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Implementation of Model-Based Calibration for a Gasoline Engine

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ABSTRACT

To meet the ever increasing requirements in the areas of performance, fuel economy and emission, more and more subsystems and control functions are being added to modern engines. This leads to a quick increase in the number of control parameters and consequently dramatic time and cost increase for engine calibration. To deal with this problem, the automotive industry has turned to model-based calibration for a solution. Model-based calibration is a method that uses modern Design of Experiments (DoE), statistical modeling and optimization techniques to efficiently produce high quality calibrations for engines. There are two major enablers for carrying out this method - fully automated engine control and measurement system, and advanced mathematical tools for DoE, modeling and optimization. This paper presents a case study of adopting this methodology for the determination of optimum steady state calibrations of ignition timing, air-fuel ratio and intake cam phasing for a gasoline engine. ORION automated engine control and measurement system is used for testing data collection. EasyDoE Toolsuite is used for DoE, engine response modeling and control parameter optimization. Major features of these tools are described. Each step in performing this process, including definition of factors and responses, DoE, automatic measurement on engine test bench, creation of engine models of sufficient accuracy, and generation of control maps using optimization techniques, is covered. The results demonstrate that the model-based approach is a well suited method for engine calibration, and the integrated system provides an effective solution for implementing model-based calibration.

INTRODUCTION

In order to improve fuel economy and lower exhaust emissions, modern internal combustion engines have been equipped with many new subsystems. More and more control features are being integrated in the engine Electronic Control Unit (ECU). When the number of control parameters is relatively low, the full factorial mapping method may be a viable solution for some engine calibration tasks. However, as new degrees of freedom are introduced, the experimental burden for the full factorial mapping method will increase exponentially which makes the method impractical. Dealing with this problem, the automotive industry has adopted the model-based calibration methodology in the recent years which has been proven very successful in dramatically shorten the time needed for various calibration tasks [1, 2, 3, 4, 5, 6, 7, 8].

In model-based calibration a design of experiments (DoE) is first performed to generate a matrix of engine test factors. Then engine test and measurement are carried out at these points. The number of engine test points should be minimal but still sufficient for obtaining data to create a statistical model that provides enough fidelity in describing the engine responses to variations in the factors. This statistical model is then used for the determination of optimum control parameters of the engine.

One key element in performing model-based calibration is a fully automated engine control and measurement system, including engine ECU and calibration tool, dynamometer control, measurement devices, and various test cell equipments that need be coordinated. In this paper A&D's ORION automated engine control and measurement system is used. On one hand, ORION communicates with engine ECU, which in this study is a rapid prototyping controller, for engine control parameter adjustment; on the other hand, it communicates with engine test cell control system for dynamometer control and engine performance measurement. ORION will perform the experiments designed from the DoE tool, and runs the sequences to command both the test cell control system and the ECU accordingly to collect the engine performance data for building the statistical model.

Another key element in model-based calibration is the tool for DoE, statistical modeling and control parameter optimization. In this study, IAV's EasyDoE Toolsuite is used. EasyDoE Toolsuite enables users to generate the experiment design and to perform data analysis, modeling, optimization, and map generation. First test points are created by EasyDoE Toolsuite, which is subsequently imported into ORION for execution. After ORION finishes the test sequences the test results are sent back into EasyDoE Toolsuite for engine modeling and optimum control map creation.

The engine used in this study is a 2.0L in-line 4 cylinder gasoline engine with intake cam phasing, i.e., variable valve timing (VVT). Engine equipped with cam phasing provides more flexibility for the designers to strive for high volumetric efficiency under various engine operation conditions, enabling increased engine torque output with simultaneous reductions in exhaust emission and fuel consumption. In this study, the optimization objective is to find the optimal combination of the major engine control parameters, i.e., to define the optimal settings for spark advance, air-fuel ratio and intake VVT across the interested operating region (speed and load), to minimize brake-specific fuel consumption (BSFC) and meanwhile keep engine exhaust emissions, engine roughness and exhaust temperature etc. within the constraints. To limit spark inside the knocking boundary, an optimization constraint of spark advance less than or equal to Maximum Brake Torque (MBT) spark is used as well.

The next sections will cover in more details the setup of the system, the design and execution of the tests, and the creation of modeling and calibrations.

