Type Paper Number Here

Modeling of Variable Valve Timing on High Performance Engine using Power-Oriented Graphs Method

Author, co-author list (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)
Affiliation (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)

ABSTRACT

Engine efficiency is one of the key aspects to reduce CO2 emissions. In order to improve the emission maintaining high performance capabilities several devices are introduced in the system; variable valve timing technology allows more flexibility for modern engines to meet peak performance, fuel economy and low emissions targets while providing good driveability. This paper describes the Lamborghini continuously-variable cam phaser model using a graphical technique, called Power Oriented Graphs (POG), that uses an energetic approach for representing the physical systems. The generally accepted approach is to calibrate an engine on a dynamometer and to adjust the operation of the engine to meet performance targets. With the current build and test approach, these adjustments may not be made until well into the development program, and this calibration is a costly and time consuming step in the engine development process: the main purpose of this works is allowing a faster model's calibration time. Furthermore the usefulness to model the system consists of analyzing in simulation many more system configurations than those available for real experiments so it's important using a simple methodology that is able to analyze the whole system's dynamic in order to reach the performance expectations. The results obtained were validated demonstrating the effectiveness of the POG technique.

INTRODUCTION

Nowadays the most of world manufactures, because of the increasingly tight emissions regulations, have been paying attention to the valve actuation. This effects on the car equipment that is provides with a cam driven systems because the experience shows that, by changing the valve timing or lifting, it's possible to rise the engine performance (such as engine power, torque, idle quality), thermal efficiency and exhaust cleanliness: one of these devices is the VVT (Variable Valve Timing) whose goal is shifting the relative angle between the crank and camshaft. The VVT control is performed by the Engine Control Unit that sets the desired values in term of cam angle, after that the solenoid valve is energized to allow the movement of the whole mechanism shifting the intake and exhaust valve timing relative to the crankshaft position. The system's modeling brings a wide range of benefits from performance system analysis, such as response time, for example, responsible of the most emission during the first engine starting, to the self-calibration parameters of many more system configurations, available for the a real experimental set-up. In this work it's been realized and validated the Simulink model using the Power Oriented Graph technique.

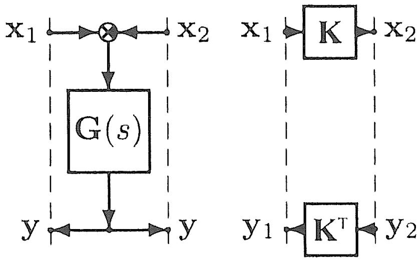
POWER-ORIENTED GRAPH, BASIC CONCEPTS

The Bond Graphs, Power-Oriented Graph and Energetic Macroscopic Representation are graphical modeling techniques based on *energetic approach* for modeling physical system, that use *Power and Energy variables* for that. Usually, all systems dissipative have the following properties:

1. a system *stores and/or dissipates energy*;
2. the dynamic model of physical system describes *how the energy moves within the system*;
3. the energy moves from point to point only by means of *two power variables.*

The POG block schemes are normal block diagrams combined with a particular modular structure essentially based on the use of the two blocks shown in Fig.1a/b:

- *elaboration block* (e.b.), for all physical elements that store and/or dissipate energy (i.e spring, mass, damper, capacities, etc
- *connection block* (c.b.), for the systems that transform the power without losses (i.e neutral elements such as gear reductions, transformers, etc.)

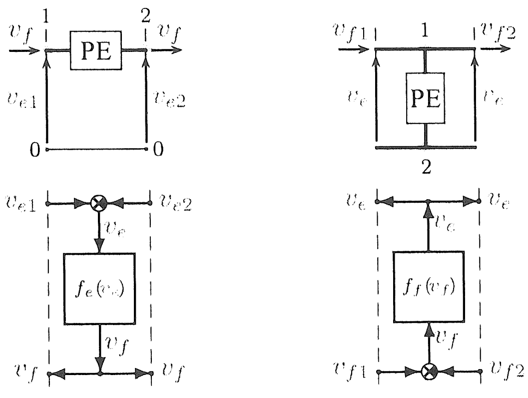


	POG Variables	
Domains:	*Across:* v_e	*Through:* v_f
Electrical	Voltage V	Current I
Mec. Tra.	Velocity v	Force F
Mec. Rot.	Ang. Vel. ω	Torque τ
Hydraulic	Pressure P	Flow rate Q

a) *e. b.* b) *c. b.* c) *Across and through variables*

Figure 1 POG basic block and variables: a) elaboration block; b) connection block; c) across and through variables

