Combined 1-D and 3-D simulation of Engine Transient Response

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Abstrakt

Simulace přechodových režimů, zvláště u automobilových motorů, jsou velmi důležité. Standardní 1-D přístup, který je vhodný pro simulace spolupráce motoru s turbodmychadlem během přechodových režimů, umožňuje optimalizovat jeho řídící algoritmy.
Hlavním cílem práce je paralelního spojení 3-D simulace s 1-D simulací v iterační smyčce. Z výsledných křivek vývinu tepla z 3-D simulací ustálených režimů jsou s pomocí nelineární regrese generovány parametry tří vrcholové Vibeho funkce vývinu tepla. Pro 1-D simulace přechodových režimů je následně použita interpolace mezi parametrizovanými vývinu tepla a informacemi o produkci emisí.

Abstract

Simulation of unsteady (transient) operation especially in the case of automotive engines becomes more and more important. The standard solution is based on 1-D approach, which enables us to predict the reaction of an engine and a turbocharger to changed demands on load and speed and to optimize engine control unit.
The main goal is to employ 3-D code in parallel to 1-D simulation of an engine transient in an iterative loop. The final result of 3-D code in steady state is used with non-linear regression to generate parameters of three-term Wiebe function for ROHR. The interpolation of parameterized ROHRs is used for every next 1-D simulation of transient regime.

Key words

1-D simulation, GT-Power, Rate of Heat Release, Non-linear regression.

1. Introduction

Simulation of unsteady (transient) operation especially in the case of automotive engines becomes more and more important. The standard solution is based on 1-D approach, which enables us to predict the reaction of an engine and a turbocharger to changed demands on load and speed and to optimize engine control unit.

The new method aiming for more accurate simulation of engine transient operation has been developed [1]. The main advantage of that is time-reducing coupling of 1-D and 3-D processes. Unlike standard serial coupling of those two simulations, the current method creates a library of quasi-steady 3-D simulated engine cycles, especially ROHR (Rate Of Heat Release) patterns and emission formation data at initial and boundary conditions found by 1-D simulation. The library filling-in process is based on repeated 1-D simulations if necessary – Figure **1**. All library inputs are used for interpolations during any following 1-D simulation, being selected according to the Euclidean distance from current cycle state variables (e.g., air excess, boost pressure, engine speed, etc.).

The method has opened a new space and set challenges for transient response optimization. The main achievement consists in the more reliable knowledge of ROHR, combustion efficiency and emission data for cycles with conditions typical at transient operation, often far from the optimized steady-operation state. The accuracy depends on 3-D code calibration level, of course, but generally it is better than in the case of empirical correlations used for 1-D approach.

The main goal is to apply non-linear regression to generate parameters of three-term Vibe function for ROHR. The interpolation of parameterized ROHRs is used for every next 1-D simulation of transient regime.

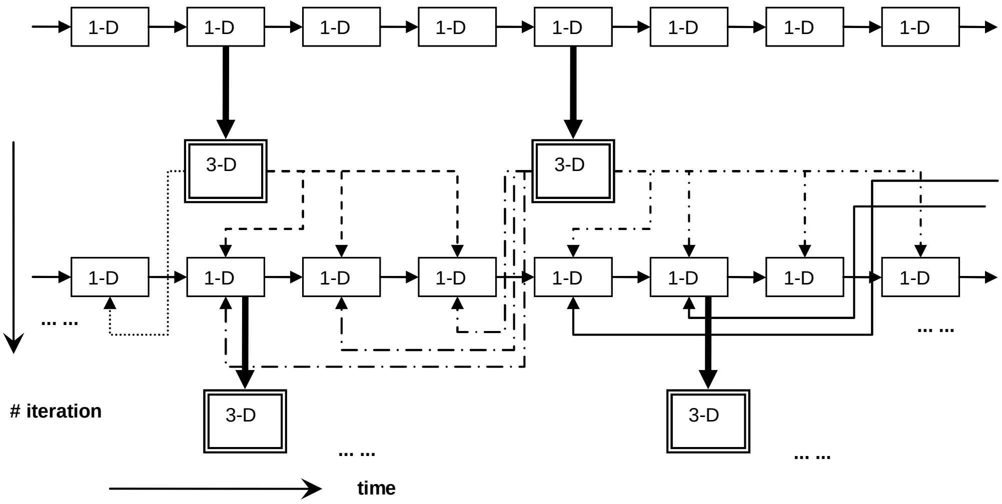

***Figure* 1** *Simulation scheme developed for transient operation simulation. Every rectangle refers schematically to a single engine cycle. The independent parallel 3-D simulations (assigned to 1-D previous run by bold arrows) provide for ROHR patterns and integral emissions per cycle. These results are stored in a library. The next 1-D run uses all previous results of 3-D by multidimensional interpolation in the database look-up tables between two most adjacent 3-D cycles.*

2. Tools of cycle simulation

The author has already acquired positive experience in coupling 1-D and 3-D methods for optimization of diesel engines in the past - [2], [3]. The accuracy of 1-D simulation is usually sufficient for the charge exchange and turbocharger modelling, while ROHR and the subsequent emission formation are obtained from a 3-D code.

