Early Stage Design of Internal Combustion Engine Cranktrain

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Summary

Stávající příspěvek si klade za cíl nastínit možný pracovní přístup k procesu navrhování klikového mechanismu spalovacího motoru. Soustavu mechanismu je potřeba navrhnout a optimalizovat z hlediska širokého spektra požadavků. Zvolený přístup kombinuje trojrozměrné parametrické CAD modely jednotlivých komponent, kinematické a dynamické vlastnosti mechanismu, jakož i problematiku tření a pevnostních výpočtů. Pro účely návrhu se využívá softwarový systém DASY, který umožňuje propojit jednotlivé výpočetní systémy a řídit a automatizovat jednotlivé procesy.

Keywords

Cranktrain design and analysis, component design and optimization, structural analysis, DASY, GT SUITE, GT Crank.

1. Introduction

Nowadays the internal combustion engines (ICE) are at a very high technical level. During the development process the newest findings from a very wide range of scientific fields are applied. However, the particular requirements and demands are getting stricter and new problems and barriers are arising. Because of that it is necessary new and optimal solutions to be found.

Some of the main current trends in the engine development are downsizing (reducing engine displacement), downspeeding (reducing engine speed), using of different systems of fuel injection, turbocharging or advanced modes of combustion, etc. Each trend requires a different design approach.

For example, the advantages of reducing the engine displacement (downsizing) are:

- increasing of engine brake efficiency because of the reduction of mechanical and thermal losses
- increasing of mechanical efficiency by reducing the friction and number of cylinders.
- improving of fuel consumption because of the engine operation in high load mode.

Turbocharging systems contribute to increase the power of the engine and together with improvement of fuel consumption. In a result, these engines are smaller and lighter, but they operate under higher peak pressures. So the dimensions of the components become smaller and at the same time combustion pressure becomes higher. In a result, the final load of the components is higher than the one in the conventional engine design. Thus, it is important for each mechanical engineer to pay attention to the design of the whole cranktrain of these highly loaded small engines as well to the design on each component. So the design approach should be adapted to this fact and it should consider the design, analyses and optimization at the same time.

2. Parametrization

Nowadays in the field of mechanical engineering it is necessary to have different flexible and powerful tools which allow shortening the time and reducing the cost for research, design, etc. Virtual design and simulation methods are at a high technical level.

In automotive industry a lot of different types of software programmes like advanced CAD systems (computer-aided design) are used. These systems allow creating of the geometrical definition of the products based on three-dimensional virtual geometrical models. These models contain all individual components, assemblies and subassemblies. CAD systems allow using of different kinds of modelling or designing techniques, e.g. parametric modelling or design.

Creating of parametric CAD models of components and connecting of geometrical elements improve geometrical representation of the product, also adding control functions and additional information important for building of the real models and prototypes or even for verifying calculations and advanced analyses. Therefore, it is possible to separate the geometry from the parameters which defines it, and to use them subsequently in complex design or calculation methods combining different design processes and also automation of the processes. For example, it is possible the design process to be combined with the process of verification and testing simulation in CAD systems.

A three-dimensional parametric CAD model of a connecting rod is shown in figure 1. This model was created in PTC Creo Parametric CAD system. In the model a system of parameters is created and the parameters are assigned to the corresponding dimensions.