SYSTEM SETUP

Figure 1 shows the overall setup of the automated calibration system. On the top of the system is ORION, which provides the capability of designing and performing customized test cell data gathering processes. On one hand, ORION accesses the A&D iTest Data Acquisition and Control (DAC) system through ASAP3, thus controls the operation of the dynamometer as well as various test cell equipments, such as combustion analysis system and emission bench etc; On the other hand, ORION communicates with the ADX Rapid Prototyping Controller which realizes the engine control functionalities. The ADX controller includes all the typical algorithms needed to run the engine and all the functions can be calibrated via ASAP3. By coordinating all the devices involved, ORION maintains control of the test cell and the engine controller to collect the data from all sources for use in the modeling process.

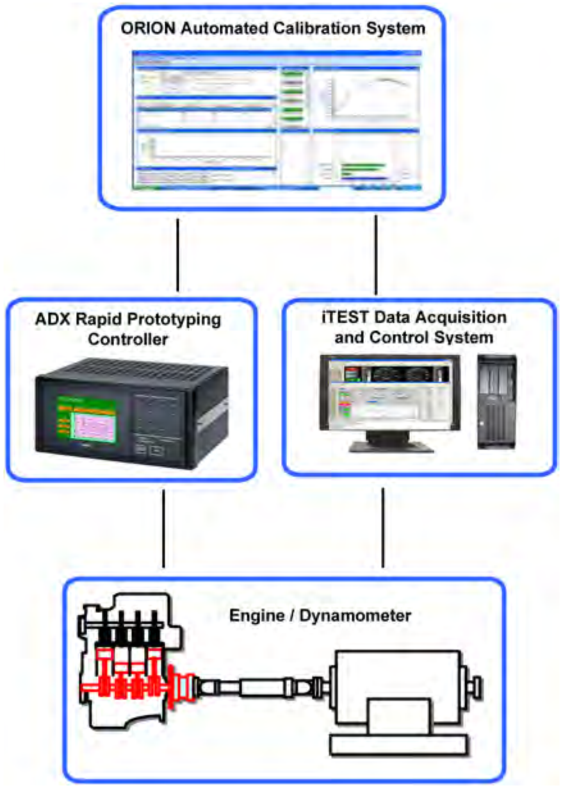


Figure 1. Automated Calibration System Setup

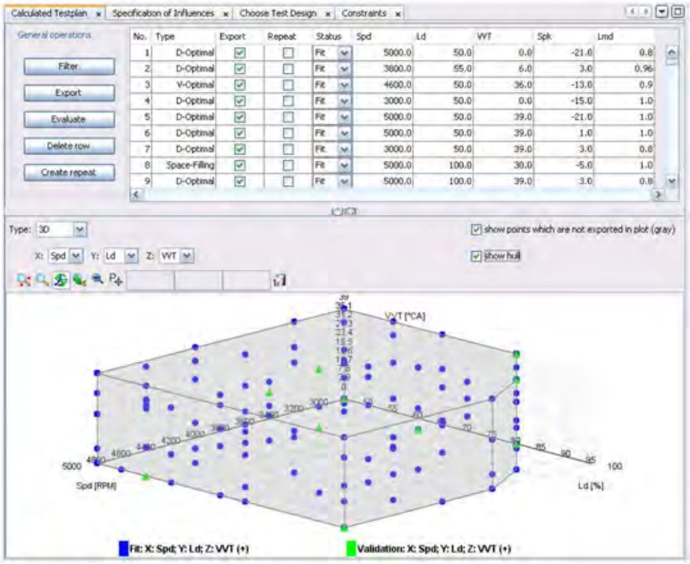
DESIGN OF EXPERIMENT

In this study the interested operating region of the engine is the medium to high speed (3000 to 5000 rpm) and medium to high load (50% to 100%) range. The optimization objective is to find the optimum spark advance, air-fuel ratio and intake VVT that minimizes BSFC. The engine test factors are engine speed, relative load, spark advance offset, air-fuel ratio, and intake VVT. The engine responses are torque, mass fuel flow, exhaust temperature, MBT spark, emissions HC/CO/NOx, and COV of Indicated Mean Effective Pressure (IMEP). Other than using the absolute values for spark timing, in this study the spark advance offset is used as a test factor. It refers to the offset from the MBT spark at each operating point, while the MBT spark is obtained during the data gathering process using an online optimization function of ORION.

Good judgment for the space of likely optimum control values is always critical for effective implementation of model-based calibration. After all the factors and responses are identified, ranges of the test factors need be first determined. Then experiment constraints of the factors and responses are specified based on experience and preliminary tests. For example, at certain engine speeds that are relatively low, higher values of relative load cannot be reached. Experiment constraints are expressed using either equations or 2D tables.