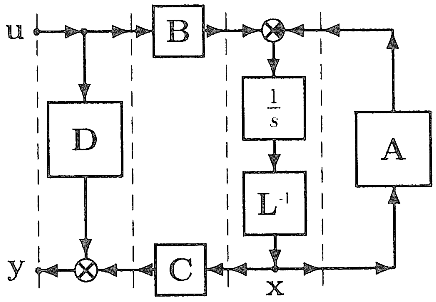
These blocks are suitable for representing both scalar and vectorial systems. In the vectorial case, **G(s)**, and **K** are matrices: the first one is always symmetric square matrix positive definite, while **K**-matrix can be rectangular. The circle in the *e.b.* is a sum element and the black spot means a minus sign that multiple the input variable. The main features of POG is keeping the right equivalence between the dashed sections of the graphs and the real power sections of the modeled system: *the scalar product of the two power section variables has the meaning of the power flowing through that section*.
The main energetic domains can be found in real world are electrical, mechanical (translational or rotational) and hydraulical, see Fig.1c. Each energetic domain is characterized by two variables: an across variables ve, defines among two points (i.e. voltage, velocity,etc.), and a through variables defines in each point of the space (i.e. current, force, etc.). Each physical elements interacts with the external world through the power sections associated with its terminals. A physical element is connected in series when its terminal share the same through-variable v_f, see Fig.2 while in parallel when its terminal share the same across-variable v_e, see Fig.2.



a) Element in series. b) Element in parallel.

Figure 2 POG representation of physical elements: a) connected in series; b) connected in parallel

Another important property of the POG technique is the direct correspondence between the POG schemes and the state space dynamic equations. For example, the POG schemes shown in Fig.3 can be represented by the state space equations (1)



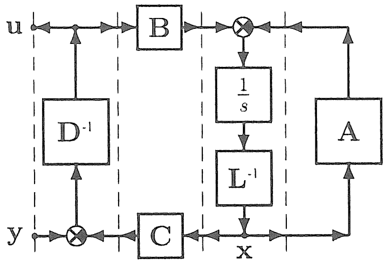
$$\begin{cases} \mathbf{L}\dot{\mathbf{x}} = -\mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \\ \mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u} \end{cases} \quad (1)$$

$$\Downarrow (\mathbf{x} = \mathbf{T}\mathbf{z})$$

$$\begin{cases} \overline{\mathbf{L}}\dot{\mathbf{z}} = -\overline{\mathbf{A}}\mathbf{z} + \overline{\mathbf{B}}\mathbf{u} \\ \mathbf{y} = \overline{\mathbf{C}}\mathbf{z} + \overline{\mathbf{D}}\mathbf{u} \end{cases} \quad (2)$$

Figure 3 POG scheme of a generic dynamic system

where the *energy matrix* **L** is symmetric and positive definite: $\mathbf{L} = \mathbf{L}^T > \mathbf{0}$. It can be easily shown that when **D** = 0 imply that $\mathbf{C} = \mathbf{B}^T$. When an eigenvalue of **L**-matrix tends to zero (or infinity), system (1) degenerates towards a lower dimension dynamic system, see (2). In this case, the dynamic model of the "reduced" system, can be obtained directly using a congruent transformation **x=Tz** where (if T is constant) $\mathbf{L}^* = \mathbf{T}^T\mathbf{L}\mathbf{T}$, $\mathbf{A}^* = \mathbf{T}^T\mathbf{A}\mathbf{T}$, $\mathbf{B}^* = \mathbf{T}^T\mathbf{B}\mathbf{T}$, $\mathbf{C}^* = \mathbf{T}^T\mathbf{C}\mathbf{T}$ and $\mathbf{D}^* = \mathbf{D}$. The POG scheme can also be input-output inverted, both graphically and mathematically as shown in Fig.4 where **L = L**, $\mathbf{A}° = \mathbf{A}+\mathbf{B}\mathbf{D}^{-1}\mathbf{C}$, $\mathbf{B}° = \mathbf{B}\mathbf{D}^{-1}$, $\mathbf{C}° = -\mathbf{D}^{-1}\mathbf{C}$ and $\mathbf{D}^{°} = \mathbf{D}$.