In addition, other exercises have shown the possibilities of data transfer from more sophisticated but slow 3-D or 1-D models to fast simplified 0-D or algebraic models. The data transfer is provided for by representing the outputs from slow models by regression substitutions or just multidimensional lookup tables - [4]. The optimum calibration of any of simplified models requires filling in the large hypercube space of independent variables if extrapolation outside of trained range has to be avoided, which is strictly advisable. It poses high demands on the parallel training runs of the more accurate model to provide for ROHR at, e.g., any combination of speed, fuelling (or b.m.e.p.) and cylinder charge state, i.e., at any air excess or EGR rate. Purely parallel running of a 3-D code would be very time demanding in such a case.

The extents of independent variable space components, which are sufficient for adequate training of a library containing all necessary data, might be determined by the simulation of transient processes themselves. The range of independent variables for filling in the DoE hypercube (the engine's state variables such as b.m.e.p., speed, air excess, EGR rate, etc.) needs not to be determined by sole mechanical combinations of every variable range in such a way. The reduction of hypercube extent may be achieved by this way and the demands on data-base contents would be significantly decreased. Therefore, the iterative scheme of 1-D simulations combined with the selected operation points of 3-D simulations has been developed, Figure **1**.

2.1 1-D Engine Model

GT Suite code (especially GT Power component) was used as a tool for 1-D modelling - [5], [6]. It provides an environment for highly complex models on one side and on the other side it features excellent flexibility for user-defined data adoption. The wide applicability of controllers and signal treatment offers high optimization potential for the future. User defined ROHR interpolation and simple Excel interface was sufficient to fulfil the needs of coupling the results from Kiva3 simulation to the following 1-D run.

2.2 3-D Engine Model

The multidimensional engine simulations for determining the emissions (especially soot and NOx) and ROHR patterns have been performed with a modified version of the Kiva3 code [7]. This code is equipped with the RNG k-ε turbulence model as implemented by Han and Reitz [8], the CAB atomization and drop breakup model [9], [10], and the LIT auto ignition model [11] of Tanner. The heat release is modelled using the laminar-turbulent-laminar (LTL) characteristic time combustion (CTC) model, along with the emission models for soot and nitric oxide. All other models used in the simulations are the standard Kiva3 models.

The LTL-CTC model is based on the CTC model of Abraham et al. [12] as adapted to diesel combustion by Kong et al. [13], but it employs only one global reaction to model the heat release. As in the original CTC model, the LTL-CTC model uses a laminar reaction rate for the pre-combustion and a turbulence reaction rate for the spray combustion. But once the fuel injection is terminated, the LTL-CTC model gradually shifts back to the laminar reaction rate. This last step is motivated by the fact that the turbulence in a diesel engine is dominated by the spray induced flow during fuel injection, but it is considerably reduced in the later phase of combustion. A study by Tanner and Reitz [14] discusses this in more detail. The gradual shift from the mixing-controlled combustion back to the laminar combustion improves the reaction rate in the late combustion phase. As a consequence, the notorious under-prediction of the heat release rate is improved, which results in a reduction of the unburned fuel at the end of the combustion. The LTL characteristic time combustion model is described in more detail in [15]. NOx formation is modelled using the extended Zeldovich mechanism which is described in [11]. The net soot density is modelled according to Hiroyasu and Kadota [16], the specific implementation see [15].

3. Tested ENGINE and operation modes

The simple constant speed, variable load transient operation mode of a highly turbocharged diesel, typically used in a generator engine, was used as a test procedure. It reflects most of the problems found in similar simulations and can be realized in reasonable time.

For this study, a nine-cylinder medium speed Wärtsilä Sulzer engine 9S20 has been used at the rated power of 158 kW/cylinder at 1000 r.p.m. The bore is 200 mm, stroke 300 mm, compression ratio 13.6:1, fuel injection by a common rail system with averaged nominal injection pressure of 95 MPa.

