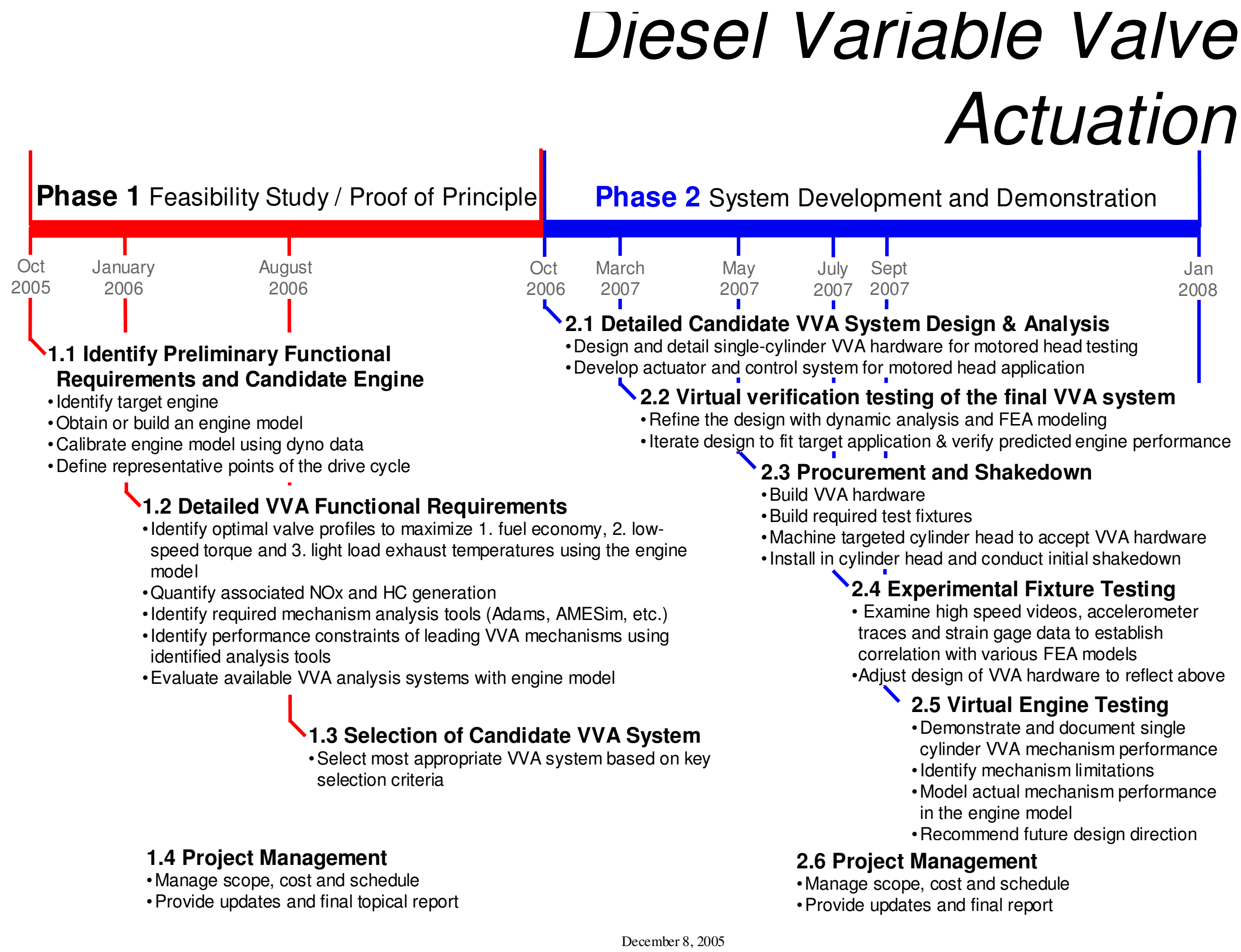


Figure 2.3-1 Project Milestone Summary

2.4 MILESTONES ACCOMPLISHED:

Figure 2.4-1 Details the overall critical milestones associated with both Phase I and II. Both Phase I and Phase II are complete and meet all of the objectives associated with the proof of principle for the VVA project. The engine selection has positioned the project to be able to take advantage of some of the technical findings from the OEM including test data, calibration experience, engine development and detailed specifications.

Task	Description	Planned Completion Date	Actual Completion
1.1 Identify Preliminary Functional Requirements	**Identify Target engine**	**2/01/06**	**2/03/06**
1.1	**Obtain or build engine model**	**07/01/06**	**03/08/06**

1.1	**Calibrate Engine Model using Dyno Data**	**7/01/06**	**03/08/06**
1.1	**Define representative points of the drive cycle**	**7/01/06**	**3/08/06**
1.1	**Literature Study/Competitive Analysis**	**3/01/06**	**3/01/06**
1.2 Detailed VVA Functional Requirements	**Identify optimal valve profiles to maximize fuel economy.**	**7/01/06**	**3/30/06**
1.2	**Identify required mechanism analysis tools**	**3/15/06**	**03/15/06**
1.3 Selection of Candidate VVA System	**Selected most appropriate system based upon key performance requirement**	**8/31/06**	**10/31/06**
2.1 Detailed Candidate VVA Design and Analysis	**Design Single cyl VA Hardware**	**4/30/07**	**5/30/07**
2.1	**Develop actuator and control system**	**4/30/07**	**5/15/07**
2.2 Virtual verification testing of VVA system	**Dynamic analysis of in cylinder air flow**	**5/31/07**	**OEM supplied data**
2.2	**Dynamic Analysis and FEA modeling**	**5/31/07**	**6/30/07**
2.2.1	**Actuator Spec. and Design**	**9/30/07**	**9/30/07**
2.3	**Prototype Hardware Build**	**11/30/07**	**11/10/08 Ver 1 3/5/08 Ver2**
2.4	**Experimental Fixture Testing**	**12/30/07**	**12/30/07 Ver 1 3/30/08 Ver 2**
2.5	**Virtual Engine Test**	**1/31/08**	**6/30/08**

Figure 2.4-1 Project Milestone Summary

3.0 PROJECT ACTIVITES

3.1 Engine Selection Matrix

An engine selection matrix, a portion of which is shown in Figure 3.1-1, was prepared evaluating 25 different engines and their respective EMS and valvetrain configurations.

An engine was selected to be the target application for all work relating to this project.

			Engine configuration					Model avaiablity			
			Engine type (L4/L6/V6/V8)	Valve train type	DOHC or SOHC	US market availability	Available packaging envelope	GT-Power model	3D In-Cylinder flow/combustion model (Star-CD or Kiva)	Engine CAD model	Emission regulation compliance
Points			L4/L5/L6: 2 V6/V8: 1	Type 2,3: 2 Type 1,4,5: 1	DOHC: 2 SOHC: 1	Yes: 2 No: 1	Yes: 2 No: 1	Yes: 2 No: 1	Yes: 2 No: 1	Yes: 2 No: 1	Euro5/US Tier 2 Bin5: 2 Euro4: 1
Weight factor			**2**	**3**	**3**	**1**	**3**	**3**	**2**	**3**	**2**
Criticality							**1**	**1**		**1**	
OEM	**Model**	**Liters**									
		6.0	1	1	2	2	1	2	2	2	1
		3.5, 4.5	**1**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
		2.2	2	2	2	1	2	1	1	1	1
		2.7	1	2	2	1	2	1	1	1	1
		1.9	2			1		1	1	1	1
		3.2	2	1	2	2	1	1	1	1	1
		3.0	1	2	2	1	2	1	1	1	1
		1.9	2	2	2	1	2	1	1	1	1
		2.4	2	2	2	1	2	1	1	1	1
		1.3	2	2	2	1	2	1	1	1	1
		3.0	2	2	2	1	2	1	1	1	1
		2.7	2	2	2	1	2	1	1	1	1
		4.2	1	2	2	1	2	1	1	1	1
		3.0	2	2	2	1	2	1	1	1	1
		4.4	1		2	1		1	1	1	1
		2.0	2		1	1					1
		2.9	2		2	1					1
		1.9	2	2	2	1	2	1	1	1	1
		2.2	2	2	2	1	2	1	1	1	1
		1.6	2		2	1		1	1	1	1
		2.0	2		2	1		1	1	1	1
		2.2	2	2	2	1	2	1	1	1	1
		2.2	2	2	1	1	2	1	1	1	1
		2.4	2	2	2	1	2	1	1	1	1

Figure 3.1-1 Engine Selection Matrix

3.2 Mechanism Approach

Two overall design approaches were investigated: a single cam design and a dual cam design. Each approach had characteristic strengths and weaknesses. While the single cam was lower cost it could not achieve the control flexibility required by the OEM. The dual cam design satisfied the control targets of the OEM but at higher cost. Based upon input from the OEM the dual cam design was selected for further development. Figure 3.2-1 shows the valve lift control curves of single cam design. Figure 3.2-2 shows the valve lift control curve of a dual cam design.

