MONTE CARLO SIMULATION OF THE MANUFACTURING TOLERANCES OF A DIESEL COMMON RAIL INJECTOR

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ABSTRACT

The Piezo Common Rail injector (PCR), part of the diesel Common Rail injection system, offers unique and unmatched advantages in nanometer resolution in high-speed applications of diesel systems. Optimal balancing of the tolerances range of parameters brings cost saving and quality increases in production process. The simulation of PCR hydraulics is one of the most powerful tools describing behavior of the system. With the help of 1D simulation in AMESim and MATLAB software using the Monte Carlo method for random parameter sampling a new approach for analyzing the manufacturing tolerances of PCR injector of the 2nd generation was developed.

1 INTRODUCTION

The goal of this project was to take advantage of 1D simulation of injection quantities for solving the problem of optimal tolerances by sampling the parameters of injector as a Monte Carlo (MC) study. MC method is based on integration of the probability distribution function of each parameter and following systematic use of random numbers in order to estimate parameters of an unknown distribution by statistical simulation according to a prescribed algorithm. Using the MC approaches has reasonable grounds. If we vary only the lower stream limit (LSL) and upper stream limit (USL) for 20 independent parameters, for instance, we should run 210 single simulations, which means setting up over a million simulations for varying two values of one parameter. If we wanted to vary not only the marginal tolerances values but also the mean value for 20 parameters, we should run 210 single simulations – that are already GIGA numbers! With the MC simulation only approximately 400 single simulations have to be carried out.

The first task was development of a simulation MATLAB-AMESim model for producing new injectors with various parameter combinations within their original tolerances. The evaluation and analysis of the results from the simulation by using statistical software STATGRAPHICS was the second task. Pursuant to the statistical analysis a view and comparison of parameters with the highest effect of their tolerances and parameters with almost no effect of the tolerances (which could lead to enlargement of tolerances range more precisely to saving the production costs) was made.

2 ANALYSIS OF PROJECT

In order to carry out a Monte Carlo simulation it was necessary to collect data pertaining to each relevant parameter – tolerances and distribution of each parameter. Data for a total number of 17 parameters were provided from quality management for MC simulation.

The hearth of MC simulation vas a validated simulation model built in AMESim software that produces results of simulation of injection quantities. Reading statistical data, sampling parameters within production tolerances and their arrangement for simulation, running simulation in AMESim with new parameter sets, reading results from simulation and saving them in an Excel file was a task for MATLAB script using classes and programmed function for sampling parameters according to MC algorithm. Statistical analysis of injection quantities as a dependent value of input parameter combinations saved in Excel were evaluated by the STATGRAPHICS statistical software.

2.1 AMESIM MODEL AND ITS VALIDATION

To produce high quality results of injection quantities it is necessary to make validation of the simulation model. Validation of the simulation model is a very important operation in simulation. To "validate" is explained as "to prove that something is true", which means "our simulation model corresponds to real injector". The goal of validation is to project a high-accuracy model with the calculation time (CPU time) as little as possible. There are several steps to validate developed injector model such as updating injector parameters according to available experimental data, using results of FEM analysis for certain parameters; validation of injector components (nozzle validation, Common Rail Validation, ECU validation, hydraulic serve system validation); comparison of proposed model variant according to time observables of the injector (ECU current, ECU voltage, needle lift, injection rate, pipe pressure etc. - see example with information about wrong acceleration of needle during simulation in Fig.1); quantity maps comparison of experimental data and quality of simulation (see Fig.2). Validation was time consuming, hard work and a study intensive process.

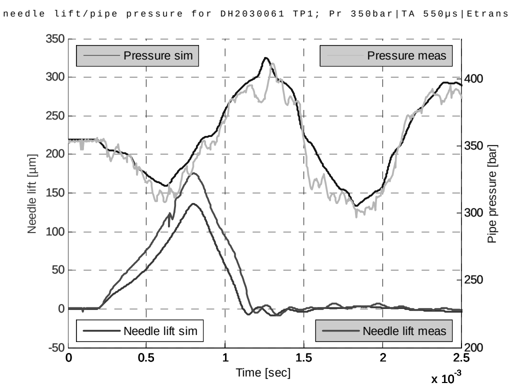

Fig. 1: *Example of multi-axes time observable plot for one of the proposed model variants*

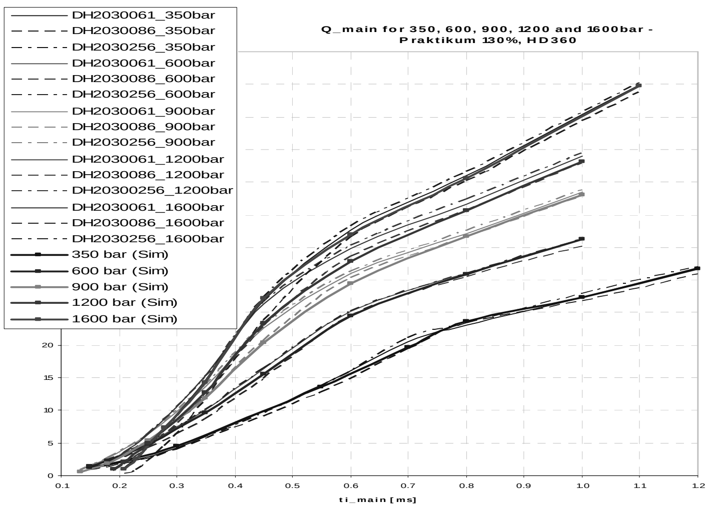

Fig. 2: *Quantity map for final simulation model*

The most complicated process was nozzle validation. The standard AMESim model of nozzle was inadequate for the smallest needle lift. Finally, according to [9] (experimental research of flow resistance) nozzle seat area was defined as 4-degree polynomial dependence on needle lift instead of using original AMESim model (linear dependence of nozzle seat area). Having the experimental data measured with high pressure test bench equipment and data from simulation saved in PC it was very useful to program automatic plotting of time observables with the help of MATLAB. Time observable plots provide a lot of information about time behavior of a real injector compared with its behavior during the simulation and refer to quality of the simulation. The proposed variant of simulation model, which produced the best results displayed in quantity map for various drive condition, was accepted as a simulation model for MC simulation.

2.2 MONTE CARLO SIMULATION OF INJECTION QUANTITIES

With available AMESim model and known method of sampling the parameters it was necessary to solve a problem of data management and processing to produce new injectors with various parameter combinations automatically without manual calculation and changing parameters in AMESim. Several MATLAB scripts and functions were programmed to realize MC simulation especially to get results of all simulations in one Excel file. There were three important points to be considered:

- influence of parameter combinations could be different for various drive conditions (experimentally measured and called as The Test Points (TP) or often named as The Customer Points (CP) – altogether five drive conditions);
- if there is any correlation between two or more parameters;
- how many simulations have to be performed to get infallible results of simulated injection quantities for determination of production tolerances.

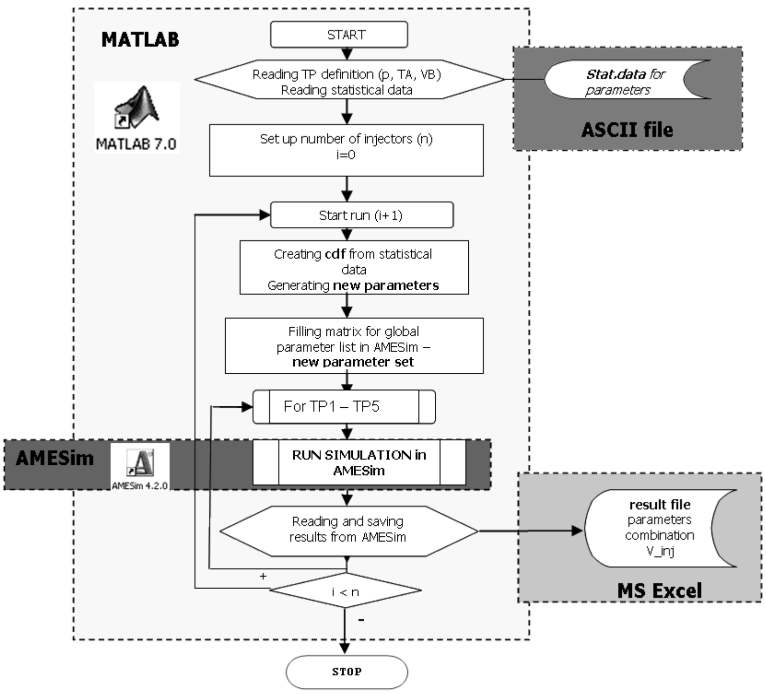

Fig. 3: *Flow chart of MC simulation of new injectors*

Problem of various drive conditions (defined by system pressure, opening control time, boost voltage and desired injection quantity) was solved by using MATLAB classes and loops for each of TP. Only one set of parameters was generated for all Test Points - see the flow chart in Fig.3. According to research and experience of quality management and other experts, no correlation among the parameters should have been considered. All the parameters were therefore sampled independently from one another.

In order to obtain the necessary conclusive number of single simulations, several numbers of simulations were proceeded (N = 200, 400, 600, 800, 1000) for some parameters. Standard deviation of injection quantities was observed in dependence on total number of single simulations. The stationary state pertained to the determined minimum number of MC simulations (N = 400). To calculate the time needed to simulate 400 new injectors we should consider the fact that simulation of one inner loop lasts approx. 45 s. For all drive conditions the whole simulation consumed about 90 000:3600=25 hrs – see Equation (1):

$$t_{total}\left[s\right] = Number\ of\ \ TP \times duration\ of\ \ one\ loop \times N = 5 \cdot 45 \cdot 400 = 90\,000 \qquad \textbf{(1)}$$

2.3 STATISTICAL ANALYSIS OF RESULTS FROM SIMULATION

Data saved in the Excel file were evaluated by the STATGRAPHICS statistical software that was programmed to describe one-variable analysis (statistical information about injection quantity distribution as dependent value such as mean value, standard deviation, variance, range, std. kurtosis and skewness) and calculate multiple linear regression analysis directly from Excel data. Effect of each parameter variation was calculated in multiple regression analysis with further ANOVA analysis as it is interpreted by relation of variances (squares of standard deviations) in fig. 4:

$$S^2_{V\_inj} = \underbrace{S^2_{p1}}_{\text{influence of the parameter 1}} + S^2_{p2} + \ldots + \underbrace{S^2_{pn}}_{\text{influence of the parameter n}}$$

Fig. 4: *Equation of sum of squares from ANOVA analysis*

The last step of the project was to simulate only parameters with high effect of variation of their tolerances. Insignificant parameters and parameters with very small effect were eliminated from the MC simulation. This time parameters were sampled within 75 % and 50 % of the original tolerances range and standard deviation was observed compared within 100 % distribution of tolerances. Results were again evaluated in an Excel file and plots obtained from data offered us information about possible tolerances modification.

3 CONCLUSION

The products of this project were methodology describing how to simulate tolerances of a diesel common Rail injector, the validated model of injector (although the nozzle sub-model has a small handicap in unrealistic definition of nozzle seat area caused by wrong pressure distribution in nozzle section), and MATLAB pre- and post-processing programs for large scope of applications. This approach could bring costs saving in case of larger tolerances range, quality increasing in case of smaller tolerances range in production. It could bring advantage of costs and time saving in the injector development process.

4 ACKNOWLEDGEMENT

The impulse for a simulation of manufacturing tolerances came originally from quality management of SIEMENS VDO Automotive Regensburg, Germany, as a consequence of question how to take advantage from simulation of solving the problem of optimal tolerances as a Monte Carlo study. This became a task of my diploma thesis. It would be impossible to manage all tasks without my prior experience as a member of the simulation team in SIEMENS VDO and without cooperation with teams of experts on simulation, measurement, AMESim and other fields of science. I would like to express acknowledgement for support to my tutor Dr. Dirk Baranowski – head of simulation team, Dipl.-Ing. Roberto Mo from quality management, Alain Saintsorny – expert on AMESim software and to people from the injector design department, laboratory team and experts of FEM computing as well as all people who provided me with necessary information. I am grateful to Prof. Stanislav Hosnedl and Doc. Jaroslav Krátký from the University of West Bohemia for giving me a chance to study in Regensburg and gain lots of experience, to take part of the development process of a high-tech component in an international company (such as SIEMENS is) for almost two years.

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