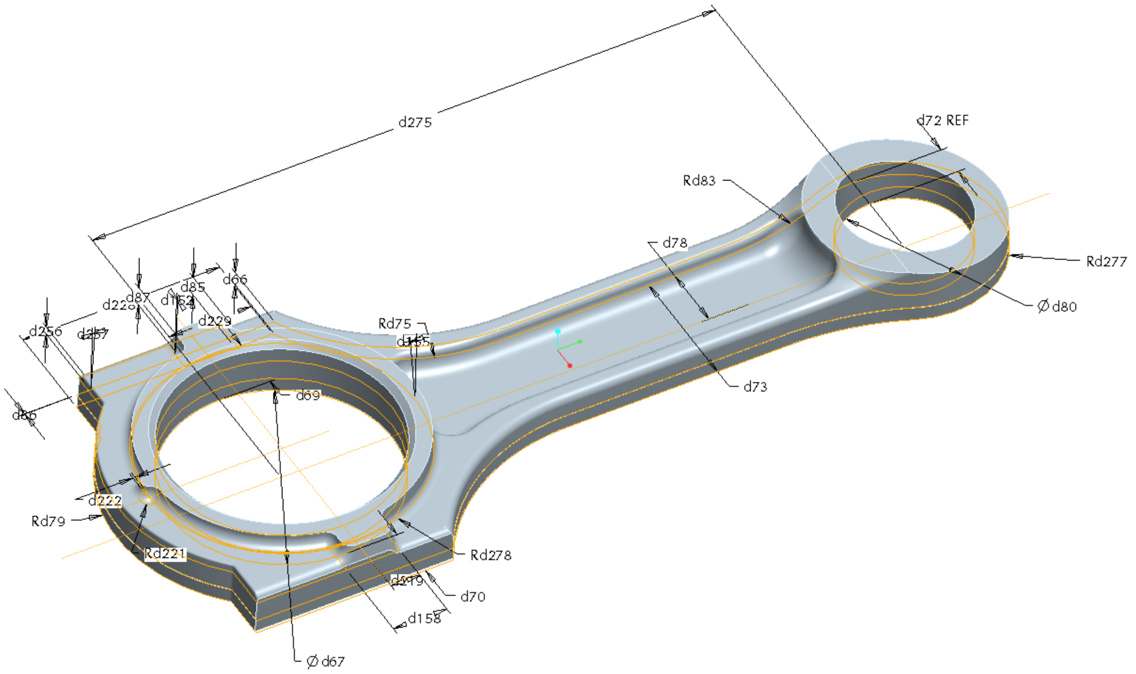

Fig. 1. *A 3D CAD model of a connecting rod with the parameters (dimensions)*

3. System DASY

Design Assistance System (DASY) is a software tool. It is under the development at the Department of Automotive, Combustion Engine and Railway Engineering which is a part of Faculty of Mechanical Engineering of Czech Technical University in Prague. The main idea of the DASY project is to have a reliable and flexible tool that helps and assists the mechanical engineers during the whole design process, a tool that minimizes the required time for solving and analysing the technical problems. As a result, system DASY allows the mechanical engineers to solve design tasks by using of a system of parameters. It allows the mechanical engineers to design by using or combining any external simulation or computer-aided systems and to create different design models or solving methods.

DASY also allows the creation of knowledge database to store findings from design process. A model created in DASY is built by different types of blocks that represent e.g. CAD models of each component or assembly of components, mathematical equations and relations or interaction with external software systems. These blocks work with systems of parameters which could be known or unknown as well input or output ones. The blocks are also connected with each other by connecting lines through the related parameters. Inside DASY these connections are presented by a system of nonlinear algebraic equations. There are also available some plugins for external software like CAD systems DS CATIA and PTC Creo (formerly Pro/Engineer) or MS Excel. In DASY system there is also implemented evolutionary algorithm for a multi-objective optimization process and a response surface method.

For our design task – an early stage design of a cranktrain mechanical engineers need to have parametric CAD models of each component which are done in a chosen CAD system. Parameters are a very important part of each CAD model. They allow DASY system to work with CAD models (through the CAD model block) – to change dimensions and geometry, to read the mass properties, etc. Parameters from CAD models can be divided into known and unknown, input and output. Then they can be easily included into required relations in a DASY model. In a result, DASY can manipulate with parameters, change them and thus adapt the components according to the requirements.

The interface of DASY with the ready simulation model is shown in figure 2. The DASY model contains CAD blocks (for each component of the cranktrain) which operate with corresponding three-dimensional CAD models directly through a plug-in. Input/Output block communicates with external simulation system e.g. GT-SUITE, Abaqus through the different kinds of input files (text files) for these systems and batch files for starting the simulation in each step.