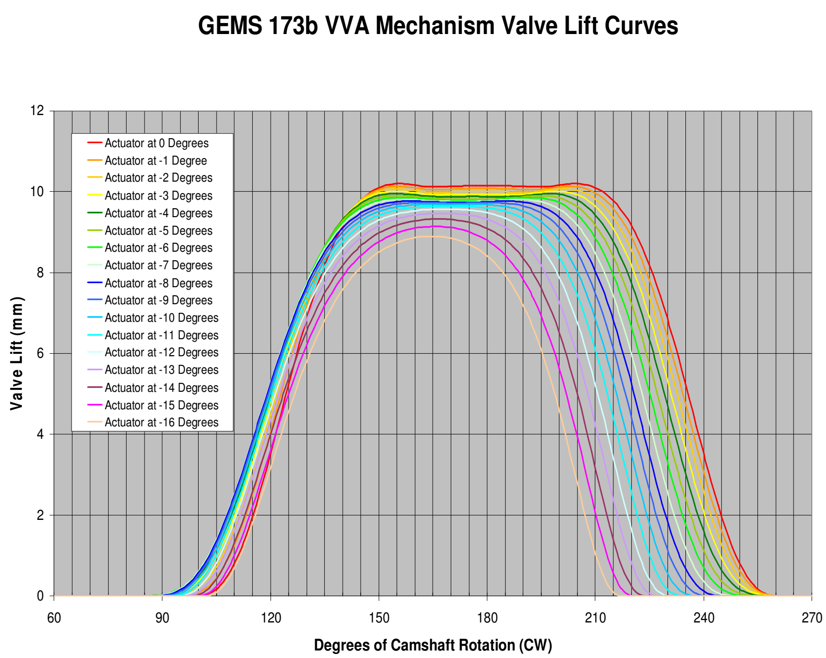


Figure 3.2-1 Single Cam Design Valve Lift Profile Family

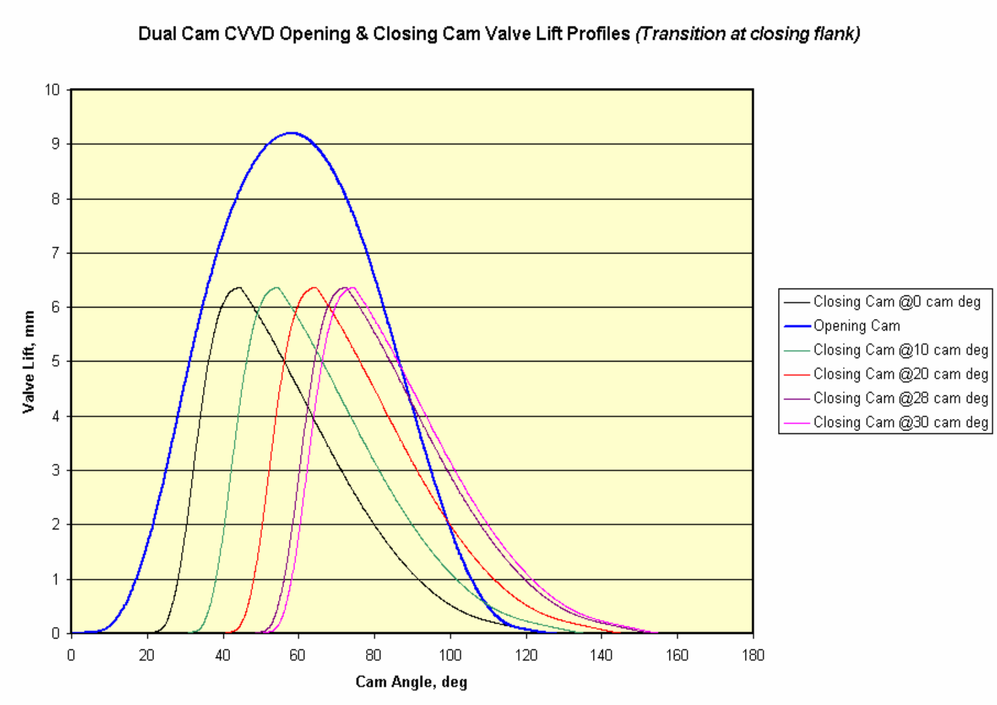
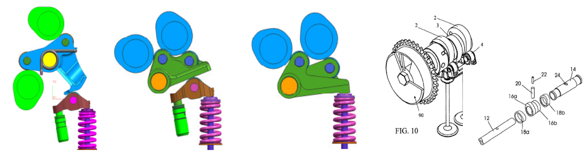


Figure 3.2-2 Dual Cam Design Valve Lift Profile Family

3.3 Concept Selection

Once the OEM's priorities we established, several designs were proposed and a concept selection matrix was prepared. Figure 3.2-1 shows a portion of the design selection matrix. One design was selected for further development.

Note
Hydraulic cam phaser is assumed for estimating the system



Comparison metric	Delphi GEMS	Delphi CVVD Design "A"	Delphi CVVD Design "B"	Delphi CVVD Design "C"	Double layer camshaft
Packaging Width	+	-	o	o	+
Packaging Height	o	-	+	+	+
Diesel Requirement Compliance	-	+	+	+	+
OEM Assembly Ease	+	+	+	o	-
Friction	o	o	o	o	-
Serviceability	+	+	+	o	-
System Manufacturing Cost	-	o	o	+	-
Remarks	-Electric motor actuator needed, with phaser -Output cam grinding needed	-Concern with packaging H and W -Output cam grinding needed	-Concern with phaser gear size for durability -Advantage in packaging	-Concern with phaser gear size for durability -Low cost design (need to re-design cylinder head)	-High engineering risk and high cost using double layer cam shafts (inner & outer)

Figure 3.3-1 Concept Selection Matrix

3.4 Detailed Description - Mechanism Layout and Cam Profile Design

3.4.1 Mechanism Layout

The CVVD mechanism design layout was fully parameterized to allow automatic updating if design parameters changed. There were many design control factors at the beginning of layout work and the driving and driven dimensions were determined to be consistent with modeling design tools such as VT-Design and ADAMS. This approach has been followed for the new LM-CVVD as well as for the stiffness improvements made to previous CVVD design.

3.4.2 Cam Profile Designs

The cam profile design began with the generation of target valve lift. The target valve lift profile are created based on customers' inputs such as maximum lift height, valve opening duration, area under the lift curve, valve seating velocity, etc.,

Since the CVVD mechanism is unique in such a way that it has three cams (opening, closing and output cams) unlike a conventional valvetrain, it requires a different approach to design cam profiles for all three. The commercial valvetrain modeling/simulation software GT-VTain can not simulate the CVVD mechanism. Decomposing the CVVD into two subset systems allowed kinematics modeling in the GT-VTrain environment.

Details of cam profile design are presented in the previous quarterly reports.

After all three cam profiles were designed, the UG Motion as shown in Fig. 3.4-1 is used to verify the CVVD kinematics. Similar analysis performed for the new LM-CVVD design is shown in figure 3.4-2. Although the modeling does not account for the effects of engine speed, mass moment of inertia, and spring stiffness, this simply rigid body motion modeling is very useful to check the valve lift results from cam profiles.

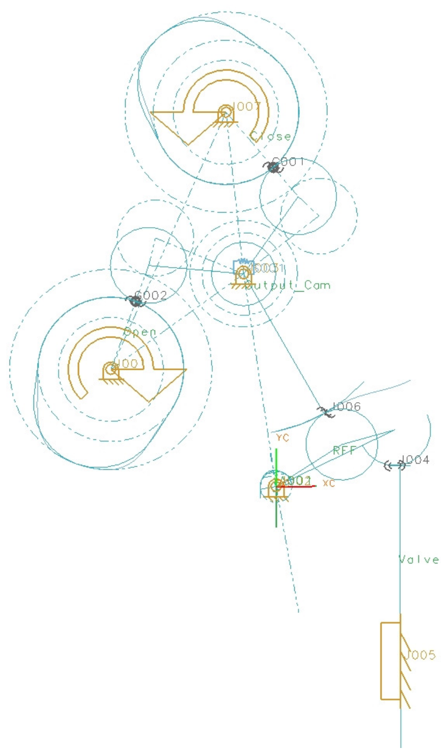


Figure 3.4-1 UG Motion CVVD modeling setup

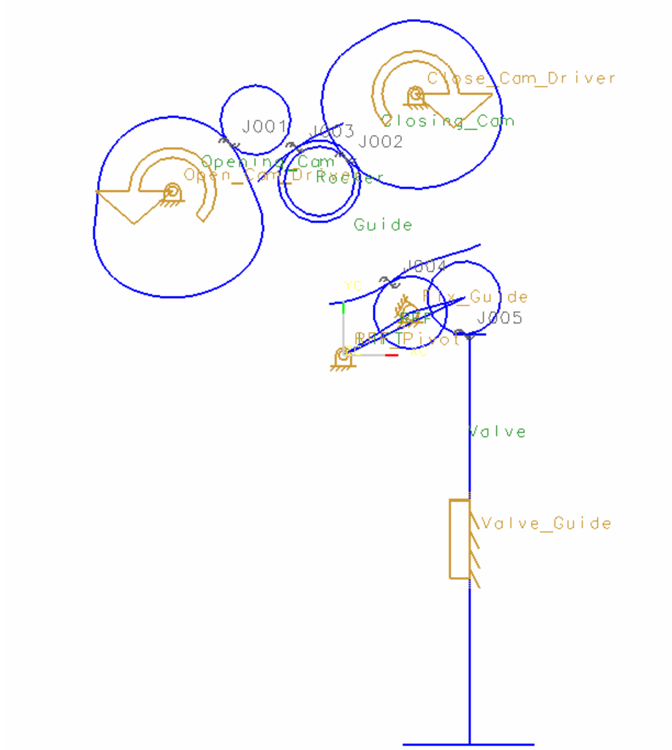


Figure 3.4-2 UG Motion LM-CVVD modeling setup

The CVVD closing lobe height is intentionally smaller than 20 micron so that it always ensures the cam follower makes a high-low transition even if there are cam grounding tolerance errors for both opening and closing cams. Also, the rotation direction of the opening cam is clockwise direction and the closing cam rotates in counter-clockwise direction because these two cams have gear meshed connection. The cam rotation directions were determined by the easiness of cam phaser adaptation on the closing cam.

The LM-CVVD closing cam lobe height is not modified since the design does not have a lobe transition to contend with. Two cams are still referred to as opening and closing cams.

3.5 CVVD Single Cylinder Fixture (SCF) Build and Functional Test

3.5.1 Overview

The CVVD component parts prints were completed and hardware returned from fabrication shops. After assembly and testing on engine cylinder head stand a potential system stiffness issue needed to be resolved.

Mechanism stiffness was determined to be inadequate prior to initial hardware testing but subsequent to hardware order. FEA analysis predicted 0.419 mm of undesired deflection at the valve (FIG 3.5.1-1).