The additional parameters, required for full 1-D model, were estimated using procedures developed for early stages in the design from similar engines using the authors' database. In such a way, the parameters are realistic but not necessarily the same as at the real engine.

The current paper is focused on improvement of features of simple transient process at constant engine speed and at load controlled just to keep the engine speed. The injected fuel mass was limited by the air mass trapped in a cylinder. Instead of detailed calculation of air excess (relative A/F ratio), instantaneous boost pressure and temperature were used to estimate A/F ratio. The simple common rail system of constant injection pressure, invariable injection advance and single unsplit injection was assumed as a first approximation.

4. Substitution of ROhr by Vibe function

Indirect multivariable interpolation using fictitious time was implemented in the previous work. The in cylinder pressure at the cycle start and air excess corresponds to fictitious time which is associated with ROHR from Kiva. This indirect interpolation is not suitable in case with higher number of inputs.

In 1-D simulation of diesel engine in software GT Power, the three-term Vibe function can be used. This three term function is sum of three Vibe functions defined (1).

$$x_C = \eta_C \sum_{i}^{3} \left(1 - \mathrm{e}^{-a\left(\frac{\alpha - \alpha_{PH}}{\Delta\alpha_i}\right)^{m_i+1}} \right) \tag{1}$$

Every Vibe function is defined by two coefficients $\Delta\alpha_i$, m_i. The parameter α_{PH} is the beginning of the combustion. Thu sum of three functions have to be 1 thus we need only two weight coefficients. The usage of combustion efficiency is necessary due to non-optimized injection pressure and spray impingement on the cylinder/piston walls. This was described in [1]. All these ten parameters must be found for every ROHR generated by 3-D code with the aid by non-linear regression tool.

There is a possibility to interpolate between scattered data table using up to five independent input parameters in 1-D software GT Power. We have two inputs in our simple load operation at constant speed of the engine (in cylinder pressure and air excess). For future work, we can use another inputs – for example engine speed, EGR content and turbine rack position, etc. One multidimensional lookup table is used for each parameter of combustion settings and emission pollutant.

4.1 Non-linear regression of ROHRs

The open source software for finite elements FEMINA contains user defined non-linear regression tool. This tool enables searching up to eight parameters with Marquardt-Levenberg method of non-linear regression. The environment of FEMINA is plotted on ***Figure 2*** and detailed description can be found in [17].

Due to the variability of three-term Vibe function (sum of function of very similar shape), we decided to keep some parameters constant, namely the premixed exponent, main exponent and premixed duration. The rest six parameters were generated by non-linear regression tool in FEMINA.

The combustion efficiency is the maximal value of the ROHR from 3-D code. For regression procedure, ROHR was rescaled to one and previous maximum value was set as the combustion efficiency in GT Power.

