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Real time performance improvement of engineering control units via Higher Order Singular Value Decomposition: Application to a SI engine

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ABSTRACT

This article presents a method that improves the real time performance of some optimisation algorithms used in engineering control units. The motivation behind the improvement is the fact that when these algorithms are based on a computationally expensive set of model equations, real time optimisation is seldom possible. This is, for example, the case of most of the existing engine control units (ECUs) in the automotive and aeronautic sectors that are based on plain interpolation between multidimensional tables rather than on an artificial intelligence approach. In this article, the model equations are replaced by a reduced model based on Higher Order Singular Value Decomposition, which has the ability to provide simplified global descriptions of multidimensional databases. Such global description is amenable to efficient integration within an intelligent search formulation and sufficiently accurate for engineering applications. To illustrate the method, a Genetic Algorithm (GA) is used to optimise the working parameters of a spark ignition reciprocating engine. The goal is to find out, in a short CPU time (less than one-tenth of a second), the values of some engine control parameters (namely intake pressure, intake pipe length, intake valve closing angle, and spark timing) that yield the requested engine power while requiring a minimum specific fuel consumption, and avoiding knock combustion instability. The GA search platform can be replaced by other optimisation algorithms and the method can also be advantageously applied to other engineering systems described by computationally expensive model equations.

1. Introduction

Real time performance optimisation of engineering systems is a multidisciplinary technology field that has an important economic impact in industry. The reasons are the increasing complexity of engineering products and systems, and the need to devise control strategies that are both robust and able to correct their behaviour in real time. It would be pointless to reference here the very extensive specialised technical literature devoted to this field, which describes approaches that explore many different strategies: most of them based on artificial intelligence methods. An idea of the very wide scope of the work published in the last two years results could be glimpsed from the work by O'Rourke, Arcak, and Ramani (2009) in the area of fuel cell control, Miller and Rock (2008) in robotics, Huang, Wu, Lin, and Chen (2010) in biohydrogen power generation, Gunnerud, Foss, and Torgnes (2010) in oil field planning, Cortes, Saez, Milla, Nuñez, and Riquelme (2010) in planning of public transportation systems, Ochoa, Repke, and Wozny (2010) in bio-chemistry processes, Kastner, Sever, Hager, Sommer, and Schmidt (2010) in sports training, and Dalvi and Guay (2009) in hybrid fuel power systems for automotive applications. Regarding R&D studies (oriented towards the development of a methodology but illustrated, nevertheless, with practical applications) it is worth mentioning the work by Mercangöz and Doyle (2008), Alvarez and Odloak (2010), Marchetti, Chachuat, and Bonvin (2010), Chachuat, Srinivasan, and Bonvin (2009), Golshan, Pishvaie, and Boozarjomehry (2008), and De Souza, Odloak, and Zanin (2009).

The work described in this article does not propose a new optimisation methodology but, instead, presents a method that could be used to improve the real time performance of already existing approaches. It happens that many search strategies implemented in real time optimisation formulations rely on the serial computation of a set complex, differential-algebraic model equations. This is, for instance, the case when addressing the real time control of automotive engines and aircrafts, especially if robust, global optimisation is required since global optimisation platforms usually require the computation of a large number of states of the system. This large number of computations results in a long execution time and interferes with the objective of getting

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results in real time. However, in the method that is proposed in this article, the states of the system are computed using a reduced model based on Higher Order Singular Value Decomposition (HOSVD) and this allows for a significant time saving. This is because HOSVD has the ability to provide global descriptions of multidimensional properties of physical systems that allow for the computationally inexpensive calculation of particular values of the physical property. These global descriptions are amenable to efficient integration with an intelligent search formulation and provide results that are reasonably accurate for engineering applications.

The method is illustrated by addressing the problem of optimising the working parameters of a spark ignition reciprocating engine in real time. The reason is that, nowadays, the automotive industry is edging towards a concept car in which artificial intelligence based systems play a significant role. This trend can be explained by the fact that although individual sub-systems are highly efficient, their integration can still be improved leading to further gains in the overall performance. Among the many aspects that would benefit from this approach, there are two that deserve immediate attention, namely the specific fuel consumption and the combustion emissions. In particular, the aim is to find out in the shortest possible time (less than one-tenth of a second using a standard desktop PC: Pentium® 4 CPU 1.66 GHz) the values of some engine control parameters (namely the intake pressure, intake pipe length, intake valve closing angle, and spark timing) that yield the required engine power with a minimum specific fuel consumption, while avoiding knock combustion instability. The search platform used for these illustration purposes is a standard GA approach, but it should be stressed that the proposed method could be used advantageously in other optimisation platforms. It is also worth mentioning that the method does not require the *a priori* knowledge of the physics-engineering equations (which will be used in the article to generate the engine database only). Thus, the method could also be applied using an engine database resulting from experimental tests.