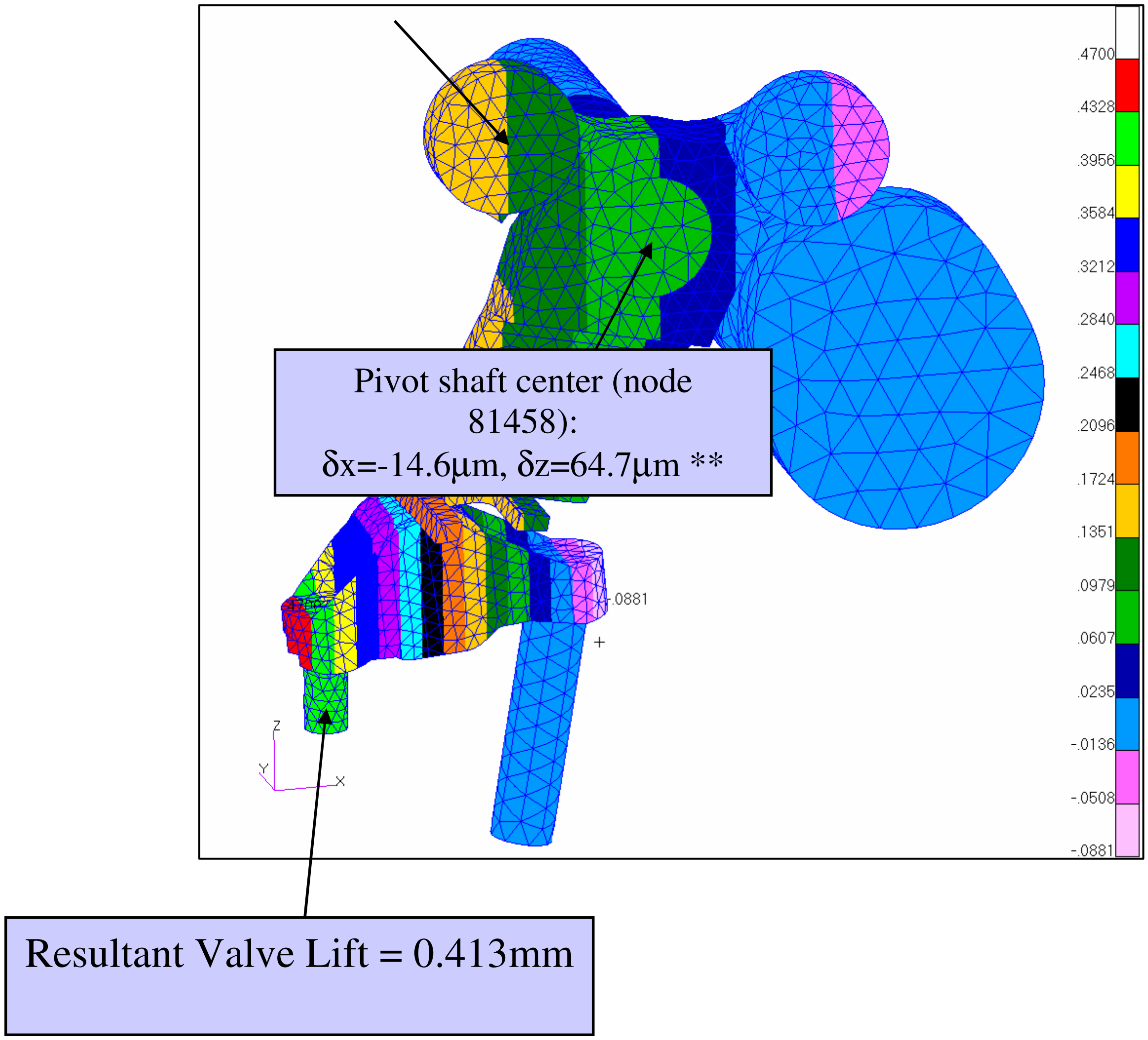


Figure 3.5.1-1: Original FEA Opening Cam Valve Tip Deflection

Changes to the carrier were made to reduce this deflection. The majority of deflection was caused by bending of the pivot shaft that the oscillating Output Rocker Cam (ORC) is mounted on. The carrier was made wider to better support the pivot shaft thus effectively reducing the length of this shaft in bending. FEA completed on this design (FIG 3.5.1-2) predicted a valve tip deflection of 0.265 mm compared to the initial 0.413 mm.

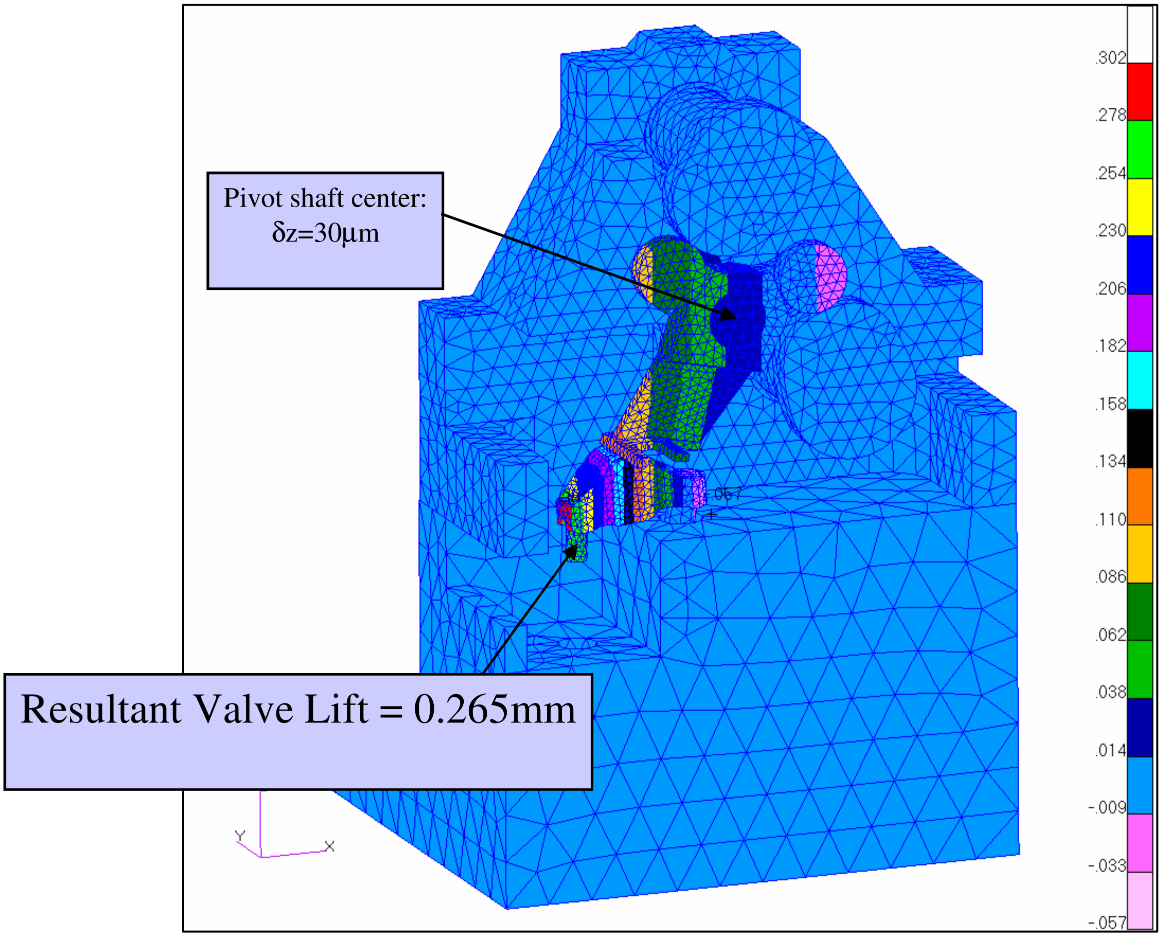


Figure 3.5.1-2: Wide Carrier FEA Valve Tip Deflection Analysis

FEA predicted opening cam deflection to be worse than closing cam deflection. Deflection would be at a minimum during the critical transition from opening to closing cam. The design intent was for a small step down in lift (preferred to a step up) at this critical transition. FEA predicted an undesirable step up at this transition. Consideration was given to modifications to either the opening and / or closing cams in order eliminate the step up condition. The design team chose to base cam modifications on measured test data due to the status of hardware delivery and the uncertainty of FEA predicted deflection. Data from initial testing (FIG 3.5.1-3) showed a step up of approximately 0.350 mm.

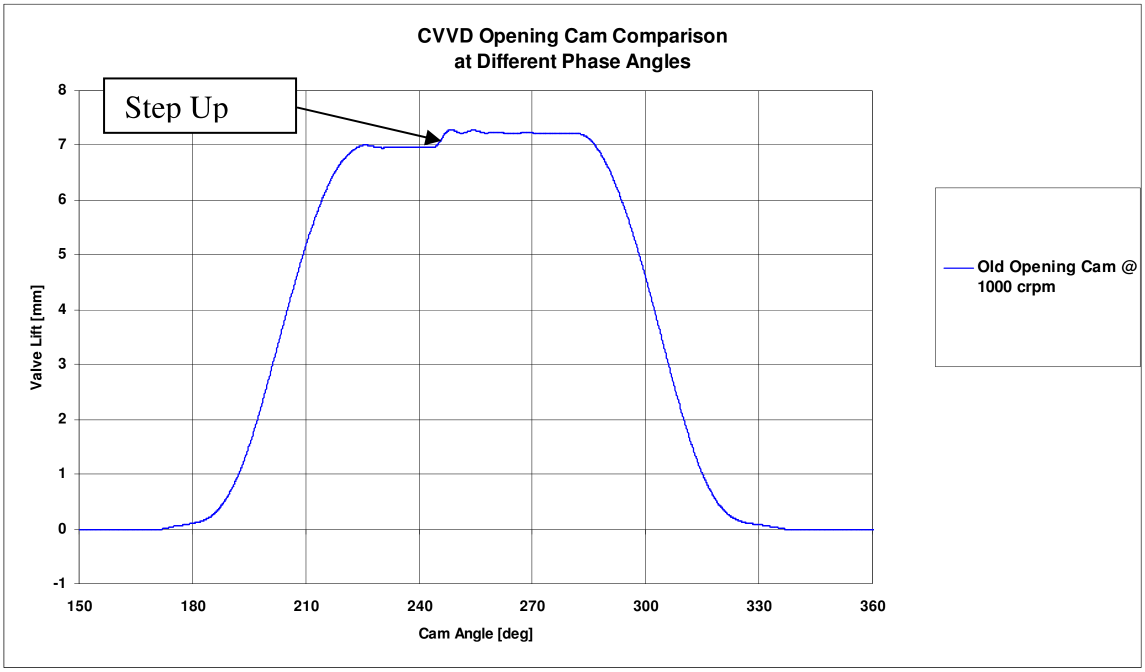


Figure 3.5.1-3: Initial Hardware Test Data showing 0.350 mm Step Up Transition

Modifications were made to the opening vs. the closing cam in order to maintain maximum lift. The new cam was delivered, tested and found to only improve the step up condition. Test results on the modified opening cam (FIG 3.5.1-4) showed a step up of 0.070 mm vs. the initial measurement of 0.350 mm.

