Institution: University of Derby

Unit of Assessment: UoA15 – General Engineering

Title of case study: Engine Test Bed Experimental Data Modelling and Optimisation

1. Summary of the impact (indicative maximum 100 words)

This research project, carried out at the University of Derby, was used to develop an engine performance monitoring system and a data optimisation method for engine management systems for Land Rover. The project delivered two pieces of software developed for data modelling and optimisation with respect to the engine test bed. This has significantly reduced the engine test time on the test bed by up to 30%, reduced the cost of each engine test and provided optimum engine operation parameters to the Engine Control Unit (ECU), which has resulted in lower emissions and improved fuel economy. The project was started in 2000 and completed in 2008. However the outcomes of the research and developed software tools are still used by the Land Rover engine test group.

2. Underpinning research (indicative maximum 500 words)

In view of Euro III and IV legislation, and the increasing customer demands for higher performance from lower cost engines, many new internal combustion engines currently under development are adopting a number of innovative technologies including Variable Valve Timing (VVT), Exhaust Gas Re-circulation (EGR) and Gasoline Direct Injection (GDI) technologies. The development of such new generation internal combustion engines is constrained by increasingly stringent requirements for better fuel consumption, lower exhaust emissions, including the avoidance of misfires and guaranteed stability. To meet these demands engines must deliver a stable combustion process at all operating conditions, thus requiring the use of sophisticated electronic Engine Management Systems (EMS) to control more variables than had hitherto been the case. The test tasks undertaken on the engine on the Engine Test Bed (ETB) are time consuming. In order to obtain the optimum data used to install the EMS, thousands of variables needs to be tested; this may take many weeks or months to complete. The more input variables are considered, the longer test period is required. Nevertheless, car manufacturers are developing their new engine with more and more control parameters to make the new engine more efficient, more economical and with fewer emissions. Conversely, they want to test their new engine with a test period as short as possible to reduce the new engine development lead time and put new models of the car into the market as soon as possible. The purpose of the research undertaken was to produce a solution to this problem.

The research work was to investigate the Generic Knowledge Base System (GKBS), which integrates the functions of control, monitoring, data analysis and decision-making together to support combustion testing of new engines on the ETB. To this end, the objectives of the research were:

(i) To create a suitable model and methodology that can be employed for the engine parameter optimization.
(ii) To adapt the developed results to analyse test combustion data automatically.
(iii) To reduce the engine combustion test times on the Engine Test Beds (ETB).
(iv) To be able to meet the demands of future more stringent legislation of engine emissions that will cause the variables to be optimised to increase from two to six.

The research project had three stages of original research findings and outputs.

Stage one: Maths model (constant + linear function + exponential function [CLE]) based modelling system (year 2000-2003)

In this stage, a new CLE maths model has been developed underpinned by a Genetic Algorithm (GA) application. The model is used to describe the parameter relationships between the engine combustion parameters and engine output showing improved results. Meanwhile, a commercial GA based software system (programmed in Visual Basic) was developed for Land Rover to use.

Stage two: Investigate a Neural Network model for data modelling of the engine's performance and outputs (year 2003-2005)

In order to improve efficiency and reduce expenditure of time in engine testing, it is very important for engine test bed controllers to develop a mathematical model from existing engine test data. This stage of the research was in the investigation of a neural network GA combined tool for engine modelling. In the modelling tool, a real-coded GA has been employed to train three different groups of neural networks (NNs); a multilayer perceptron group, a radial basis function group, and a bar function networks group, then finally finding the most suitable NN model for engine modelling. The work produced a unified approach for training different NNs for engine modelling with the derivative of the specific activation function not being required, making it possible to train different NN models without concentrating on the specific activation functions involved in the NN structure. The experimental results were realised with a Visual Basic application, with the developed tool having been successfully used for Land Rover engine testing.

Stage three: Investigate the parameter optimisation methods for Engine operation (year 2005-2008).
In this stage, a Matlab based software solution was developed that can deal both with multiple inputs and one output optimisation task, as well as with multiple inputs and multiple outputs optimisation task, for Land Rover's engine test analysis. Examples are based on minimising the brake specific fuel consumption and maximizing the output power torque simultaneously. It's based on NN modelling and a real number GA model to work on both modelling and optimisation in the parameters which could then be fed back into the ETB in order to shorten testing time.

3. References to the research (indicative maximum of six references)

Journal References

Wu, M., Lin, W. and Duan, S. 2008. Investigation of a multi-objective optimization tool for engine calibration. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 222 (2), pp. 235--249. (Best Quality 1 of 3)

Wu, M., Lin, W. and Duan, S. 2006. Developing a neural network and real genetic algorithm combined tool for an engine test bed. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 220 (12), pp. 1737--1753. (Best Quality 2 of 3)

Lin, W., Wu, M. and Duan, S. 2003. Engine test data modelling by evolutionary radial basis function networks. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 217 (6), pp. 489--497. (Best Quality 3 of 3)

Conference Proceedings

Wu, M., Lin, W., Duan, S. 2012 Experimented engine test data modelling method *ICMIC2012*, 24-26 June, Wuhan, P R China.