Next the model structure need be specified, which will affect the minimum number of measurement necessary for building the engine statistical model. While some responses can be modeled very well using low order polynomials, responses like emissions etc. need higher order polynomials for modeling, which determines the number of test points needed. In this study, the model structure is selected to be 4th order polynomials with 3rd order interactions, which results in a polynomial of 61 terms. Based on experience, this structure can efficiently model engine responses with high fidelity. To avoid over-fitting, for each response, various methods are used and compared during model fitting and some of the 61 terms will be removed.

After the range, constraints, and model structure information is entered into EasyDoE Toolsuite, the set of target points to be measured are created based on the design method selected. D-optimality minimizes the generalized variance of the parameter estimates. V-optimality minimizes the variance of the predicted response. In this study, first sufficient number of D-optimal points are specified, then V-optimal points and space-filling points are added to arrive at the final number of experiment points. Altogether 269 experiment points are generated. As an example, Figure 2 shows the DoE result for intake VVT with respect to engine rpm and relative load. The results of DoE are exported to a file which will be read into ORION test plan for execution.



No.	Type	Export	Repeat	Status	Spd	Ld	VVT	Spk	Lmd
1	D-Optimal	☑	☐	Fit	5000.0	50.0	0.0	-21.0	0.8
2	D-Optimal	☑	☐	Fit	3800.0	55.0	6.0	3.0	0.96
3	V-Optimal	☑	☐	Fit	4600.0	50.0	36.0	-13.0	0.9
4	D-Optimal	☑	☐	Fit	3000.0	50.0	0.0	-15.0	1.0
5	D-Optimal	☑	☐	Fit	5000.0	50.0	39.0	-21.0	1.0
6	D-Optimal	☑	☐	Fit	5000.0	50.0	39.0	1.0	1.0
7	D-Optimal	☑	☐	Fit	3000.0	50.0	39.0	3.0	0.8
8	Space-Filling	☑	☐	Fit	5000.0	100.0	30.0	-5.0	1.0
9	D-Optimal	☑	☐	Fit	5000.0	100.0	39.0	3.0	0.8

Type: 3D

X: Spd Y: Ld Z: VVT

☑ show points which are not exported in plot (gray)

☑ show hull

Figure 2. Intake VVT Experiment Points

EXECUTION OF TEST PLAN

ORION automated control and measurement system imports the DoE results and performs the engine tests accordingly. ORION facilitates the engine calibration process by taking control of both the ECU calibration tool and the test cell system to run experiments as part of an automated calibration process. ORION is composed of two applications: the Measurement Definition Application (MDA) and the Measurement Application (MA). The MDA provides a set of standard actions to create the sequences used to direct test cell systems to perform test and measurement tasks. The sequence is then run on the MA real-time system in a test cell, commanding the test cell system and calibration tool according to the actions specified in the sequence. During the process, the MA directs the calibration tool and the cell data acquisition system to collect data to characterize the engine. After the test completes, the data that has been logged by the test cell system can be used in the subsequent modeling and optimization process.

For this study, the test cell is configured to run in speed/ relative load mode. A typical steady-state test sequence is used and a set of actions are executed in a specific order to accomplish the experiment. For this study, a brief description of the test sequence is as follows:

1. Set speed, load, VVT and air-fuel ratio according to the test plan.

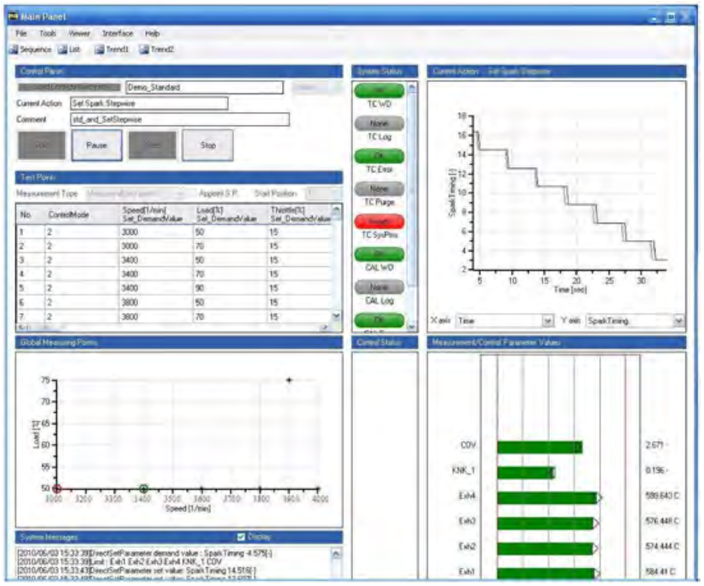
2. Find MBT spark using the online optimization function.