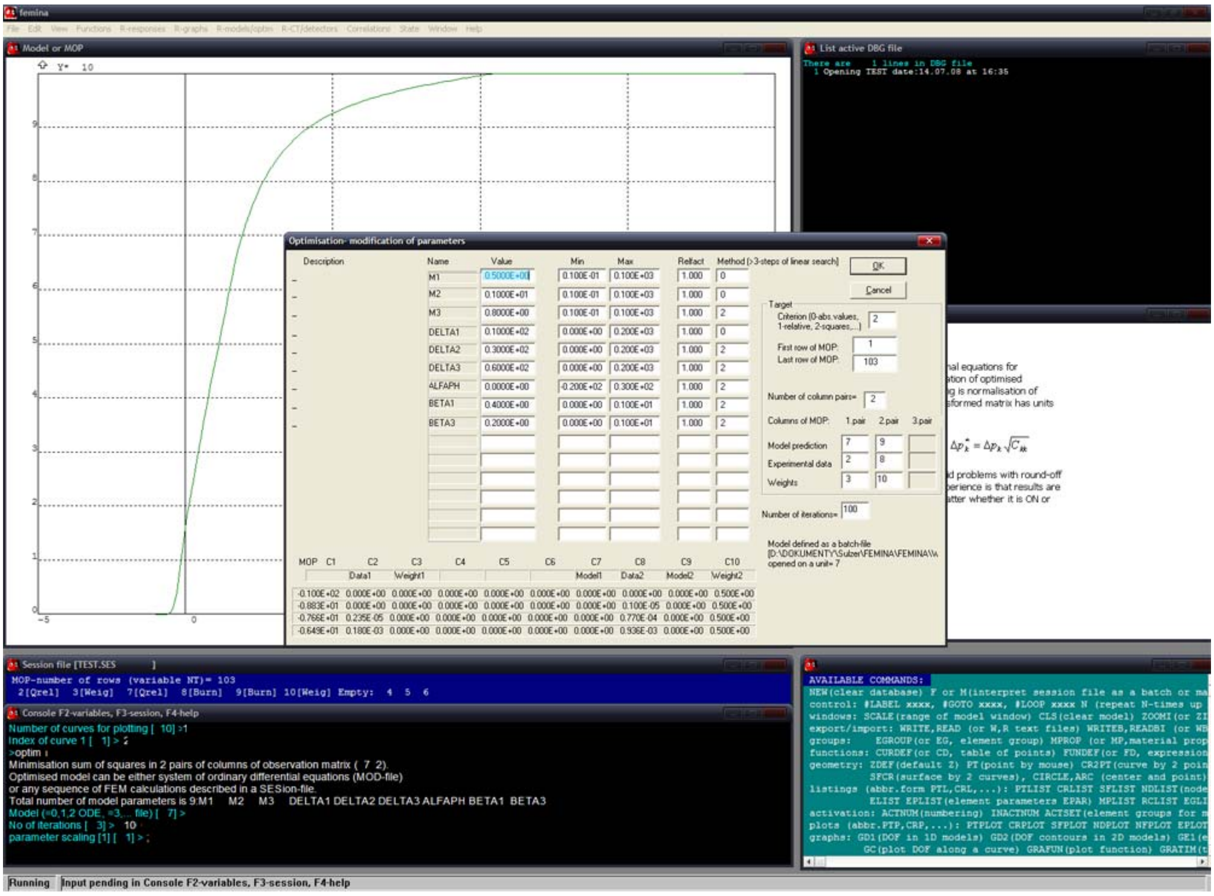

***Figure* 2** *The environment of non-linear regression tool in FEMINA software.*

4.2 Application of developed method in transient operation

All ROHR patterns calculated in Kiva3 code were transformed to coefficients of three term Vibe function, combustion efficiency and crank-angle of the start of combustion. All these coefficients were inserted into multidimensional lookup tables in GT Power.

Computation in Kiva3 code provides information of production of emissions (Soot, NO_x, HC) in grams per cycle. These data was inserted in multidimensional lookup tables. Simple conversion calculation was applied to output of specific production of emissions in g/kW.h.

Transient operation at constant engine speed was set to change load from 2 to 19.37 bar of b.m.e.p. The transient operation was computed with two limits of relative A/F ratio, namely 1.25 and 1.5. The turbine has fixed geometry and no waste-gate. PID controller was used for controlling of injection rate to keeping required b.m.e.p. The results for both limits of relative A/F ratio are plotted in one graph for each monitored value. These are engine power and air excess in ***Figure* 3**, boost pressure and turbocharger speed in ***Figure* 4**. Pollutant emissions are plotted in ***Figure* 5**. Faster transient operation for case with air excess 1.25 is obvious while emission production is slightly higher.