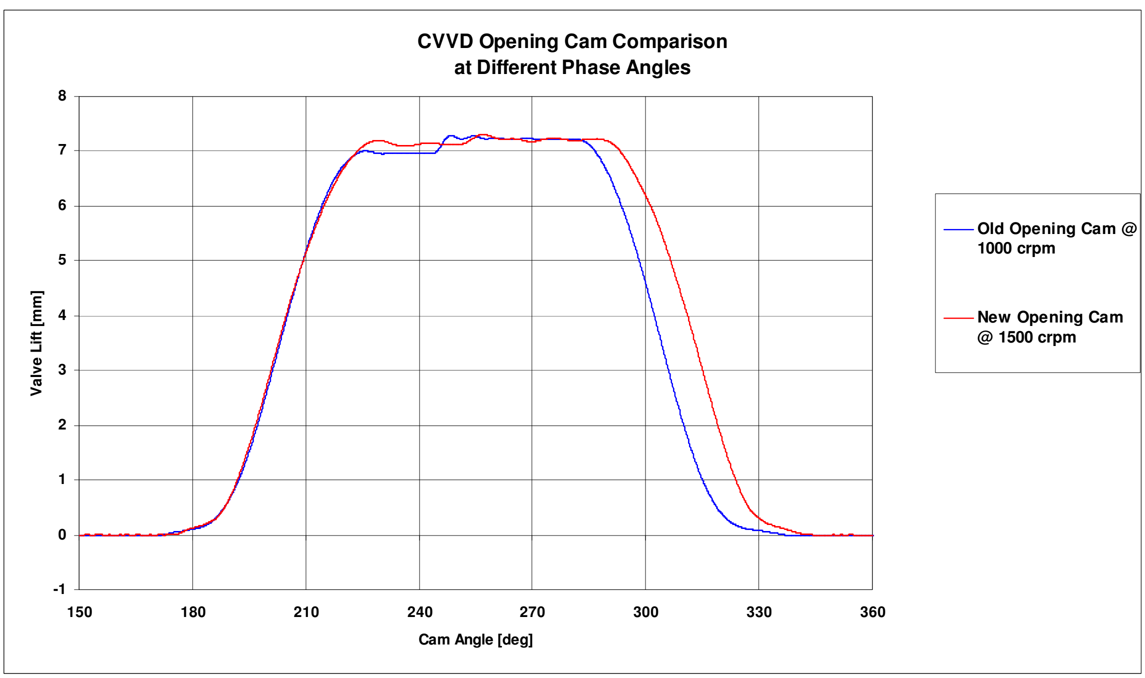


Figure 3.5.1-4: Step Up Comparison of Initial Hardware vs. Modified Opening Cam

3.5.2 Deflection Optimized Design Test Results

Hardware for the reduced deflection design was tested on a motored cylinder head stand. Full test results are discussed below.   Figure 3.5.2-1 shows the single cylinder fixture on the test stand .

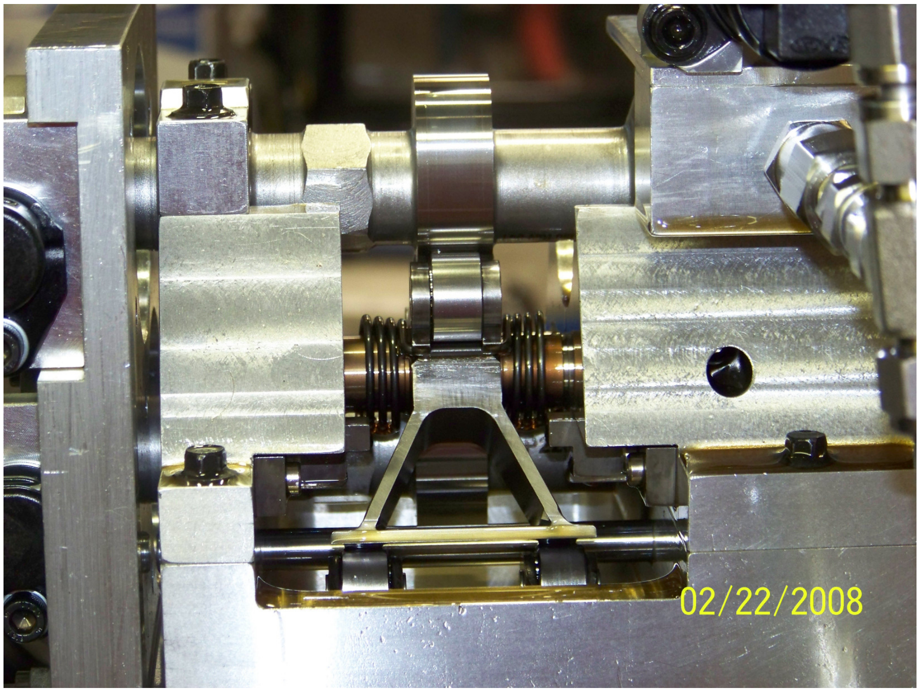


Figure 3.5.2-1 Test Hardware on Stand

Valve Lift

Valve lift was measure with long range proximeters at various cam RPM from idle (300 cam RPM) to max speed (2400 cam RPM). The results are shown below in Figure 3.5.2-2.

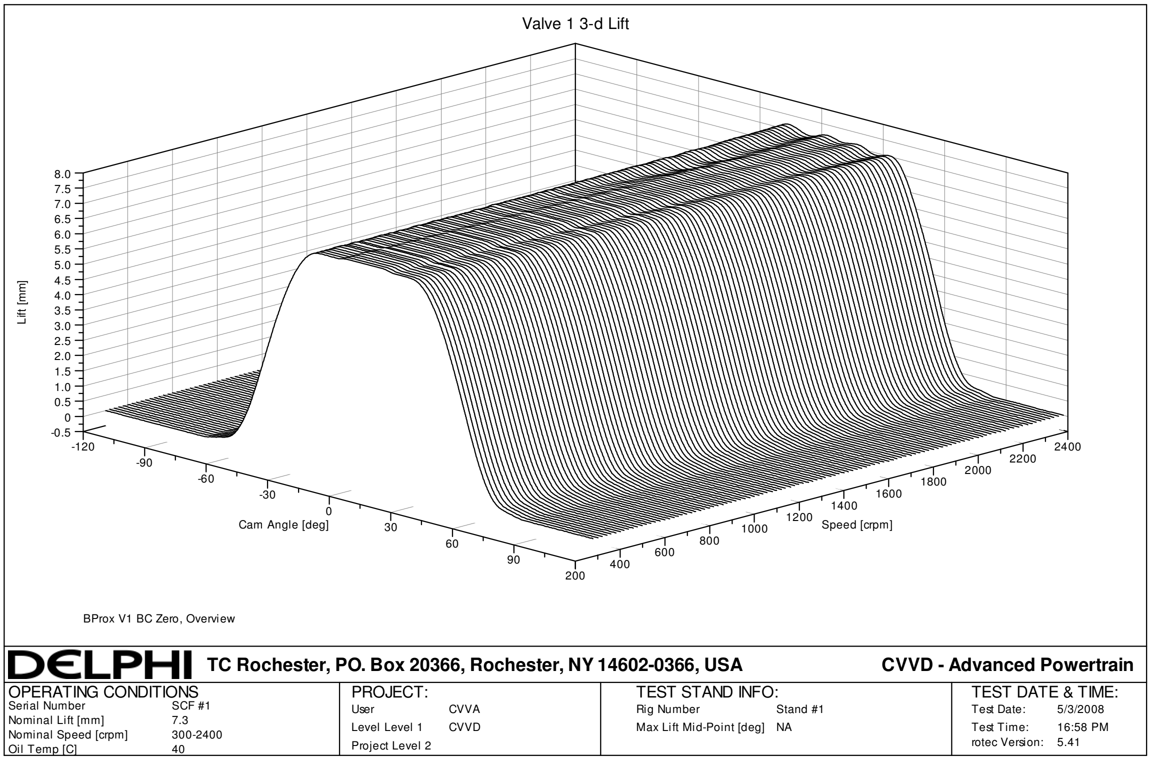


Figure 3.5.2-2 Valve lift measurements at various cam RPM

The step up condition previously noted with all hardware levels was still evident although improved. A comparison of step up conditions is shown in Figure 3.5.2-3.

