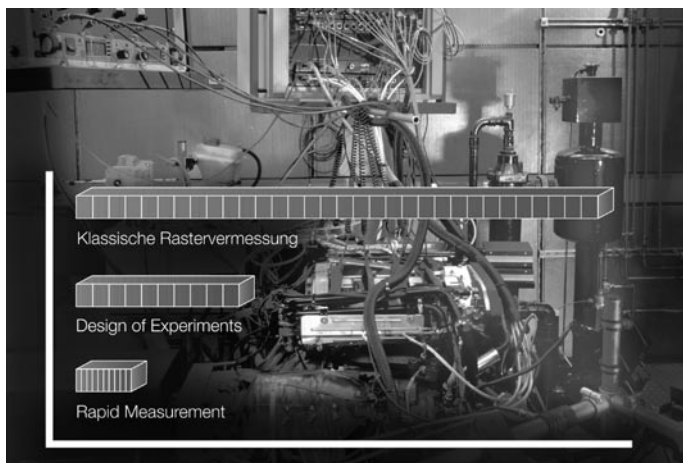Rapid Measurement –
Grundbedatung eines Verbrennungsmotors
innerhalb eines Tages?

Rapid Measurement
Basic Combustion Engine Calibration In One Day?

Fast-tracking the basic calibration of combustion engines is an ambition of many engine developers. Yet, at the same time, there is a trade-off between the speed and accuracy of basic calibration. IAV has developed a method that relaxes this conflict as it quickly produces models of sufficient accuracy to permit basic calibration. This is one way of coming close to the aspiration many engine developers have of completing the measurements for basic combustion engine calibration in just one day.

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1 Introduction

Basic calibration is a major constituent component in calibrating spark-ignition and diesel engines. It provides the starting point for a whole host of stages in the calibration process. This is why basic calibration needs to be done with meticulous care since modifications later on come with far-reaching consequences.

Basic calibration of the control unit is understood to mean determining optimum steady-state maps on the engine test bench with the aim of ensuring safe and reliable engine operation. Optimization criteria encompass emissions, fuel economy and running smoothness on the SI engine side, and combustion noise in the case of diesel engines.

With spark-ignition engines, this involves optimizing the maps for charge sensing, timing and ignition angle and calibrating any torque interface that may exist. In the case of diesel engines, the focus is on air mass, boost pressure, rail pressure and the various injection events.

Many engine developers employ models for the basic calibration process, i.e. just a few measurement data are taken as the basis for training a – mostly statistical – model which is then used for optimizing the basic maps. The DoE (Design of Experiments) method is often employed for this purpose as it can help to slash measurement input.

However, as frequent changes must be expected on the hardware side – particularly in the early stages of developing an engine – maps are often used from a previous construction stage or comparable engine. This can lead to incorrect component assessments since the maps used are not ideal for the data record in hand. For the early phase of development, therefore,

methods must be found that permit high-speed basic calibration. At this point in time, it is admissible to accept minor compromises on the accuracy side. In the late development phase, when it comes to generating production-level data, it is calibration accuracy and robustness that are of paramount importance. Here too, of course, processes and methods must be used that save time and resources while still ensuring quality.

2 State Of The Art

The process of basic model-based calibration is presented in **Figure 1**. The DoE method is used here for selecting the necessary measurement points and for modeling. This is done by creating a steady-state model that predicts the effects adjustments variables have on output variables. This model can be a polynomial, a neural network or any other approximator. The quality of the model is assessed on the basis of statistical characteristics, with its prediction-making ability being the most important criterion. To assess this prediction capability, measurements are used that were not employed for creating the model. Comparing the predicted values with data actually measured provides a statement on model quality.

To parameterize the DoE models, steady-state measurements must be performed on the engine test bench. This generally takes place automatically since model accuracy is largely dependent on the quality of measurements. Setting the target values automatically involves the need to observe a number of engine limits. These include various temperatures, the smoke-emission value and peak pressure in the case of the diesel engine, and exhaust gas temperature, running smoothness and knock for the spark-ignition engine.

To ensure measurement accuracy, good test-bench automation practice employs the following procedure, **Figure 2** a:
– Iterative adjustment of adjustment parameters: Here it is important not to violate any test space limits. If any such limits are violated, the last admissible intermediate step is selected for measurement. This ensures that any limit violation is only short-term and that engine and test bench are not burdened unnecessarily.
– Stabilization time: This duration is selected in a way as to ensure that all transient processes in the engine are concluded.

– Measurement time: The output variables being modeled are averaged to reduce external influences.
This process takes approx. 5 minutes for each test point. Of this, about one minute is used for calculating the average value and for DoE modeling, as can be seen in Figure 2 a.