3. Take measurement and recording of all data items to be used in the model, including data from test cell, ECU, combustion analysis system, and emission bench etc.

4. Perform test for each spark offset value defined in the test plan. Take measurements and recording of all data items.

5. Repeat for all test points in the test plan.

During the execution of the experiments, a lot of details need be considered, such as storing original values for future reset, maintaining the emission bench, stabilizing the system for sufficiently long before triggering the measurement, handling of persistent error, and repeatability check etc. ORION provides the capability and flexibility for taking care of all these details. When the test is executed, the progress of the test and the status of the system will be displayed on MA windows. Figure 3 shows a MA window while executing the test. After the whole test plan is finished, the test results are read by the EasyDoE Toolsuite for engine modeling and parameter optimization.



Demo_Standard

Current Action: Set Spark Stepwise

Comment: std_and_SetStepwise

No.	ControlMode	Speed[1/min] Set_DemandValue	Load[%] Set_DemandValue	Throttle[%] Set_DemandValue
1	2	3000	50	15
2	2	3000	70	15
3	2	3400	50	15
4	2	3400	70	15
5	2	3400	90	15
6	2	3800	50	15
7	2	3800	70	15

```
[2010/06/03 15:33:39]DirectSetParameter demand value : SparkTiming 4.575[-]
[2010/06/03 15:33:39]Limit : Exh1 Exh2 Exh3 Exh4 KNK_1 COV
[2010/06/03 15:33:43]DirectSetParameter set value: SparkTiming 14.516[-]
```

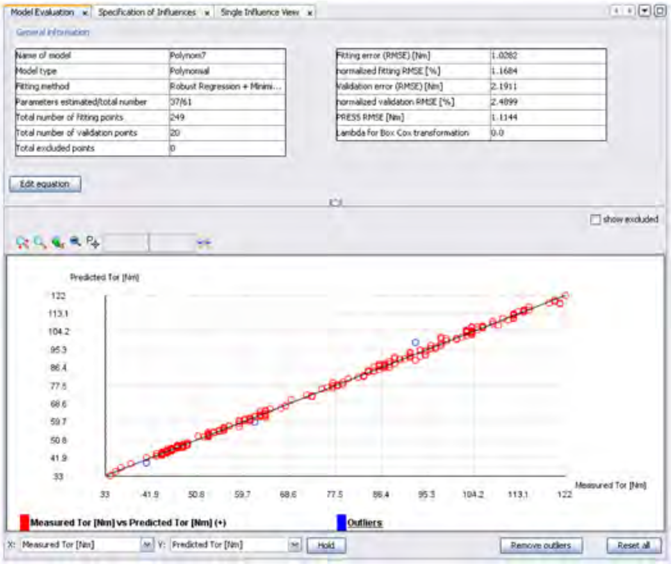
Figure 3. MA Window while Executing the Test

MODELING, OPTIMIZATION AND MAP CREATION

The measurement data taken from the test cell is imported into the EasyDoE Toolsuite for engine modeling. As mentioned before, the model form is specified as 4th order polynomial with 3rd order interactions. For each response, multiple fitting methods are used and the quality of each model fitting is evaluated. After the statistical characteristics of each candidate model are studied, a best fit model is selected which will be used for the subsequent parameter optimization and map creation. As an example, Table 1 summarizes the torque modeling performance of 9 different fitting methods. Number of terms of the polynomial and Root Mean Square Error (RMSE) of the fitting data are listed for each method. In this study, Polynomial 7 which gives the smallest root mean square error (RMSE) for the fitting data is chosen. The number of terms in this polynomial is reduced from 61 to 37. Figure 4 further shows the more detailed performance of this selection. Data for 249 test points is used for calculating the model, while another 20 points are used for validating the model. The measured torque and model calculated torque are compared against each other. The validation points show that the model gives good performance and the normalized validation RMSE is less than 2.5%.