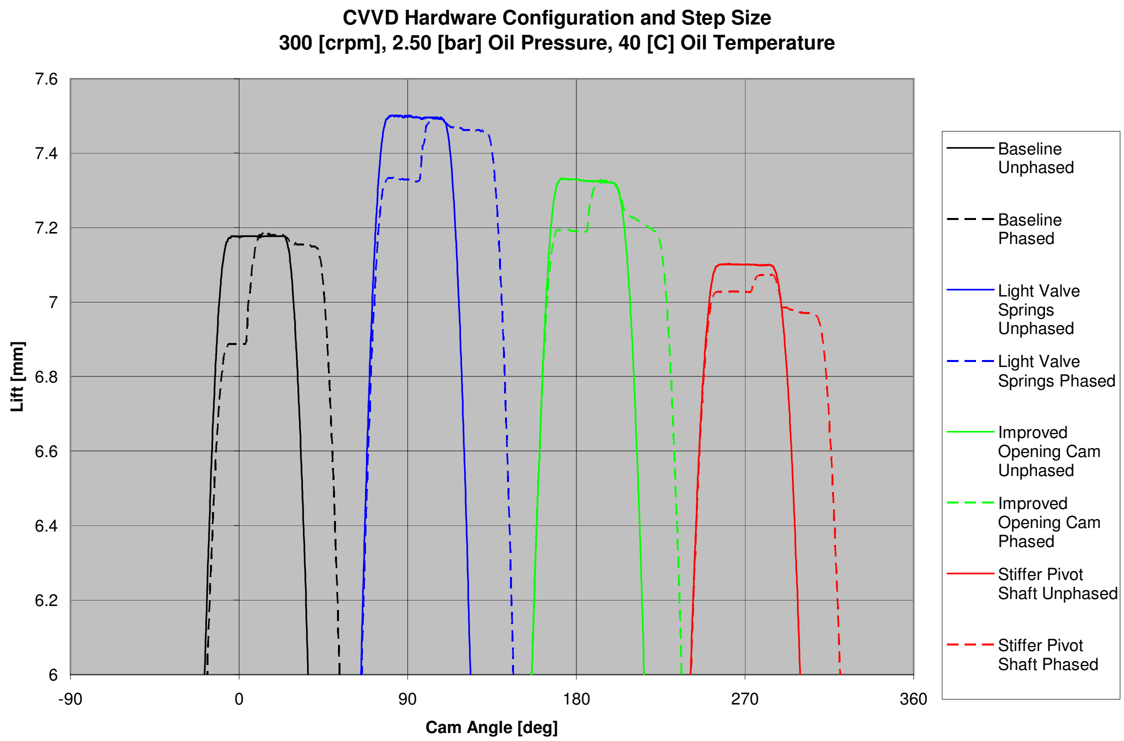


Figure 3.5.2-3 Comparison of step up conditions

<u>Valve Opening, Closing, Duration, and Seating Velocity</u>

Valve duration was evaluated at 3 cam phase angles which correlated to minimum duration, 12 degree duration increase, and full duration increase of 24.5 degrees. Variation in duration as a function of cam RPM (note engine RPM is double the cam RPM shown on graphs) was evaluated. Duration in a function of valve opening and closing angles which were also evaluated in order to determine if duration variation was caused by opening, closing, or a combination of these. Results for the 3 conditions are shown in Figures 3.4.2-4 thru 3.4.2-6.

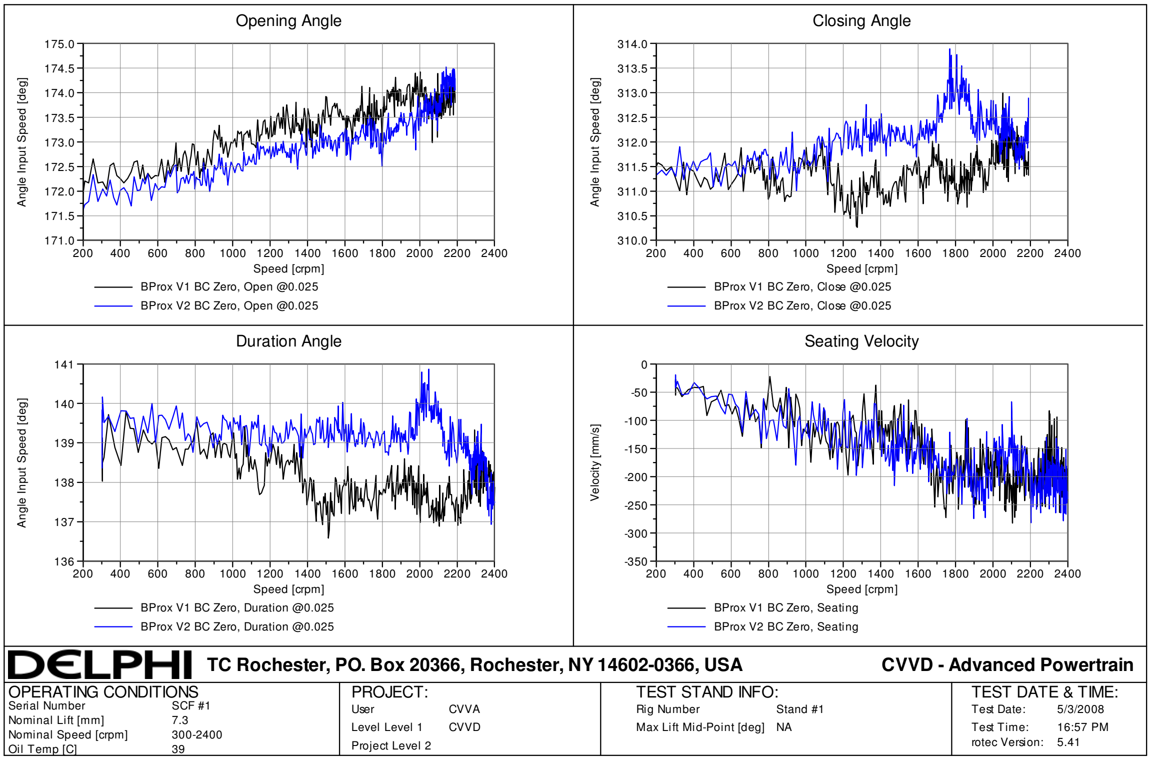


Figure 3.5.2-4 Minimum duration opening, closing, duration and seating velocity

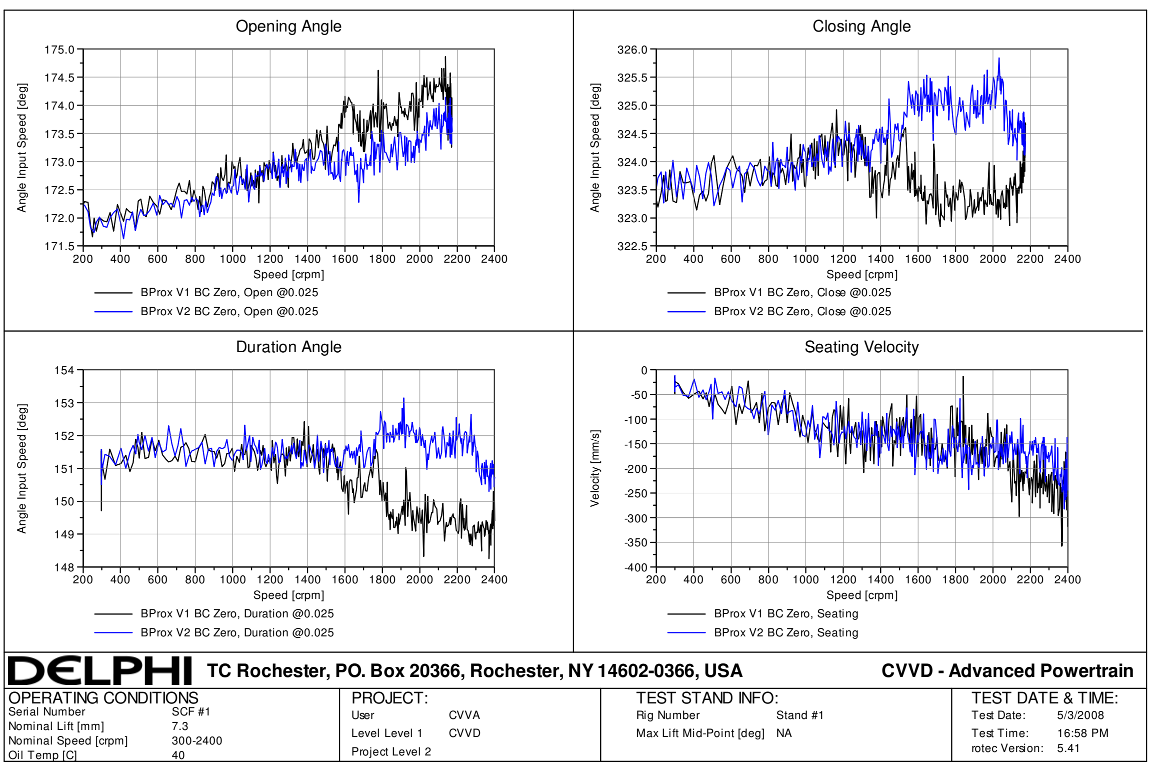


Figure 3.5.2-5 12 degree duration opening, closing, duration and seating velocity

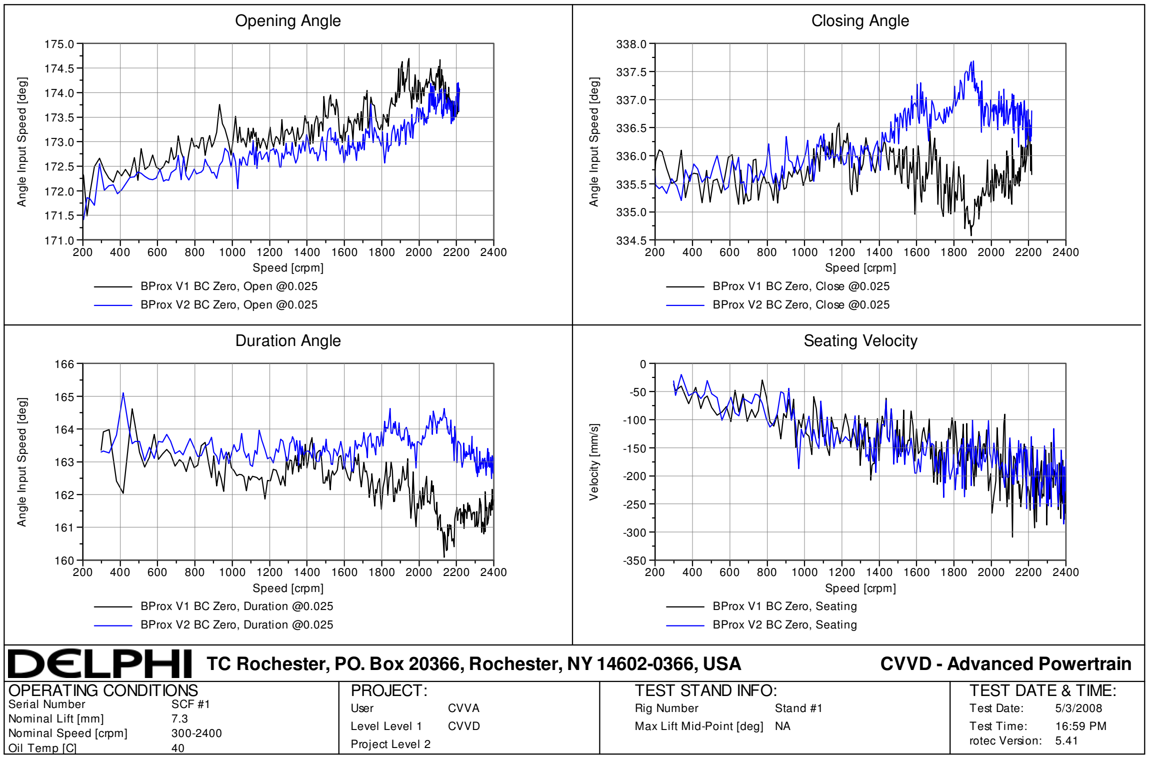


Figure 3.5.2-6 24.5 degree duration opening, closing, duration and seating velocity