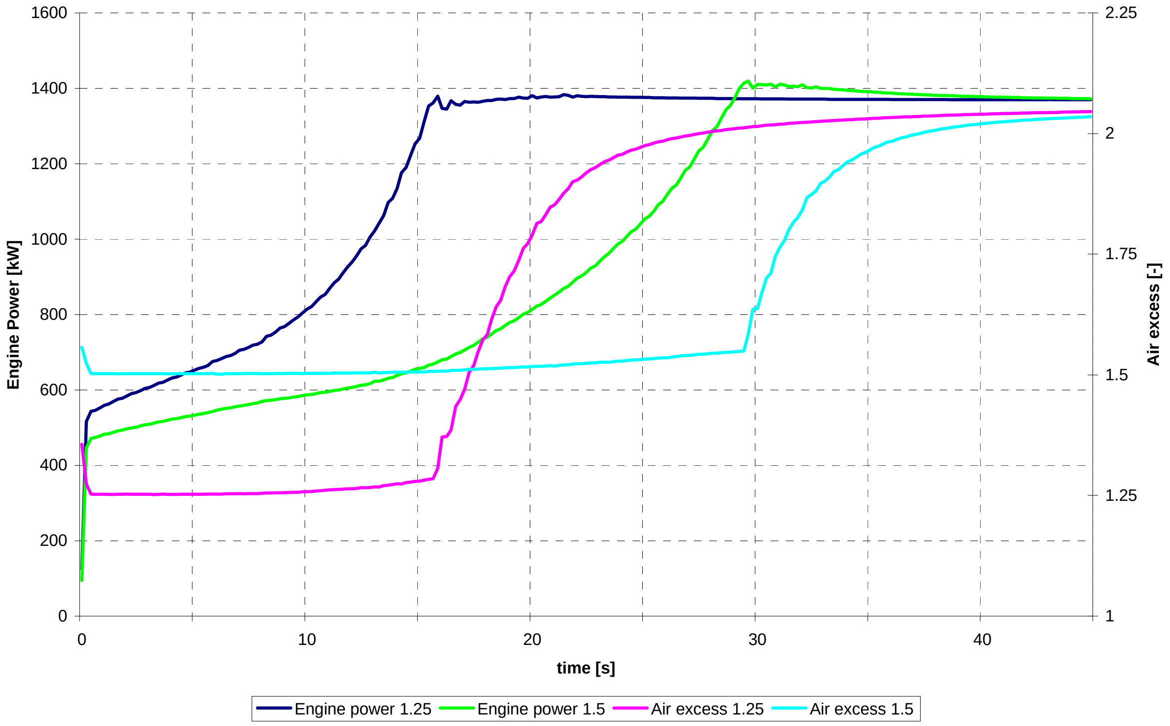

Figure 3 – *Engine power and relative A/F ration as a function of time at different limit values of relative A/F ratio during transient response to load change at constant engine speed*

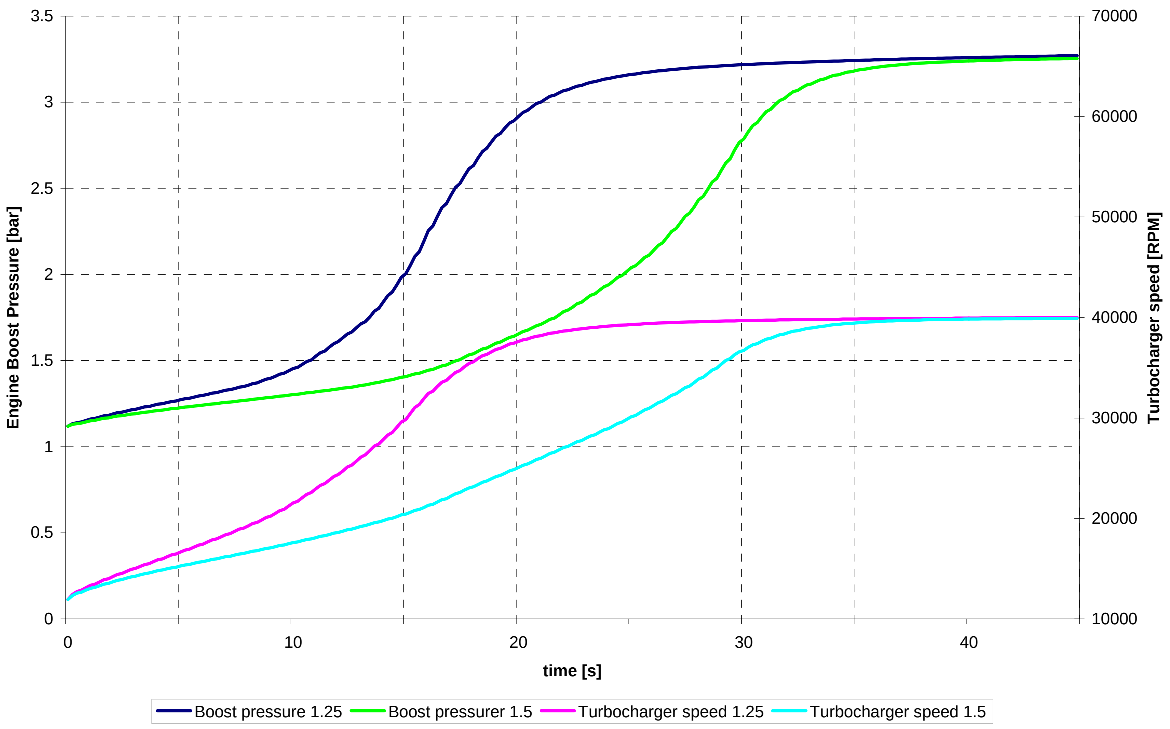

Figure 4 – *Pressure of intake air and turbocharger speed as a function of time at different limit values of relative A/F ratio during transient response to load change at constant engine speed*