Table 1. Torque Modeling Performance of Different Fitting Methods

Polynomial	Fitting Method	Number of Terms	RMSE (Nm)
1	Standard Regression	61	2.37
2	Minimize PRESS	32	2.39
3	Stepwise Fit	33	2.49
4	Orthogonal Least Squares Estimation	35	2.42
5	T-test	27	2.34
6	Robust Regression	61	2.37
7	Robust Regression + Minimize PRESS	37	1.03
8	Robust Regression + Stepwise Fit	33	2.49
9	Stepwise Regression	38	1.94



Name of model	Polynom7
Model type	Polynomial
Fitting method	Robust Regression + Minimi...
Parameters estimated/total number	37/61
Total number of fitting points	249
Total number of validation points	20
Total excluded points	0

Fitting error (RMSE) [Nm]	1.0282
normalized fitting RMSE [%]	1.1684
Validation error (RMSE) [Nm]	2.1911
normalized validation RMSE [%]	2.4899
PRESS RMSE [Nm]	1.1144
Lambda for Box Cox transformation	0.0

Figure 4. Evaluation of Torque Modeling

After the models for all the responses are determined, the EasyDoE Toolsuite can perform the optimization of the test factors based on the optimization criterion. For this study, the criterion is set to minimize BSFC and meanwhile keep engine exhaust emissions, engine roughness, which is indicated by COV of IMEP, and exhaust temperature within the constraints. Another constraint is that the spark advance should be less than or equal to the MBT spark. Figure 5 shows the BSFC contour map calculated by EasyDoE Toolsuite. By carrying out the optimization algorithms, EasyDoE Toolsuite generates maps for all the test factors of spark, air-fuel ration, and intake VVT using the models. As an example, Figure 6 shows the optimized VVT map. After the optimized maps are obtained, some verification tests need be performed to check the optimization results. Typically a grid of speed and load points is run with the obtained optimized control maps and the engine performance is studied.

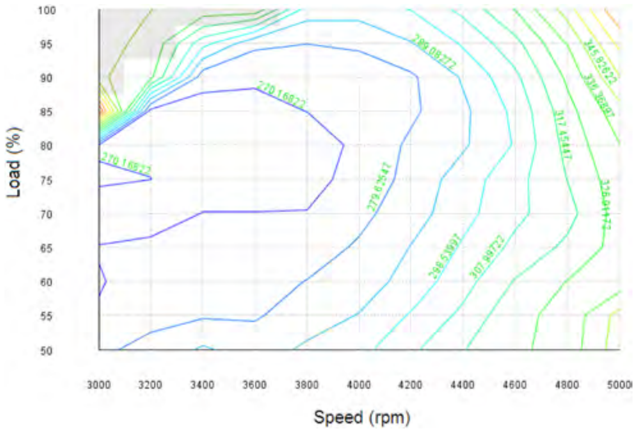
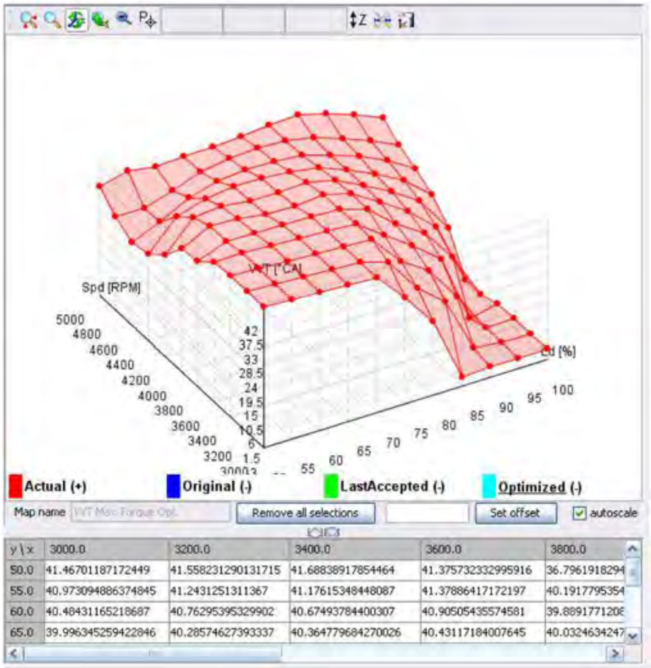


Figure 5. BSFC Contour Map



Map name VVT Map Torque Opt.

y \ x	3000.0	3200.0	3400.0	3600.0	3800.0
50.0	41.46701187172449	41.558231290131715	41.68838917854464	41.375732332995916	36.7961918294
55.0	40.973094886374845	41.2431251311367	41.17615348448087	41.37886417172197	40.1917795354
60.0	40.48431165218687	40.76295395329902	40.67493784400307	40.90505435574581	39.889177120
65.0	39.996345259422846	40.28574627393337	40.364779684270026	40.43117184007645	40.0324634247

Figure 6. Optimized VVT Map

SUMMARY

A model-based calibration of spark, air-fuel ratio and intake variable valve timing is carried out for a gasoline engine using ORION and EasyDoE ToolSuite. The application indicates that ORION automated engine control and measurement system and EasyDoE ToolSuite provide effective methods for implementing model-based calibration.

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