Once assessment shows that a model is sufficiently accurate, it can be used for optimization purposes. The aim of engine calibration is to define engine control maps in such a way that they meet a wide range of criteria. For instance, consumption must be kept as low as possible, emissions are at least to meet the statutory requirements and drivability is to be make-specific in character. The demand for good drivability makes it necessary to smooth individual maps, the degree of smoothness only being defined during the course of calibration.

3 „Rapid Measurement" Idea

Figure 2 a shows that only a small proportion of measurements is saved and used for further purposes. The basic idea behind the new method lies in using the measurements of transient engine states, thereby avoiding lengthy transient phases. This requires a model that is able to predict the steady-state condition on the basis of transient measurements.

Making sure that adjustment limits are observed, the procedure after each adjustment in classic adjustment strategy is to wait until the change in important output variables is sufficiently small over time. It is only then that measured values are recorded and that adjustment continues.

Under the new adjustment strategy presented in Figure 2 b, the output values are measured quasi-continuously (i.e. at a sufficiently high sampling rate) and used for adapting a dynamic statistical model. This on-line model is employed for estimating the final steady-state value of output. This estimate is taken as the basis for deciding whether engine limits are met. This way, a decision can be taken in a matter of seconds. The speed of adjustment is no longer determined by the convergence of output values but by the number of measurements necessary for adapting an accurate statistical model.

Having completed the measurement series, a global dynamic model of the entire measurement series is fitted off-line. This is done merely by using the measurements recorded during the shorter adjustment phases – stabilization and averaging are no

longer necessary and can thus be dispensed with. „Rapid Measurement" is therefore a way of significantly shortening the time required for measurement.

Non-linear extension of the ARMAX models (Auto-Regressive Moving-Average with eXogenous input) provides a substantial range of statistical dynamic models. To assess stability better, non-linearity is abandoned in the auto-regressive part, thereby producing the extended parametric Volterra series.

An extended parametric Volterra series, **Figure 3**, consists of a steady-state, non-linear part and a dynamic linear part. Selecting appropriate non-linearity (polynomials, local approximators, such as the radial basis functions and others), all model parameters can be determined through analysis using the estimation equation.

Assuming that stability is given, the final steady-state value is easy to estimate as it is possible to derive the formula from the equation model (final steady-state value model). It corresponds to a steady-state DoE model and can be applied analogously to steady-state data.

4 Application Examples

4.1 Spark-Ignition Engine
The ignition angle is the fundamental adjustment parameter in stoichiometric spark-ignition engines. It has a major influence on fuel consumption, on torque and on emissions. It is limited by knock, combustion stability or maximum exhaust gas temperatures. The range through which the ignition angle can be adjusted is heavily dependent on operating point and freely adjustable calibration parameters such as timing. One possibility in DoE measurements is to define the ignition angle as the difference from the optimum ignition angle in the test plan. This makes it necessary to optimize the ignition angle in relation to maximum torque on the engine test bench. In the case of pressure-indicated engines, the main center of heat release can be set to 8 °crank angle ATDC as the first approximation for the torque maximum. A method for rapidly optimizing the ignition angle, including measurement of spark sweep, as well as a map-modeling process are presented below.

In classic spark sweep measurement, ignition timing is retarded from the ignition angle with optimum torque. A mean value is measured at defined intervals. The torque, temperature and emission curves

measured are used for optimizing the calibration parameters as well as for calibrating control unit functionalities, such as the torque model or the map of the latest selectable ignition angle. The DoE method only measures selected ignition angles from the spark sweep and predicts the steady-state characteristic by means of statistical models, **Figure 4**.

In the case of rapid spark sweep, ignition timing is continuously adjusted in one direction and then in the other. All of the relevant variables are recorded at a sampling rate of 10 Hz. This cuts adjustment and measurement time to a third of the extent required in the steady-state DoE method.

While timing is being advanced, knock intensity is monitored in real time, with individual knock events as well as a statistical knock value from 50 preceding combustions producing a response. Other variables monitored are exhaust gas temperature as well as stability of engine combustion.

The method of rapid ignition-angle optimization was examined on a spark-ignition engine with continuous intake and exhaust-camshaft phasing. The first phase of the project determined the effect of ignition timing speed on the torque curve and on the resultant ignition-angle optimum. Dynamic models for exhaust gas temperature, HC and NO_x emissions were fitted to the spark sweeps measured. The final steady-state values estimated with the aid of the dynamic models were verified on the basis of additional steady-state measurements. A second phase involved on-line model generation while spark sweep timing was being rapidly adjusted on the test bench. Depending on the estimated final steady-state value, appropriate action was taken to adjust timing. It was possible, on a reproducible basis, to determine the torque curve and optimum ignition angle independently of timing speed. By way of example, **Figure 5** shows the exhaust gas temperature curve during timing adjustment, the simulated curve and the steady-state estimate from the dynamic model. The model error amounted to 5 Kelvin. As a result of the measurement principle, emission measurement gave rise to significant delay times that were taken into consideration at the model-generation stage. Hence, it was also possible to predict the emission curves for HC and NO_x with a high degree of accuracy.