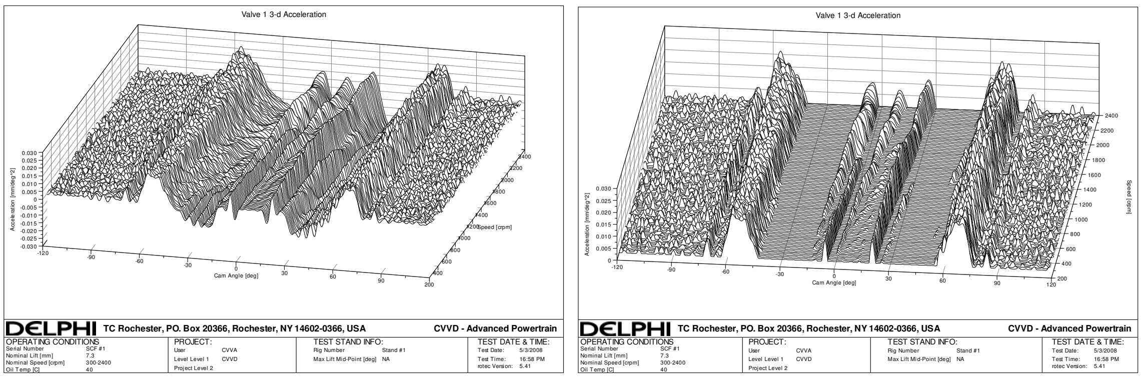
Valve lift duration was relatively constant through the speed range. There was variation between the 2 valves which is not uncommon based instrumentation variation as well as tolerances including conventional valve train components such as roller finger follower geometry which effects rocker ratio and valve tip position. We noted that valve opening angle occurs later as speed is increased. This is expected based on the higher opening velocities and loads which occur at higher speeds. Valve opening behavior is very similar between both valves.

Valve closing also has a general trend of occurring later as speed increases up to about 1300 cam RPM. This behavior is likely the result of lash adjuster leak down reduction at higher speeds due to reduced load dwell time. It is interesting to note the divergent behavior between valves which occurs at varying cam speeds for the different conditions. This may likely be caused by an undesirable dynamic conditions caused by the new mechanism. In summary there are issues to be investigated and improved, but overall valve lift duration was fairly consistent at the 3 conditions evaluated.

Valve seating velocities were very good through all test conditions. This is an indication that system deflection is below the level compensated for by cam ramps. This leads to quiet operation as well as good durability. There was no evidence of valve bounce throughout all test conditions.

Valve Acceleration

Valve acceleration was measured in order to better understand valve behavior. Results of this testing is shown in figure 3.5.2-7. Full valve acceleration data is presented. Positive acceleration data is also presented with the graph basically truncated at 0 acceleration.



Full Acceleration Data Positive Acceleration Data

Figure 3.5.2-7 Valve acceleration

Measured results indicated a peak positive acceleration of 0.025 mm/cam degree squared. This value was higher than our design value of 0.020 mm / cam degree indicating somewhat unintended valve behavior. The absolute value may not be a concern for the low RPM diesel application, but the lack of correlation with design value presents the greatest concern. The positive acceleration data plot clearly shows the presence of positive accelerations during the constant peak lift portion of the valve event. This is uncommon for a conventional valvetrain, but is not completely unexpected for a CVVD mechanism. It is interesting to note that positive accelerations are very high during this phase of the lift profile. These high accelerations are likely a result of the step up condition.

Cam Drive Torque

Cam drive torque was measure as an indication of overall valvetrain friction. This is an important consideration as valve train friction directly impacts fuel economy. Minimizing valve train friction was a major design goal for this project. The results are shown in Figure 3.5.2-8.

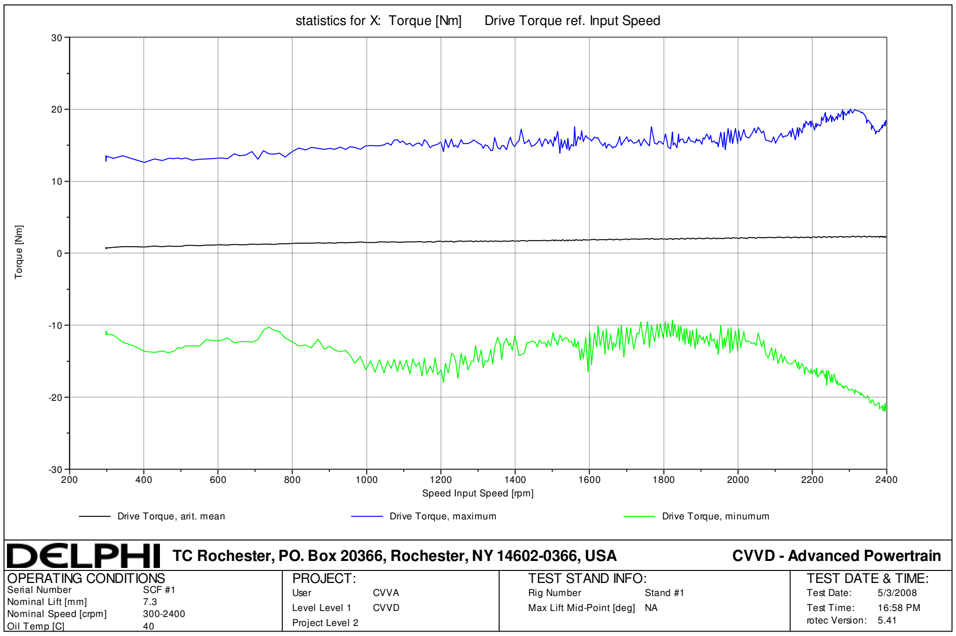


Figure 3.5.2-8 Cam drive torque

The cam drive torque data presented shows mean torque as well as positive and negative torques. It is the mean torque which we are concerned with as this is net effect on the crankshaft. These results are consistent with typical valve train systems and indicate a peak torque of 2 N-m.

3.5.3 Test Summary

This design level exhibited typical valve train behavior under test conditions. Valve seating velocity and cam drive torque were both acceptable. Valve duration variation with cam speed had some concerns, but did not present a specific problem. The valve step-up condition as shown by valve lift and acceleration data present a concern and area for improvement in future revisions. The step up condition was caused by component deflection in the area of transition from opening to closing input cams. Further reductions are possible in future designs.

3.6 Improved Design LM-CVVD Design Description:

3.6.1 Overview

LM-CVVD design, shown in Figure 3.6.1-1, employs an opening and closing cam, each acting on a needle bearing follower mounted to a common output cam. Opening and closing cams are commonly referred to as input cams as they provide the oscillatory motion to the output cam. Output cam contains a third cam surface acts through a conventional roller finger follower to provide valve lift by converting oscillatory motion provided by input cams.

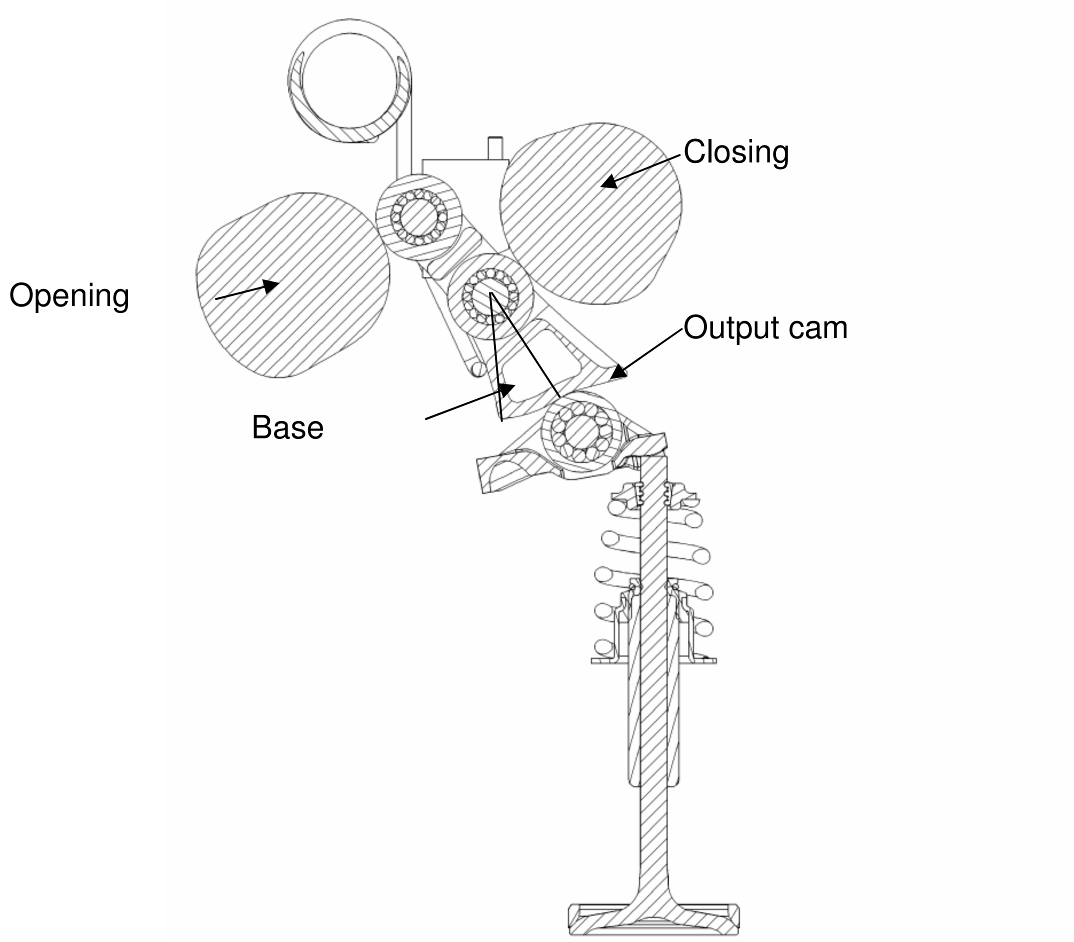


Figure 3.6.1-1 LM-CVVD Design

Valve lift event occurs in four step sequence described below.
<u>Initial Stage</u> – In the initial condition both opening and closing input cams are on their base circle as shown in Figure 3.6.1-2. The opening cam is at the full counterclockwise rotation. At this stage both opening and closing cams are at base circle (or minimum lift).