Wu, M., Lin, W., Duan, S. 2011 Developing a Software Tool for Engine Tested Data Modelling, *ICMIC2011*, 26-29 June, Shanghai, P R China

4. Details of the impact (indicative maximum 750 words)

The impact of the research carried out at Derby based around engine test bed and engine control unit optimisation is related directly to both the project itself and the outcomes of the research papers disseminated through journals and conference reports. Land Rover sponsored the work as legislation for the next generation of petrol engine has put tighter requirement on engine performance, e.g. fuel consumption, exhaust emissions with avoidance of misfiring and instability. In order to meet these requirements, the electronic engine management system (EMS) must become increasingly sophisticated. A large number of parameters or variables in the EMS (which controls engine performance) need to be optimised and calibrated with Land Rover's methodology in 2001 being a system based on empirical testing methodologies where each of the input variables are changed with a multi-dimensional grid of points tabulated and observed to find the optimal combination for attributes such as fuel economy, torque and emissions. Once an optimal area of input parameters are observed, more detailed testing can then take place in this reduced search space in order to hone in on the optimal settings. The more input variables and selected section points on each variable involved, the longer the calibration time required. Just a few input variables could lead to weeks worth of tests. For example, three or four weeks is required to

calibrate an engine for two parameters and 100 selected section points with the number of inputs used being greater than this in industry.

The work carried out at Derby had a well defined goal; allowing for much faster calibration testing, but keeping the accuracy and precision of the calibration results. As the number of inputs to the system could not be altered, the number of test points needed to be reduced; this can be achieved if a model of the dataset is created combined with a robust optimisation strategy. The research was fed directly with data from Land Rover with the research work detailing the optimum strategy needed to successfully model the behaviour of the engine test bed using a reduced data set for input, with a unified approach for Neural Network training methodology selection combined with a robust and detailed approach specifying how to deal with practical engine modelling problems such as data pre-processing, data partitioning, model selection and model validation. These are all necessary for the system to be used in the workplace, and maximise usefulness and impact. The realised Neural Network engine model was then used as a test bed and optimised which, through the research undertaken, was found to be optimally satisfied using a multiple objective genetic algorithm. The research worked directly on data from Land Rover and the output of the Neural Network based engine model with inputs of engine speed, load efficiency, ignition timing, variable valve timing, and exhaust gas recirculation rate. The output variables are the Brake specific fuel consumption (BSFC), torque (TQ), and coefficient of variance (COV). The software allows Land Rover to optimise one or multiple output variables whilst simultaneously constraining others, allowing for a more complex relationship between input and output parameters to be tested and fed into the design and testing process. Previous to this work, Land Rover needed to produce engine test data sets which consisted of altering five input parameters resulting in 1100 tests to be undertaken. Each test would take around 10 minutes to setup (including engine warm-up time) which gives a total test time of around 183 hours. The combined Visual Basic and Matlab based system produced by Professor Wu at Derby reduced the number of tests needed to be initially taken to 500 in order to model the engine, followed by a further 200 sets once an optimal area for fuel consumption, for example, has been found. This gives a total testing time of 116 hours, saving Land Rover 67 hours per engine, or over 36%. This demonstrates clear economic impact, in terms of the time saved per engine test due to the increased performance of the engine test bed whilst maintaining the required accuracy and precision of the results, impact on the environment in terms of allowing the development of fuel efficient engines whilst maintaining low exhaust emissions, and impact on improving the professional practices of the test bed team at Land Rover.

The final single and multi-objective version of the software, which was a Visual Basic application combined with a Matlab toolbox, was delivered to Land Rover in 2008 and is still in use as a tool to model the engine test bed off-line using pre-measured data whilst being able to optimise the engine parameters using multiple, competing, objectives. This allows the model's predictions to then be used to direct the actions of the on-line test bed, with the work also being an important part of Land Rover's on-going research.

5. Sources to corroborate the impact (indicative maximum of 10 references)

Publications:

1. Investigation of the Multi-Objectives Optimisation Tool for Engine Calibration on web: http://pid.sagepub.com/content/222/2/235.abstract
2. Developing a neural network and real genetic Algorithm combined tool for an engine test bed on Web: http://pid.sagepub.com/content/220/12/1737.abstract
3. Engine Test Data Modelling by Evolutionary Radial Basis Function Networks on Web: http://pid.sagepub.com/content/217/6/489.abstract
4. Experimented engine test data modelling method on Web: http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=6260177&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D6260177