$$\begin{cases} \tilde{\mathbf{L}}\dot{\mathbf{x}} = -\tilde{\mathbf{A}}\mathbf{x} + \tilde{\mathbf{B}}\mathbf{y} \\ \mathbf{u} = \tilde{\mathbf{C}}\mathbf{x} + \tilde{\mathbf{D}}\mathbf{y} \end{cases} \quad (3)$$

where

$$\tilde{\mathbf{L}} = \mathbf{L}, \quad \tilde{\mathbf{B}} = \mathbf{B}\mathbf{D}^{-1},$$

$$\tilde{\mathbf{A}} = \mathbf{A} + \mathbf{B}\mathbf{D}^{-1}\mathbf{C},$$

$$\tilde{\mathbf{C}} = -\mathbf{D}^{-1}\mathbf{C}, \quad \tilde{\mathbf{D}} = \mathbf{D}^{-1}.$$

Figure 4 POG block scheme of the input-output inverted system

DESCRIPTION OF THE ANALYTICAL MODEL

The main purpose of the system, see Fig.5, is to shift rapidly the controlled cam position toward the desired: usually this is implemented by closed loop position control. The system is composed by a variable cam phaser, oil control valve, solenoid and its driver, crank and cam position encoder, and phase controller.

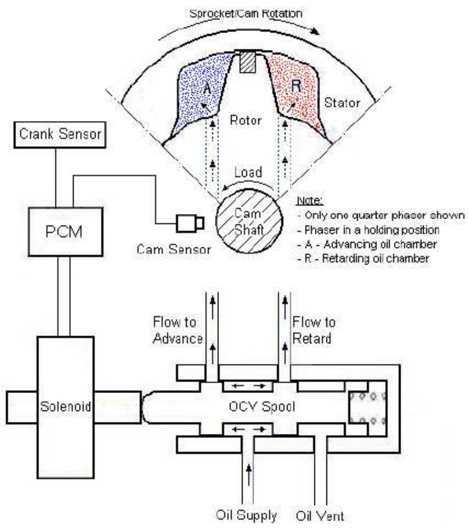


Figure 5 Scheme of Variable Valve Timing system

The oil control valve, see Fig.6, used is a four-way and two-position spool valve that directs the engine oil flow toward the front or rear rotor chambers. The valve is composed by an electromagnetic solenoid (in grey), actuated by Engine Control Unit by a PWM signal, a spool mass (in orange), bounded to slide within the seat, a plunger mass (in pink), a spring (at the end of the plunger body), holds the spool in rest position, and plunger body.

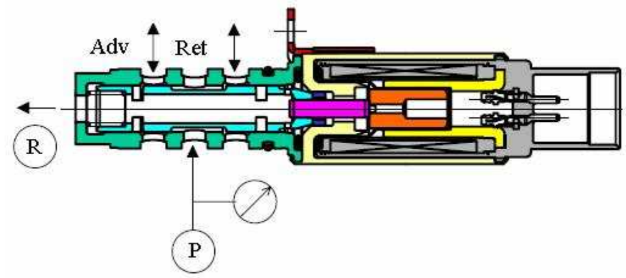


Figure 6 Scheme of Oil Control Valve system

When the solenoid is energized the axial-force, generated by magnetic field (were neglected the force effects due to the different direction) on the spool mass, pushes against the spring allowing the plunger movement. Varying the duty cycle of the PWM signal it can be changed the mean energy value supplied to the system so the mean axial-force value applied to the spool disclosing the orifice area, build on the body mass, and the oil pressurized can reached the chambers depending on where the advanced or retard position direction. (see Fig.6). When the duty cycle value to the valve is zero (de-energized) the spool position, thus the plunger, is located to connect that chambers, rear, to which the rotor is blocked so no cam shaft angle is possible (pin locked position). As the duty cycle increases the spool valve moves forward, toward the unlocked pin position, cutting off the pressure in the rear chamber and supplying to the front. As 0.5 of duty cycle is reached the valve is in the rest position so that engine oil can't flow in both chamber and the rotor should be stopped. However due to the valve train friction and the rotor leakage, the latter can't stay in position rest so it will move, furthermore this holding spool valve position correspond to the very small mechanical region such that the duty cycle can vary: just the modeling can be capable of handling the uncertainty in the hold position parameter. In the Fig. it showed the POG scheme of the Oil Control Valve.