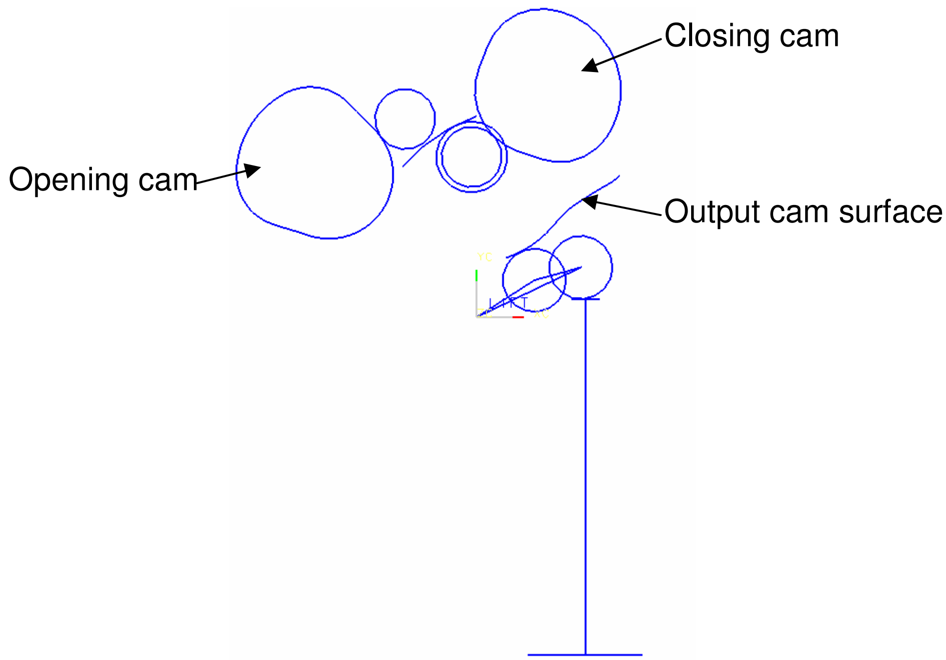


Figure 3.6.1-2 LM-CVVD Initial condition

Step 1 – Closing cam rotates output rocker cam through the full base circle portion of the cam surface as shown in Figure 3.6.1-3. At this stage the closing cam is a full cam lift and the opening cam is still at base circle (or minimum lift). Full closing cam lift is taken up by the base circle portion of output cam, thus no valve lift is produced since output cam is still on base circle. This step is described as closing cam stages output cam.

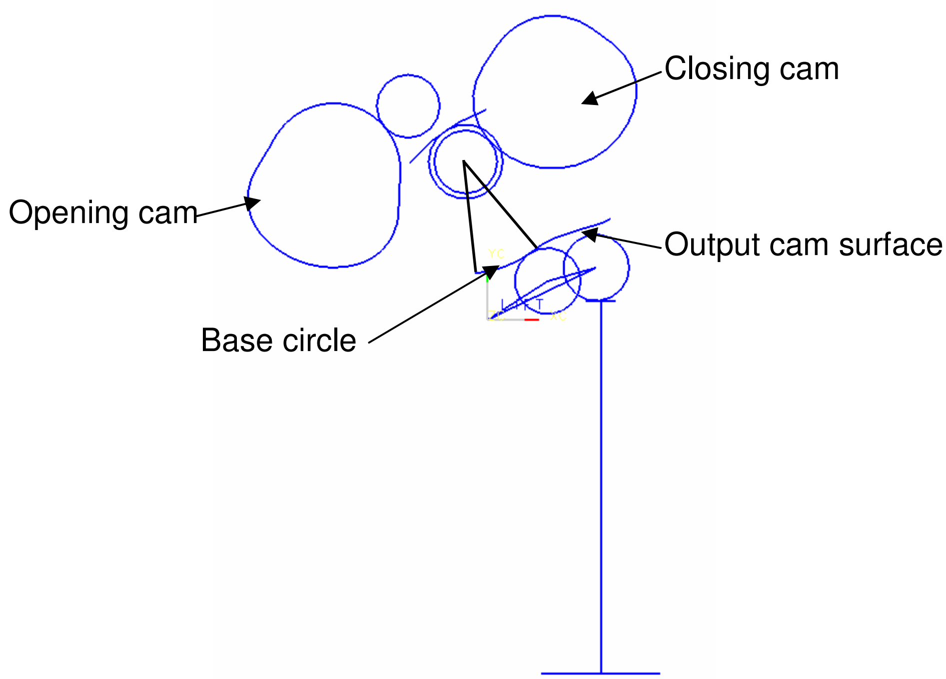


Figure 3.6.1-3 LM-CVVD Step 1 Closing cam stages output rocker cam

Step 2 – The opening cam rotates the output rocker cam through full stroke to peak lift condition as shown in Figure 3.6.1-4. At this stage both cams are at full cam lift conditions. Output rocker cam is at full clockwise rotation and full valve lift is produced at the peak lift portion of the output cam surface.

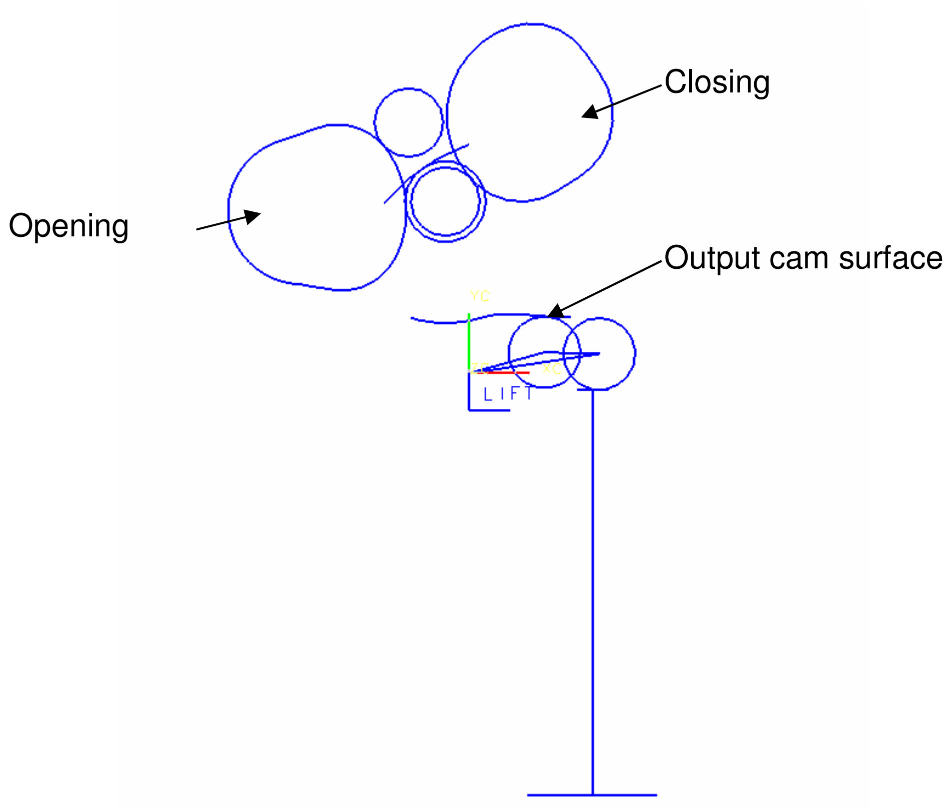


Figure 3.6.1-4 LM-CVVD Step 2 Full lift

Step 3 – Closing cam rotates to base circle while opening cam remains on lift portion of lobe profile as shown in Figure 3.6.1-5. At this stage output cam has rotated counterclockwise from full lift position to base circle thus closing the valve.

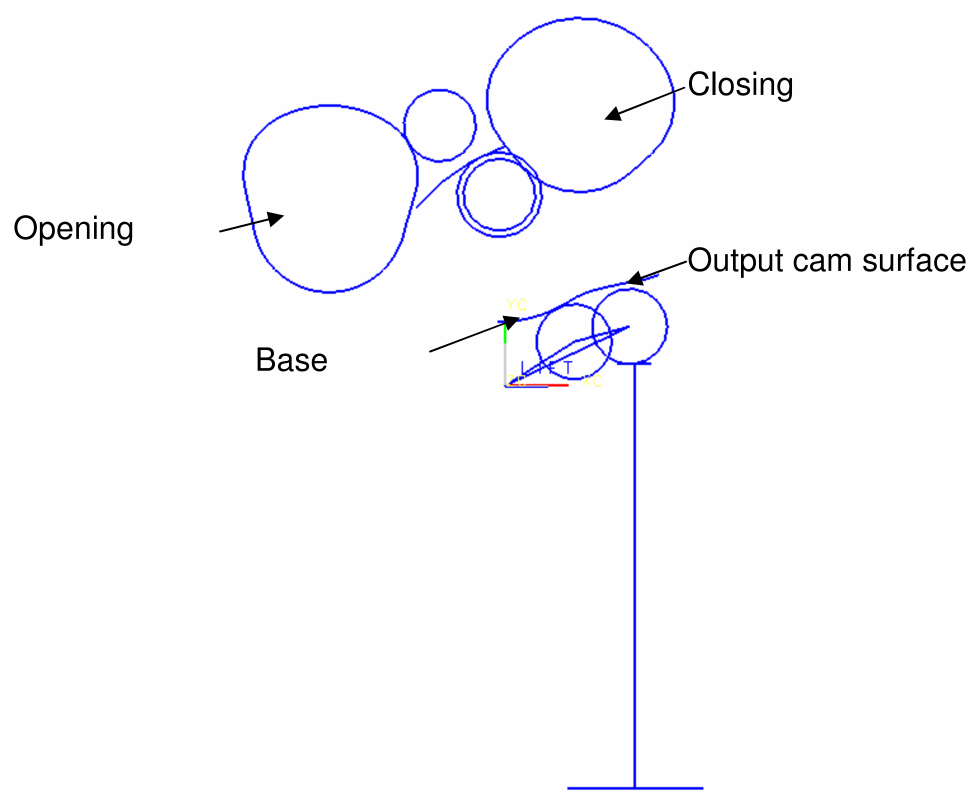


Figure 3.6.1-5 LM-CVVD Step 3 Valve closed by closing cam

Step 4 – Opening cam rotates to base circle while closing cam remains on base circle returning mechanism to initial condition previously shown in Figure 3.6.1-2. Motion from reduction in opening cam lift occurs completely on base circle portion of output cam thus no lift change produced at valve.