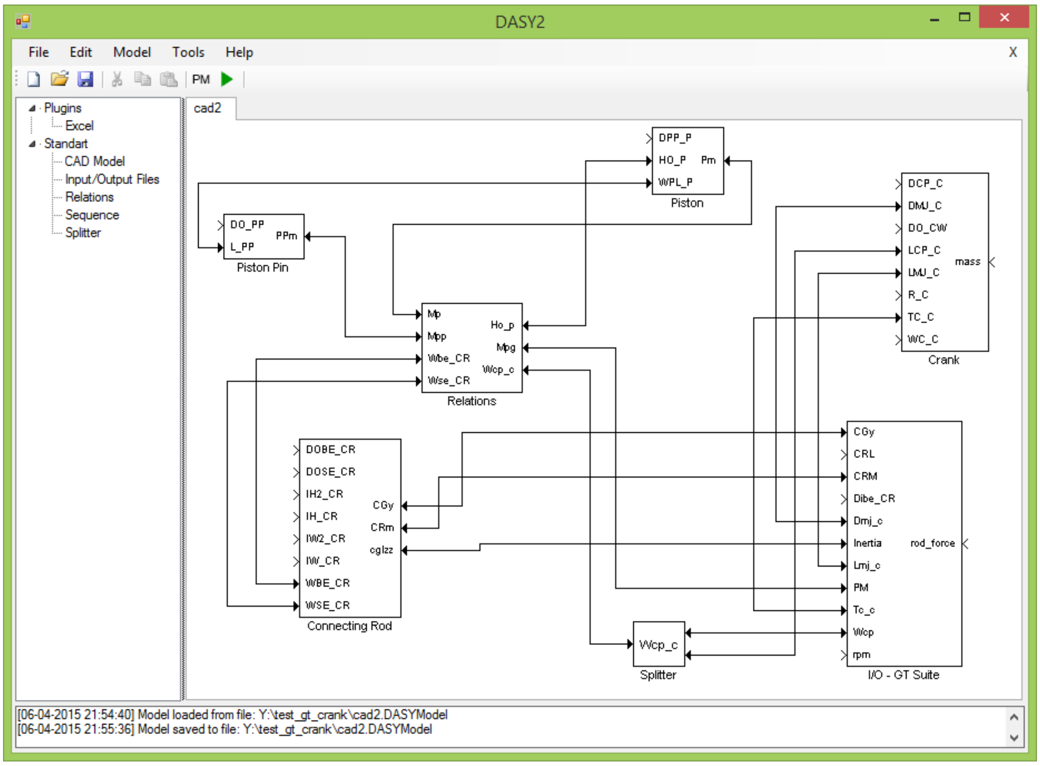

Fig. 2. *A simulation model in DASY*

4. Research design study – cranktrain design

The aim of the current design study is to research the creating possibility and using of a complex virtual model of a cranktrain mechanism of an internal combustion engine applying and combining the available simulation (software) tools. The final model will make easier the process of initial proposal, design, optimization and verification of the cranktrain during the phase of development of the engine. For using of this model it is required to know the basic requirements and parameters of the developing engine, the results from different analyses and simulations, e.g. thermodynamic analysis of the cycle or progress of cylinder pressure. It is suitable to combine three-dimensional CAD models, different relations for proposal and verification of each component (e.g. empirical relation from technical literature), optimization and so on.

The current research design study is in an early stage of experiments and therefore a basic possible workflow is sketched with example of using the particular software. It does not aim to present a real output solution of a cranktrain design applicable in the practice.

For creation of the virtual cranktrain model it is required to choose one of the common available CAD products for creating of a three-dimensional model of each component – e.g. PTC Creo or DS Catia. These programs allow creation of three-dimensional geometry and its parametrization – assigning of the parameters to the component dimensions. Using of these parameters make possible to control geometrical models, change them and adapt according to the necessity or according to the requirements.

The model of the cranktrain should be completed so it should include all components – piston, gudgeon (wrist, piston) pin, connecting rod, bearings and crank. The mechanical engineers have to take into consideration all characteristic features and attributes of the components, properly to choose basic dimensions and proportions, determine critical places and critical moments during the design (e.g. to prevent possible component collision, etc.). It is important to have available as many as possible detailed information about the designed engine, fundamental kinematic and dynamic analysis, cylinder pressure (e.g. for the start point) and also about the chosen operating mode of the engine.

Two different approaches for creation of the models can be considered. The first approach supposes creation of separate three-dimensional CAD models of each component and subsequently their connection by separate CAD model blocks (e.g. with direct connections or by mathematical relations) in DASY system. For making relations it is important to determine and define correctly the known and unknown parameters.

The second approach supposes creation of a complete cranktrain assembly directly in the chosen CAD system and after that all parameters to be connected by internal CAD parameter system. The result will be only one CAD model block in DASY system.

For first steps a simplified model of cranktrain components is used. Its components contain main dimensions. The aim is the effectivity of each process in the chosen workflow to be tested and checked.