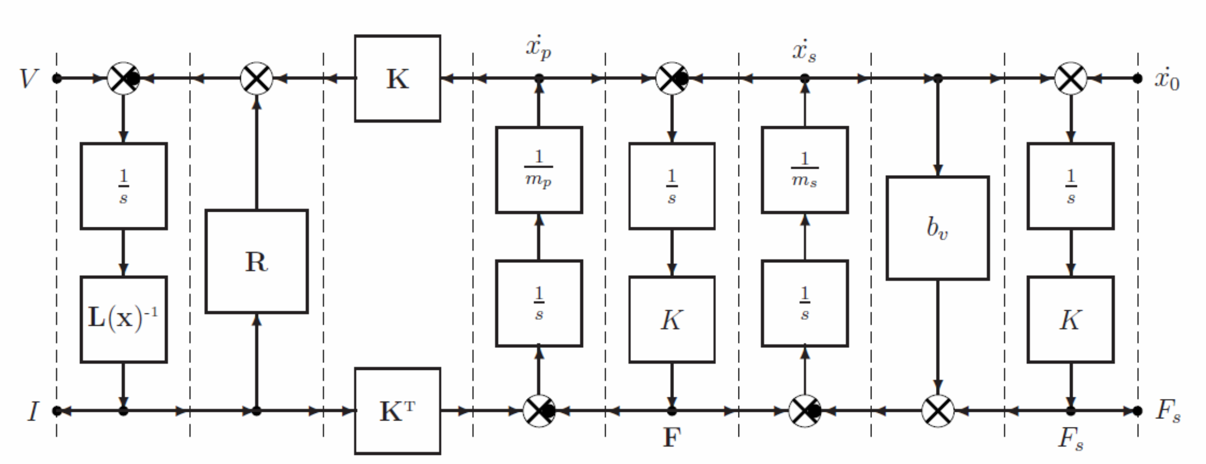


Figure 7 POG scheme of Oil Control Valve system

The cam phase, used for modeling, is a rotary hydraulic actuator with multiple chambers separated by vanes; the rotor is rigidly connected to the cam shaft while the stator to the cam pulley that is, in turn, attached to the crank shaft. The system has two degree of freedom, the stator, ϑ_s, and the rotor, ϑ_r, positions, and it's subject by a resistance torque, M_{res} due to the valve train, the motion torque M_m on the stator and the spring torque M_{pre} . By supplying pressurized oil into the chambers, the rotor moves (due to the torque generates by the oil pressure acting on the volume contained between two diameters d_e and d_i) in advanced or retard position respect the stator so that the phase displacement is produced. The rotor is equipped by a pin allows the rotor locking when no cam shift angle is required. According to the [1] no formulas was showed.

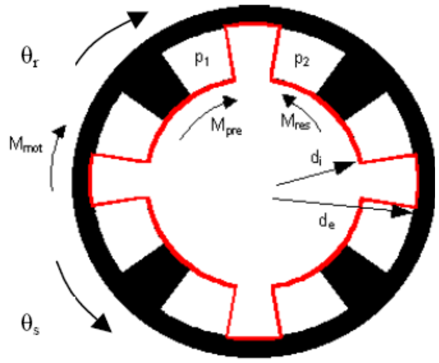


Figure 8 VVT dynamic system: forces acting on the system and state variable

MODEL VALIDATION AND EXPERIMENTAL TEST

The model was validated by data post processing it required the need signals acquisition, in particular: the cam position sensor, the crankshaft sensor and the PWM signal control voltage, respectively signal output and inputs. Furthermore was acquired the oil temperature to consider the temperature influence on the cam phase whose effects didn't investigate in this work. For the acquisition Labview Signal Express tool, by National Instruments (see Fig.10), was used: thanks to it was possible carrying out several tests time costless and recorded the data rapidly.

At the meantime the resistance torque of the camshaft, M_{res} ,was acquired using an experimental motoring test-rig as described in Reference [3]; in particular it was focused the attention in sensitivity variation by speed, temperature and oil viscosity.