3.6.2 Valve Lift Duration Variation

Variation of valve lift duration is produced by changing angular orientation of the two input cams. Conventional cam phaser is used to produce the desired relative angular variation between both input cams. Minimum valve lift duration occurs when opening cam peak lift is achieved just as closing cam peak lift is finishing. Maximum valve lift duration occurs when opening cam peak lift is achieved very shortly after closing cam peak lift is achieved. Valve lift duration is close to the complete dwell time of the closing cam full lift profile with this input cam phasing position.

3.6.3 Hardware Design

A demonstration fixture shown in Figure 3.6.3-1 has been designed and built as a proof of concept activity. Full load, stress, deflection, and stiffness evaluations have not been completed on this fixture.

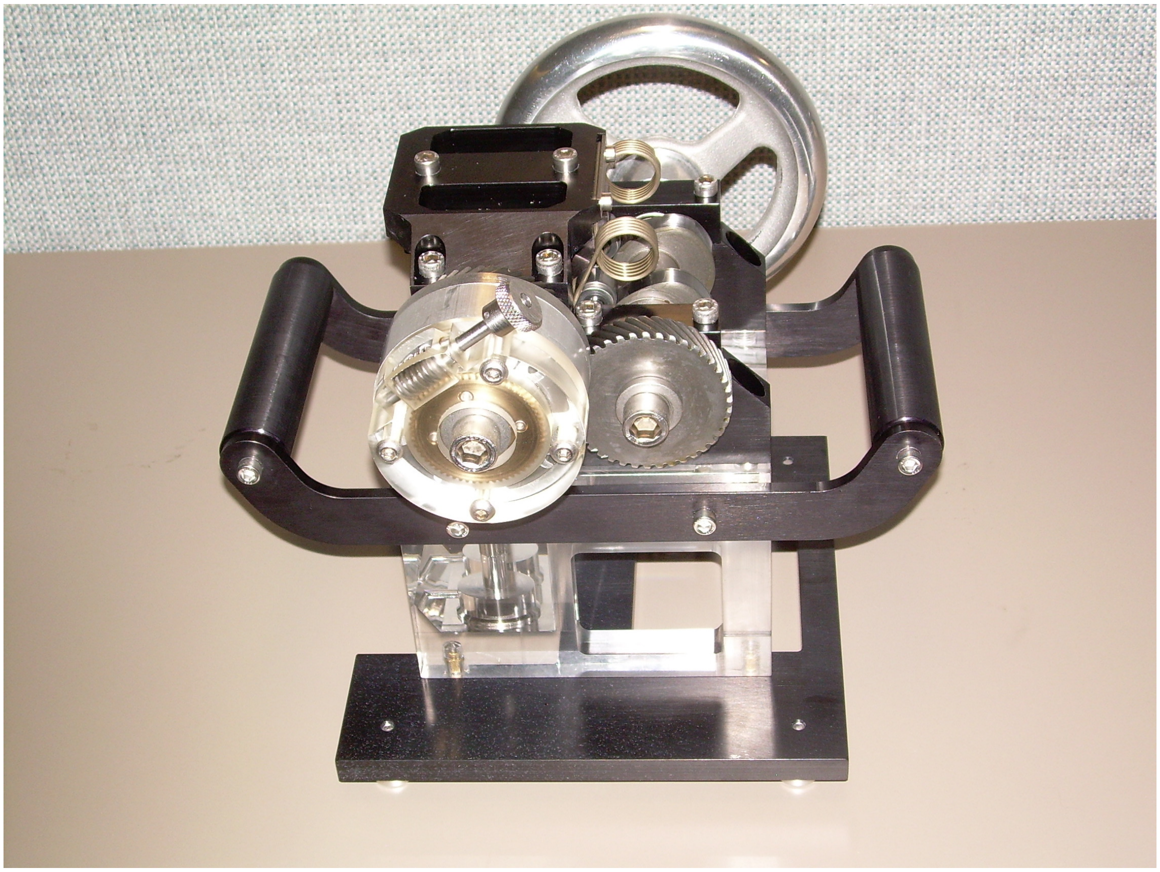


Figure 3.6.3-1 LM-CVVD Demonstration hardware

Geometry for LM-CVVD demonstration fixture was created through multiple analysis loops aimed to optimize peak loads, pressure angles, packaging, and required cam phasing authority in order to achieve required valve duration profiles. ADAMS rigid body dynamic analysis software was used to perform a final design evaluation. ADAMS model, shown in Figure 3.6.3-2, was set up and used in order to fully validate the design before building hardware.

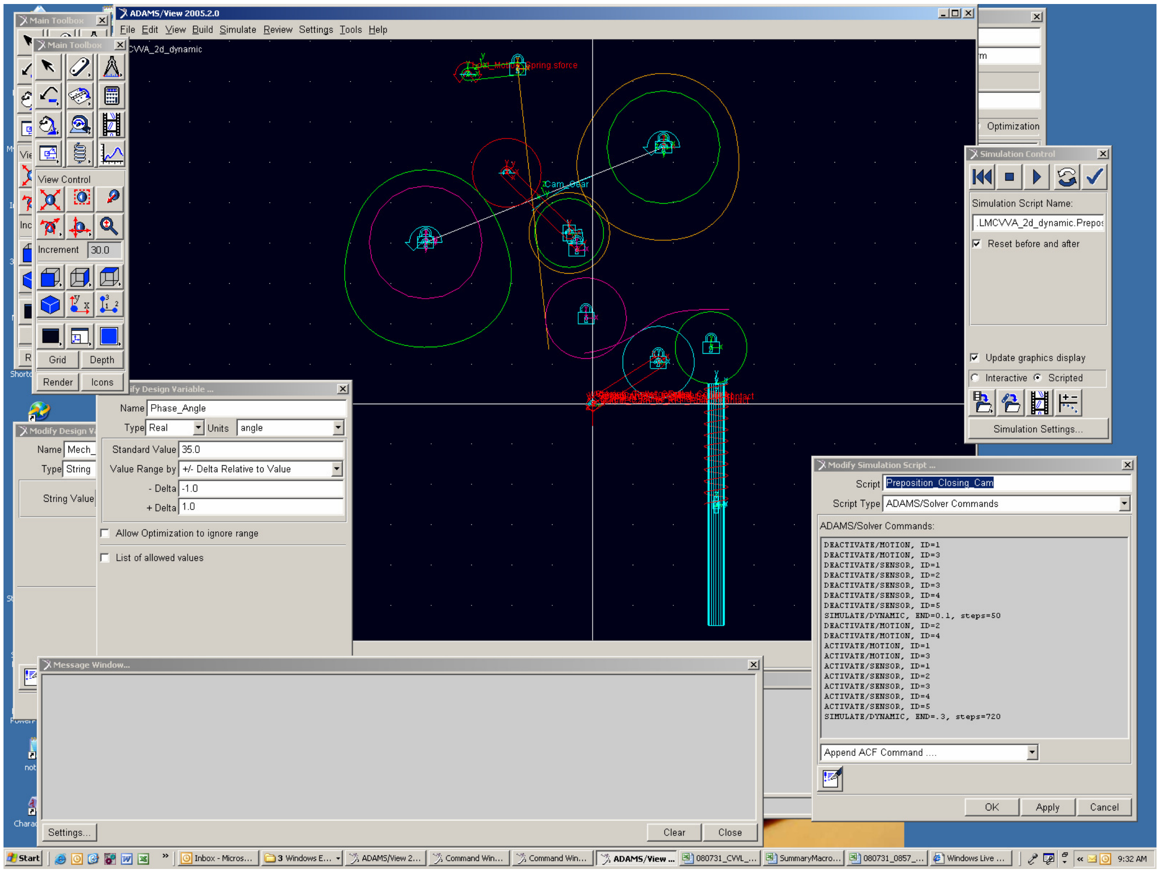


Figure 3.6.3-2 LM-CVVD ABAQUS FEA Simulation

4.0 RESULTS AND CONCLUSIONS SUMMARY

- The overall design approach of the LM CVVD Mechanism satisfies the OEM's control and durability requirements.
- Design proposals to address the step up condition in valve motion at the cam transitions point were completed and tested.
- Latest design improves but does not eliminate step up condition which is currently considered to be a dynamics concern.
- Valvetrain dynamic testing indicates operation consistent with typical production valvetrain systems.
- Valvetrain power consumption due to added bearings and related components is similar or slightly higher than conventional valvetrain systems.
- It is possible to achieve a smooth transition from opening to closing cams. However, new designs must be considered as an integral part of the engine and head assembly.

- The LM-CVVD (lost motion CVVD) design is a more robust configuration and will eliminate the transition discontinuity over a wider range of operation.

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5.0 TECHNOLOGY TRANSFER ACTIVITIES:

5.1 Publications

- A description of the project has been published in DOE Advanced Combustion Technologies Annual Report. in 2006, 2007 and soon to be released 2008.

5.2 Presentations

- Meetings were held with OEMS Several design meetings were held with OEMS to introduce and refine the design
- This project was presented at 2007 and 2008 Merit Review Meetings, SMMR and MMR, requested and sponsored by DOE. These presentations resulted in two OEMs contacting Delphi for further information and possible future collaboration.

5.3 Collaborations

- The selected OEM supplied engine drawings, data and system requirements which were used to develop and optimize the final design.
- Oak Ridge National Lab is now using a Delphi supplied variable valve train to study combustion in an engine optimized for Ethanol operation.

5.4 Patents

- Three patents granted for mechanism design
- Two Filed for control system and design
- Three in process for dual cam designs