A considered workflow is described next. The geometry of each component is created in a chosen CAD system by all standard operations. According to the chosen approach a system of parameters is prepared including the known and unknown values. Simulation models of the cranktrain are built in specialized software (e.g. GT-SUITE, Abaqus, etc.). Then DASY model is created combining all CAD models and simulation ones with defining the known and unknown parameters and connecting them.

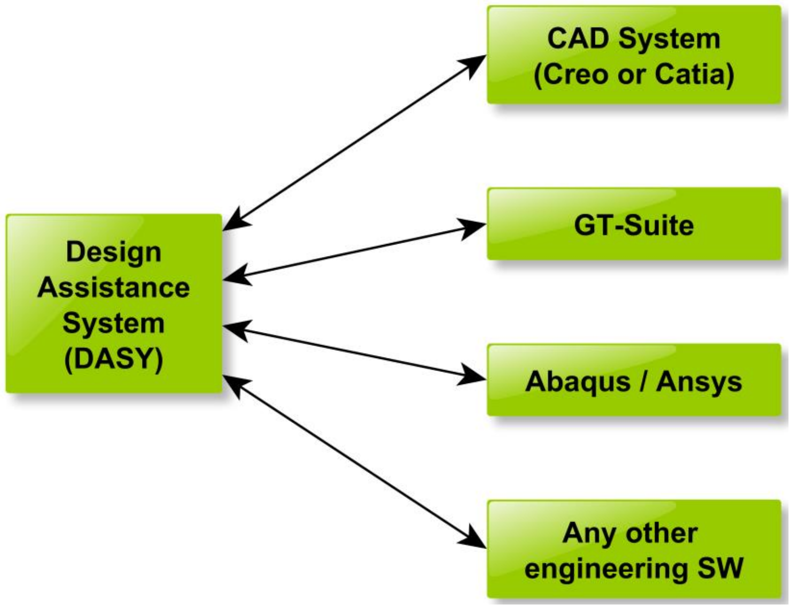

Fig. 3. *Design Assistance System (DASY) and connections with different types of software*

4.1 Cranktrain simulation model

GT-SUITE is a leading software simulation system for automotive industry. It offers a lot of functionalities for ICE simulation - for our task it is possible to use capabilities for cranktrain modelling and simulating. For this early stage it is suitable a simple model of the cranktrain to be used. This could be a simple one-cylinder model or more complex one-cylinder model with predictive modelling of friction (this model considers realistic component joints (e.g. bearings, piston rings – cylinder, etc.), connections are physically-based – with oil films and asperity contacts. With these models it is possible to analyse kinematic and dynamic properties of the cranktrain (positions, velocities, acceleration, forces and so on). The second model is extended with analyses of the engine bearings, piston rings, the all connections of the components, tribology analyses.

DASY can import the values of the parameters for current step into the GT-SUITE model (which is a text) trough Input/Output, start the solver with a batch file and import back the value of the parameter which we are interested in. Both models contains main engine specification (like cylinder bore, piston stroke), main component dimensions, etc. As an output from simulation it is possible to obtain progresses of many different physical quantities as well the peak values of them (e.g. maximal values of speed and acceleration or force load in different points of the cranktrain).

A simple simulation model of the cranktrain in GT-SUITE is shown in figure 4. It is a simple one-cylinder engine model. It contains all necessary information (dimensions, physical properties, etc.) to describe the cranktrain. It is possible to create parameters and assign them to the corresponding items. These parameters allow the simulation model of the cranktrain to be connected with DASY.

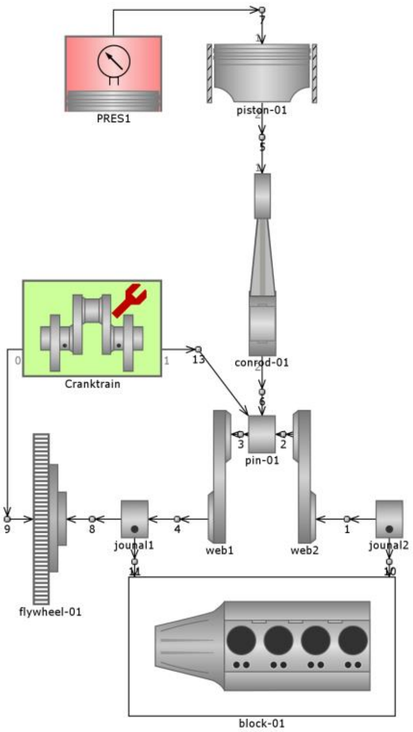

Fig. 4. *A simple simulation model in GT – SUITE*

4.2 Mechanical engineering simulation

Another important part of the design process are realistic mechanical engineering simulations of the cranktrain system as well the each separate component – different types of structural analyses, dynamics analyses, failure analyses, multi-body simulations. All these kind of simulations can be added in the discussed design workflow. As an example, a structural analyses of the connecting rod using finite element simulations system (e.g. in Abaqus system) could be shown.