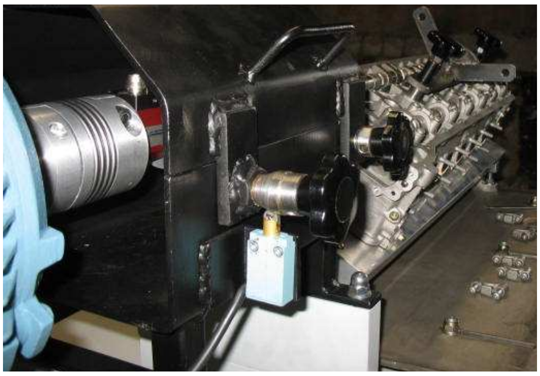


Figure 9 Test rig photo

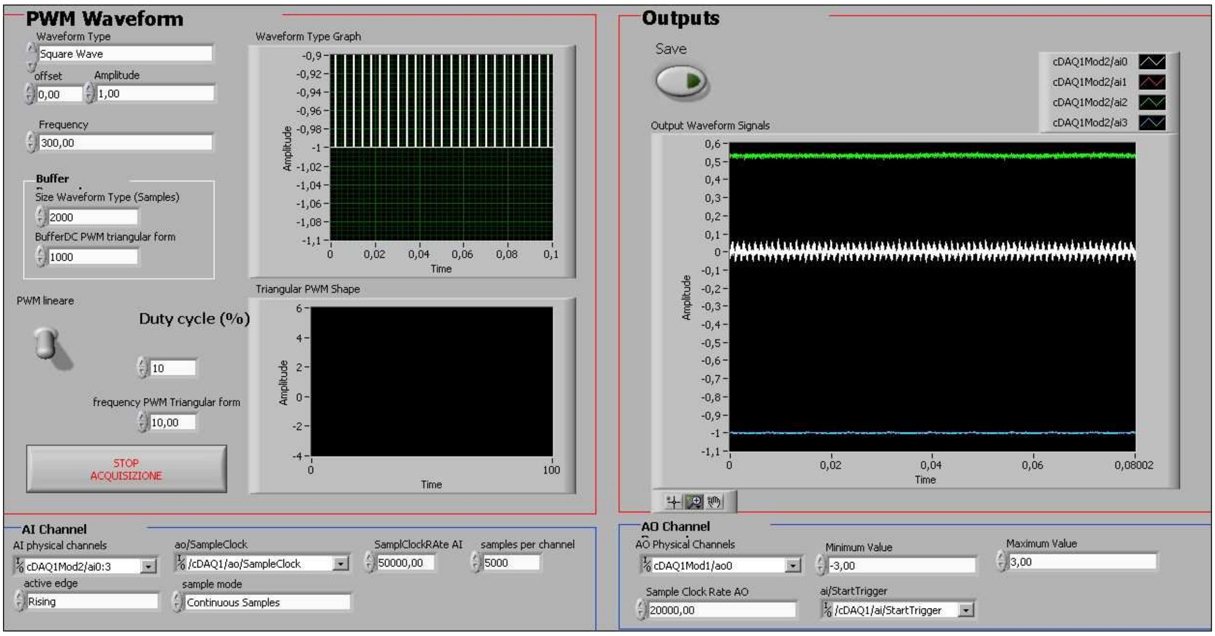


Figure 10 LabView control panel for signals OCV acquisition (no signals are showed)

Before using the processing data for model validation, the signals acquired were elaborated with Matlab script, in particular was rebuild the engine timing signals to calculate the engine revolution, one of the input signals, and the cam phases, intake and exhaust, one of the output signals (see Fig.11)