As it could be expected, the use of intelligent systems for automotive applications started in the sports and luxury high end of the market. A good example is the 6.0 l V12 Aston Martin DB9 that packs 335 kW (450 hp) and is able to detect cylinder misfires by using an artificial neural network (ANN). Interestingly enough, Ford is implementing the same technology on the heavy duty V10 Econoline van, which is a completely different vehicle since it caters to the industrial market niche. Then, it seems that the potential advantages of using artificial intelligence systems in the automotive sector are large and promising for the mid-term future. Another important aspect to be reckoned with has to do with legislation. In particular, directives in the countries of origin of the major manufactures, United States (http://www.epa.gov/nvfel/testing/dynamometer.htm#engcycles), the European Union (http://ec.europa.eu/enterprise/automotive/directives/vehicles/index.htm), and Japan, have started to address the issue of engine transient performance although restricted, for the time being, to Diesel based cycles. The idea is that transient operation, which tends to be off-design, is the most common mode of operation and, therefore, the natural target for real time optimisation purposes. It is because of these reasons that the R&D effort associated to the development of "intelligent" engine control systems based on different approaches has increased significantly during the past few years. See, for example, Sayin, Ertunc, Hosoz, Kilikaslan, and Canakci (2007), Vance, He, Kaul, Jagannathan, and Drallmeier (2006), Vance, Kaul, Jagannathan, and Drallmeier (2008), He and Jagannathan (2005), Jimbo and Hayakawa (2011), Shaver (2009), and Kwiatkowski, Werner, Blath, Ali, and Schultalbers (2009). In the specific field of the use of Genetic Algorithms (GA) for engine optimisation purposes. It is worth mentioning the work by Montazeri, Poursamad, and Ghalichi (2006), Huang, Wang, and Xu (2006), Yang, Wang, and Li (2008), Sawaki, Kaji, Yamamoto, and Sakoda (2009), Kesgin (2004), Alonso et al. (2007), Hiroyasu, Miki, Kamiura, Watanabe, and Hiroyasu (2002), Verma and Lakshminarayanan (2006), and Togun and Baysec (2010). As a summary, it could be said that recent developments published in the specialized literature show that artificial intelligence methods may provide a means to improve significantly automotive engine performance. In fact, it could be that this technical area is so intrinsically multidisciplinary that these methods might be the only ones capable to achieve an optimisation breakthrough. Nonetheless, modest forward steps are also welcome because the automotive industry has a size such that even small design improvements may have a large economic impact.

In this article, the proposed method is illustrated by searching (in less than one-tenth of a second) for the SI operational parameters (inlet pressure at the intake manifold, spark timing, intake collector variable geometry, and intake valve closing time) that yield the requested engine power with minimum fuel consumption. This is done avoiding combinations of parameters that might lead to knock combustion instability. Optimisation is based on a GA that uses a reduced engine model (REM) obtained from a truncated Higher Order Singular Value Decomposition (HOSVD) of a set of engine output data that was obtained *a priori* using a full engine model (FEM) input–output data. The REM is able to obtain the engine output data for any value of the input engine parameters (not necessarily equal to those used to construct the REM) via modal interpolation (reducing each multidimensional interpolation to a series a one-dimensional interpolations), which is both fast and precise. A sketch of the proposed methodology is illustrated in Fig. 1.

In other words, the basic idea of this article is that instead of running an expensive FEM for each individual of the GA, the GA uses the REM outputs obtained via HOSVD+modal interpolation as its input. In this way, it is shown that it is possible to obtain minimisers from the optimisation algorithm in less than one-tenth of a second using plain Fortran 90 software in a Pentium IV based PC (with a 1.66 GHz processor and 1.99 Gb of RAM memory). Such target time has been chosen according to two criteria:

(a) It should guarantee a smooth driving performance since it involves two engine cycles only at 2500 RPM.
(b) One-tenth of a second is well below the reaction time of the average driver, which stays in the range from 0.3 to 1.2 s, depending on age and mental workload, see Ma and Andreasson (2006) and Makishita and Matsunaga (2008). Of course, migration of the method developed in this article to an actual engine control unit (which is outside the scope of the paper) could increase the required CPU time, but the factor of 10 between our target CPU time in the PC and the actual average driver reaction time should account for this increase. In addition, we anticipate that the required operations in the proposed method involve multidimensional array manipulations that could be easily parallelized through appropriate hardware architecture of the engine control unit.

We emphasise that this is a methodological article, which aims at illustrating a new methodology that allows for performing engine control in real time. Thus, the intention will be to obtain the same results as those provided by the full engine model in a much smaller computational time, not to improve the full engine model results themselves. In this sense, instead of minimising the specific fuel consumption (which could be somewhat misleading when comparing with the results provided by the full engine model and the reduced order model), the optimisation platform will be required to