The DASY system operates with input files of this external system by an Input/Output block. These files are also very often just text files, so the access to them is very easy to they can be modified. The Input/Output block also runs a simulation of the models through a simple batch file which calls the appropriate solver. Abaqus System uses input scripts written in Python programming language. This script describes parametrically the geometry of the component in the simulation model, material properties, loads, boundary conditions, mesh settings and so on. So during the optimization process, in each step DASY imports chosen parameters directly into the Abaqus script, and then, using the batch file starts computation of the FEM model. In a result, we obtain mechanical response (deformation, stress etc.) of many different variants the connecting rod or response of one connecting variant to the variable loading force - in each step for the newly chosen parameters.

For this early stage estimation of the mechanical response of the components it is better to use a FEM simulation model with simplified geometry. This will reduce rapidly the needed amount of time due to faster running of computational steps. After the acquiring of the mechanical response it is possible the chosen parameters to be verified by transferring them to a simulation model that contains the original geometry of the component. A simplified model of a connecting rod is shown in figure 5. This model presents only 1/4 of the whole connecting rod. It allows symmetric boundary conditions to be used.

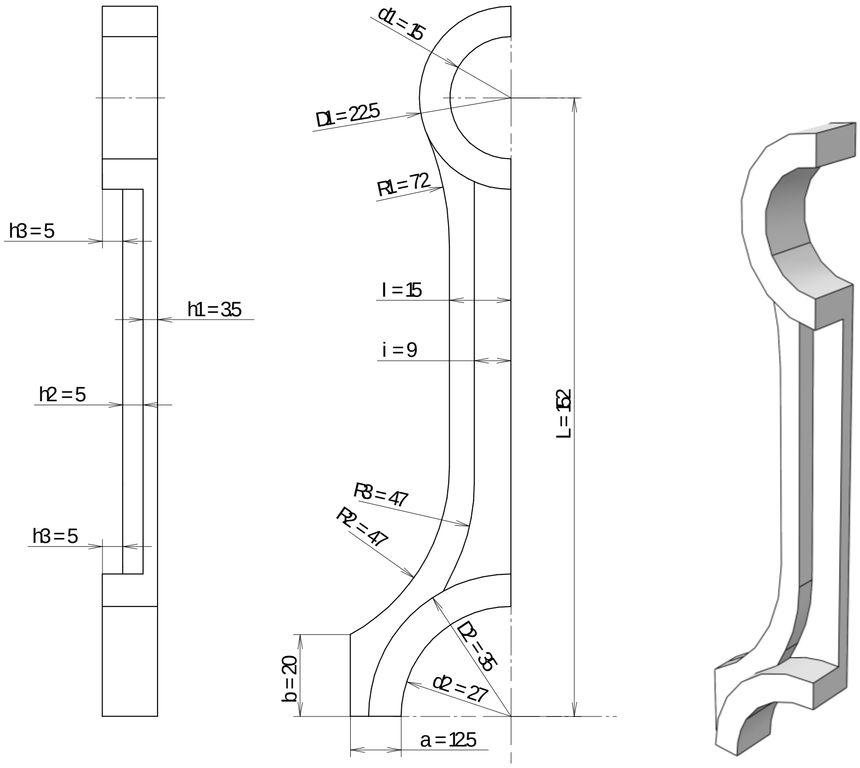

Fig. 5. *A simplified model of the connecting rod with parameters for simulation in Abaqus system.*

A structural response to the loading force for three different design variants of the connecting rod according to the chosen design point from the Pareto set is shown in figure 6. These variants have e.g. different values of masses and different values of maximal stress that appears in the structure.

4.3 Results - the output from the design process

After the preliminary optimization process is finished, DASY presents the optimization results in a form of a Pareto set or Pareto frontier. It presents a trade-off graph of all potentially optimal (best) solutions, according to the objectives (optimization goals) and constraints of the optimization. