Evaluation of Different Design Space Description Methods for Analysing Combustion Engine Operation Limits

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Title: Evaluation of different design space description methods for analysing combustion engine operation limits
Issue Date: 2014-11-11

7. Conclusions and recommendations

Since the test planning and modelling methodology, or design of experiments (DoE), is now widely used in engine calibration tests, the need for finding design spaces and using them becomes more important. With detailed information on the design space boundary, the DoE tests can be planned such that they lie exactly within the available design space. This will contribute to a more efficient use of the test bench, and thereby saving time and money in the development process.

Many of the design space description and determination methods, so far implemented in engine calibration and DoE software solutions, use a convex hull-based method. It turns out that a convex hull-based method is unsuitable to describe non-convex boundaries, which becomes even more evident in higher-dimensional cases. Furthermore the calculation effort to determine a convex hull for seven and more dimensions is large and will be a limiting factor for future applications.
The need for four- and higher-dimensional optimisation problems comes from the increase of the number of variables resulting from the implementation of new technologies that are required to cope with the higher demands on fuel consumption and emission regulations. For global optimisation problems, for which also the engine speed and load are variables, the shape of the available design space is likely to be non-convex. Furthermore, with an increase of variables it is not possible to know if the boundaries have a convex or non-convex shape.

The previous three chapters have shown the results, with respect to the research questions and the related subquestions. The analysis related to the research questions is summarised in Section 7.1. The evaluation concerning the overall problem statement based on the answers to the research question is presented in Section 7.2. Finally Section 7.3 focuses on future application possibilities and possible steps how the goals might be achieved.

7.1. Answering the research questions

The results have been discussed in detail with respect to the correctness of the classification of new test points, the time needed to train the boundary as well as the time required to allocate new test points as to be within or outside the boundary. For all the results the number of training points, the problem dimension as well as the type of boundary shape have been varied, where it was considered possible. The research questions have been discussed accordingly and the results are repeated below.

RQ1 *Which design space description method provides the best boundary quality?*

The answer to the first research question is depending on the situation. For an unknown boundary shape the two SVM-based methods provide the best boundary quality. For problem dimensions of seven and higher the SVM-LOO method provides an even better quality than the SVM method, as it can find the best tuning parameters for the problem. In case the user has a problem up to four variables and knows for sure that the boundary is convex, the CH method will give the best results, with no false negative assessments. Only in this case the results will describe a design space within the true operating boundaries. In all other cases a small region at an unknown location outside the true operating boundaries will be present. The number of training points need to be selected by the user. Except for the convex boundary case combined with a convex-based method, a larger number of training points will improve the boundary quality.

RQ2 *Which design space description method is fastest to train the boundary?*

Considering the related discussions the PEV method is the fastest method to train the boundary, except in the two-dimensional case, where the CH method is slightly faster for an increased number of training points. The SVM-LOO method is the slowest method in all cases. The CH method is most strongly affected by the problem dimension and becomes slow in the seven-dimensional case, but is still faster than the SVM-LOO method.

RQ3 *Which design space description method is fastest to assess new test points?*

Analysing the subquestions it can be said that up to four dimensions the CH-method is fastest, followed closely by the PEV method. For the seven-dimensional cases the PEV method is much fastest than all other methods.
Comparing only the two SVM-based methods is can be seen that up to four dimensions the SVM-LOO method was faster, but in seven dimensions the SVM method was faster.

7.2. Answering the problem statement

Theoretical data have been used to learn about different influences on the boundary quality and calculation efforts. In addition engine calibration test data have been used to analyse application possibilities and restrictions for engine calibration purposes. Looking at the benefits for engine calibration purposes it may be concluded that similar effects have been seen for the engine cases as for the theoretical cases.
The aim of the study presented in this report was to find the best technique to determine and implement design spaces for arbitrary boundary shapes and at least up to seven dimensions.
The problem statement has thus been defined as follows.

> **Problem statement:**
> *Which design space description method is most suitable for combustion engine calibration test applications?*

The two SVM-based methods showed the best results in term of boundary quality, independent of the boundary shape. Also for higher dimensions the results of the two SVM-based methods proved best of the methods shown. The SVM-LOO with a leave-one-out optimisation even improved the quality slightly. The quality of the assessment will be the primary selection criterion and therefore the SVM-LOO shows the most potential. In terms of calculation time the two SVM-based methods are rather slow. Since the initial application of a design space description method will be offline, a longer boundary training time and new test point allocation time required for the SVM and SVM-LOO methods, are acceptable for the current calibration problems.
Therefore, for offline applications, the most suitable method is the SVM-LOO method.

7.3. Recommendations for future application

It may be concluded that the two SVM-based methods will be the most suitable method to describe a boundary, since they produce good results independent of the boundary shape and the best results in the higher dimensions shown. The shape of the boundary is not known in higher dimensions, thus the use of an SVM-based method will be less risky in terms of the number of false negative assessments and will give a larger available area 'inside the boundary' than the PEV or CH method. The SVM-LOO also produces better results in the higher dimensional cases, where the number of the critical false negative assessments is even further reduced due to the optimisation loops. For further use and successful implementation three recommendations are presented below.
The training of the SVM with a LOO optimisation is time consuming. In the first stages of the application of the design space the determination will be offline, in which case the training time can be acceptable, since offline calculations can, e.g., be run over night. For future purposes the SVM-LOO might be used for online design space determination. In that case an optimisation of the training time will be required, since the optimisation will need to be calculated while running the engine test.
Another important issue for performing an online boundary description will be the implementation of an appropriate control strategy. The main focuses will be how to reach a new point as fast as possible, without damaging the engine and taking into account the response time of, e.g., the critical temperatures, pressures or knock-occurrence.
Furthermore it will have to be considered, especially in the higher-dimensional applications, where the available area within the boundary becomes small, what strategy to place the points more effectively within the boundary is most applicable.