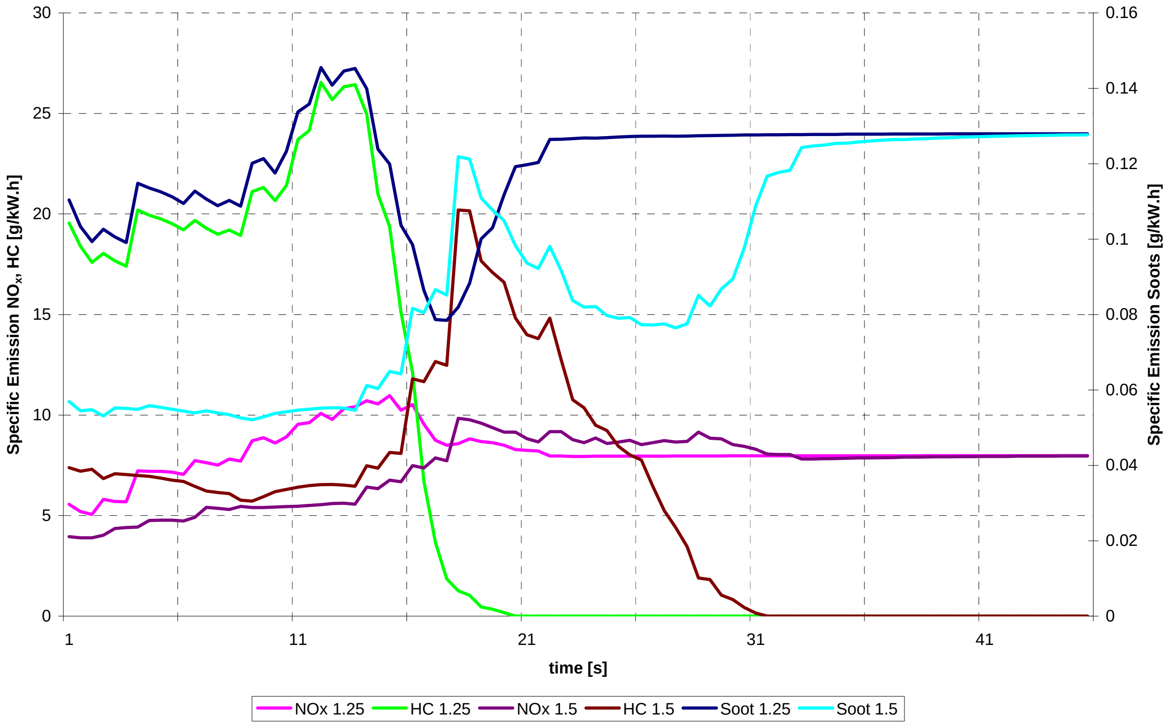

Figure 5 *– Specific brake emissions as a function of time at different limit values of relative A/F ratio during transient response to load change at constant engine speed*

5. Conclusion

The methodology for transformation ROHR pattern to coefficients of Vibe function with help of non-linear regression tool was developed. The results of developed methodology (including all procedures mentioned in [1]) were built in GT Power 1-D model of Wärtsilä-Sulzer engine. Engine model was tested in simple transient response of load change at constant engine speed 1000 RPM for two cases with different air excess limit. The initial results proved the developed methodology.

Increasing the accuracy of ROHR in 1-D engine model leads to higher accuracy of engine output parameters. The model also predicts production of pollutant emissions more accurately. Increase of accuracy is important during transient operation simulation, which is very sensitive to small changes. We used data from 3-D engine model, but it is also possible to use data from engine test bench.

The database of parameters of ROHRs will be filled in the near future for transient operation for the case of variable engine speed. The developed methodology will be tested in this type of transient operation. The following inputs are supposed to be applied for this case (GT-Power enables to use no more than 5 independent variables for multidimensional look-up tables): boost pressure, air excess and engine speed. There are two free variables. EGR rates, VG turbine rack position, engine wall temperatures etc. can be used as inputs for database for future engine simulation and optimization of control system of an engine.

The long-term goal of this research is to develop a simulation tool which can be used to address the most fundamental issues in engine design with respect to minimizing fuel consumption and minimizing pollutant emissions below regulated emission standards.

6. List of symbols

α	crank angle	[deg]
α_{PH}	angle of combustion start	[deg]
$\Delta\alpha_\iota$	combustion phase duration	[deg]
η_C	combustion efficiency	[1]
m_ι	combustion phase exponent	[1]
$ROHR$	rate of heat release	[1]
x_c	normalized heat release	[1]

7. References

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