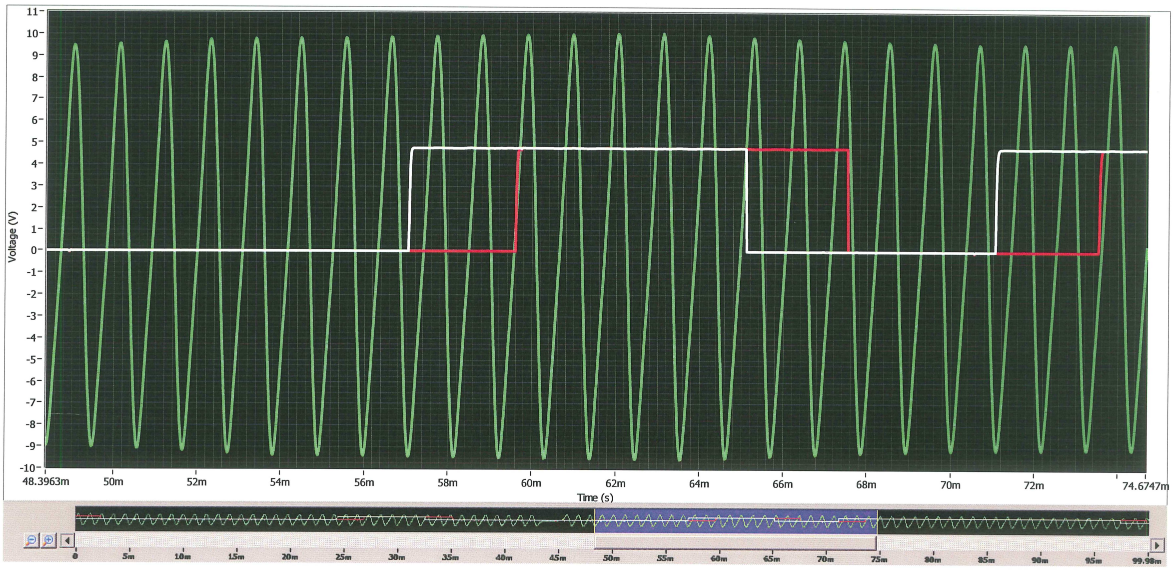


Figure 11 Voltage engine time signals: a) green, crankshaft signal, b) white, intake cam phase; c) red, exhaust cam pahse

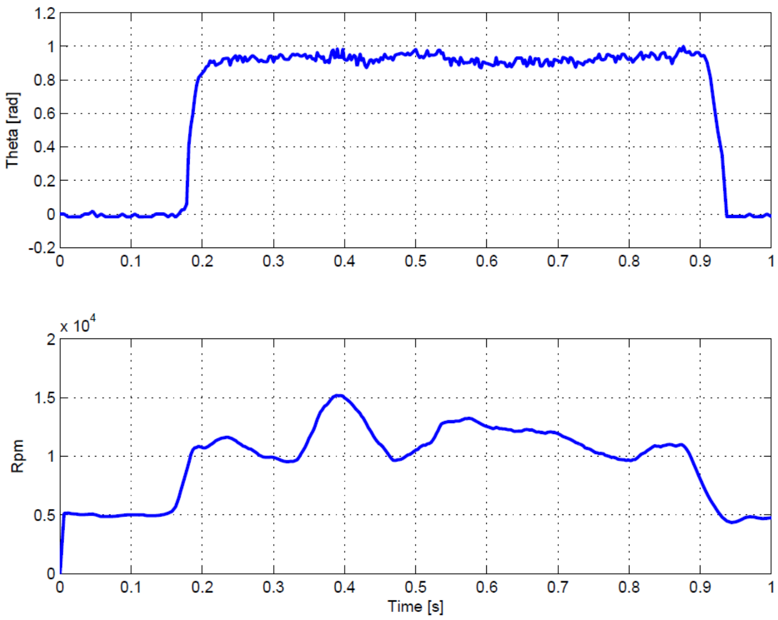


Figure 9 Elaborating signal: rpm and intake valve phase

As shown in the figure can be appreciate the good results between simulation and actual physical system which confirms the energetic approach modeling is very useful facing complex problems above all when you have to collide with the production ECU less performance than the micro controller used for example for Hardware-In-The-Loop or Rapid Prototyping. It's nice observe that when the VVT is not working the chambers have a delta pressure, due to the fact that the oil pressurized initially fills only a retard chamber, so being hydraulic power available it's possible to move the rotor consequently modifies the cam phaser. When the duty cycle is applied, this hydraulic power is exchanged between the chambers, filling the other one (advanced). At this time, when the desired cam phasing is reached, both chambers present the same pressure so no delta pressure is available to modify the cam phase angle: the controls works in this phase to guarantee the working point.