The second example describes a method for modeling map areas. Here, additional data were recorded at 10 Hz during a standard automated DoE measurement for opti-

mizing camshaft timing and ignition angle. Dynamic models were fitted into the dynamic measurement without stabilization times and mean-value measurement. The mean values measured were used to generate a steady-state reference model. **Figure 6** shows a good level of correlation between the optimization results for the intake and exhaust camshaft in relation to both model versions. In most cases, consumption is only higher by 0.5 % and always less than 1 %. Combined with rapid spark sweep, the total measurement time can be reduced to one third of the measurement time currently needed.

4.2 Diesel Engine

A standard task in developing diesel engines is the calibration of exhaust emissions during the New European Driving Cycle. The map area covered by the driving cycle is normally described in the form of a DoE model.

Two different measurement series were conducted. To begin with, steady-state measurements were obtained using the method described in Section 2 for generating a steady-state DoE model. Adjustment time was then recorded for the same test points with all the necessary signals in a much shorter stabilization time and without averaging time. The sampling rate was 10 Hz. These data were used to generate a dynamic model. The time for a measurement series can be reduced to less than 50% of the time needed in the steady-state method.

The input variables for generating both models are the start of injection, air mass, boost pressure and rail pressure calibration parameters. The output variables are the main target variables, i.e. NO_x, soot and HC emissions as well as fuel consumption.

Steady-state models are often generated using derived variables, such as mass flows and specific variables. These derived variables are computed from the variables measured directly. For gaseous emissions, computation incorporates concentrations and other measured variables (e.g. exhaust-gas mass flows). Soot mass flow is obtained from the smoke-emission value. The smoke-emission value is a variable that can only be determined in the steady state because the measurement method demands a certain averaging time. In the dynamic mode, it is initially only possible to analyze the variables that are measured directly. The mass flows for the steady-state case must be derived after model generation because the measurement signals needed to do this would otherwise not be synchronized. The

smoke-emission value is at first substituted by recording opacity of the exhaust gas which is measured dynamically using an opacimeter. As a clear correlation can be constructed between opacity and smoke-emission value, it is also possible to model soot mass flow as an important factor in optimizing emissions. Partly limited, measurement accuracy of the opacimeter can be counteracted by regular calibration.

To compare model quality, both models are validated with the same additional steady-state measurements. The additional measurements are not incorporated in the steady-state DoE model or in the dynamic model used for computing the steady-state values.

Dynamic models were created for all of the variables needed to describe emission mass flows. The resultant final steady-state value models are capable of predicting the validation measurements, **Figure 7**. Their mean errors are in the same order of magnitude as DoE model errors. The slightly poorer values obtained from using the final steady-state value models can be explained by the limitations still inherent in the capabilities of model generation. So far, dynamic modeling has only used polynomials. As yet, these have undergone insufficient model-term significance testing (which provides an estimate of their significance) and output-variable Box-Cox transformation. Model quality could be improved substantially by including other regression processes and by making intensive use of the above-stated methods. So far, significantly higher computing time required has restricted any use of these techniques. Obtained from dynamic data, these final steady-state value models can, however, still be used for optimizing engine behavior.

Figure 8 shows the curve of a target function computed from nitrogen-oxide and soot emissions. It is calculated from the weighted square sums of emissions and plotted for a part-load operating point as a function of air mass and boost pressure on the one hand and as a function of start of injection and rail pressure on the other. The first step in the optimization process involves finding settings that minimize this target function. Even if the target functions of the dynamic model do have somewhat different values than those of the steady-state model, the optimum lies in the same input-variable regions. These are low air mass at low boost pressure and late start of injection at a rail pressure in the lower half of the variation range. Selection of the actual calibration parameters for this part-

load operating point furthermore depends on other variables, such as noise generation and fuel consumption. In addition, the calibration parameters selected must fit harmoniously into the map structure so as to ensure a good drivability. Therefore, a combination of calibration parameters will doubtlessly be selected which, although close to the emission optimum, also meets other additional conditions demanded.

5 Summary

This article describes a new method that nearly complete dispenses with stabilization and averaging times. Instead, the transient curves of measured variables are recorded while the operating-point and calibration parameters are being adjusted. These curves are fitted to dynamic models used for predicting steady-state values. The approach presented is capable of reducing measurement times to one third of classic DoE measurement times. Dynamic on-line models are used for detecting engine-range limits. Two examples have been successful in showing that dynamic models can be used for optimization purposes. Both results – optimized camshaft phasing on a spark-ignition engine and optimized emissions on a diesel engine – demonstrate that the models can be employed to the desired effect. The robustness and user-friendliness of this method is currently being enhanced for future application in production development.

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