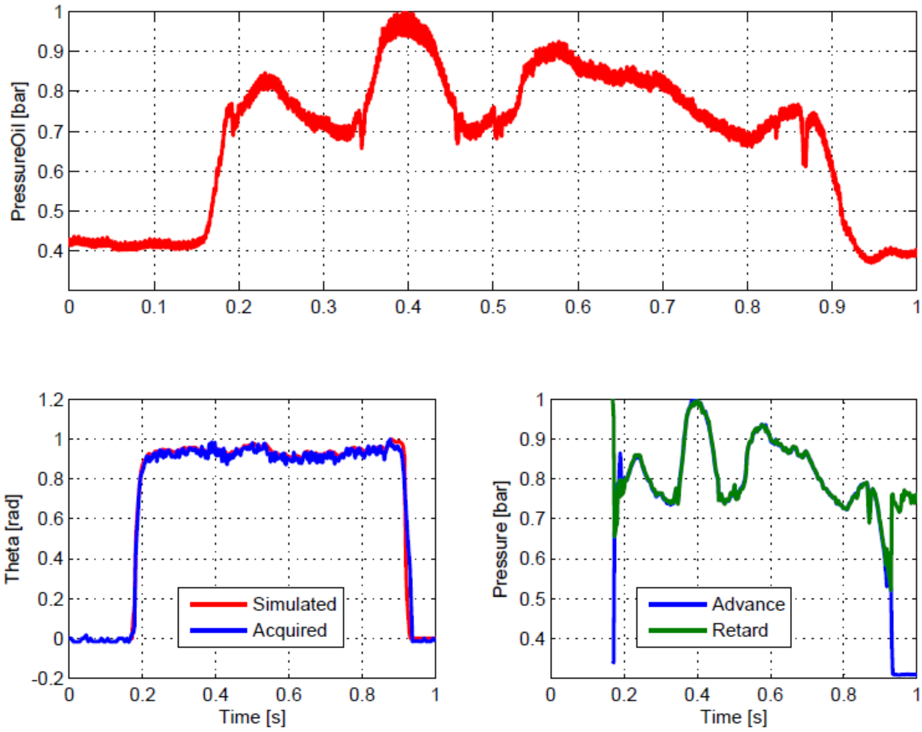


Figure 10 Data comparisons

CONCLUSIONS

This paper summarize the analytical approach used by Lamborghini to assess the dynamic of variable valve train system, it is a robust way to do optimization, sensitivity analysis and different layout studies.

To obtain reasonable predictions at concept design phase for a complex VVT does require experience to choose the right modelling level, in this casa it was used all the expertise coming from Lamborghini engine Know-how, and to estimate sensible values for stiffness and damping at many locations.

The results shown in this paper demonstrate the reasonable level of correlation that can be achieved on a complex VVT system. The model correlation is good enough to be useful for component optimization and engine upgrade assessment.

The use of a simplified dynamic model based on Power-Oriented Graph is a efficient way to make calculations in order to support the decision process during concept design. It is used as an efficient way to understand and optimize the system with a deep knowledge of single detail and as an important way to take layout decision in a very short time

REFERENCES

1. M. Astarita, A. Caraceni, V. Cioffi, A. Riegel, E. Sepe, A. Vetrano and Peter Siebke "*EngineVirtual Testing and Design of Experiment for Functional Validation of Cam PhaserControl*" SAE Paper 2004-01-0785.

2. J. Pohl, M. Sethson, P. Krus, J. Palmberg "*Modeling and simulation of Fast 2/2 Switching Valve"* Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering; Volume 216, Number 2 / 2002.
3. M. Calabretta, D. Cacciatore, P. Carden. " *Valvetrain Friction - Modeling, Analysis and Measurement of a High Performance Engine Valvetrain System* ", SAE Paper 2010-01-1492, 2010.
4. L. Zheng. " *Characterization of Engine Variable Cam Phaser Fluid Dynamics and Phaser's ability to reject Disturbances*", SAE Paper 2004-01-1389.
5. J. Pfeiffer, M. Kulpa, K. Simpson, D. Reed and J. Yoo *"A verification study for Cam Phaser position Control using Robust Engineering Techniques"*, SAE Paper 2001-01-0777

CONTACT INFORMATION

Christian Corvino
Automobili Lamborghini S.p.A.
Via Modena, 12
I-40019 Sant'Agata Bolognese
Italy
Tel. +39 051 795 70 67
e-mail: cristian.corvino@lamborghini.com

ACKNOWLEDGMENTS

The authors would like to thank Automobili Lamborghini S.p.A. for allowing this information to be published.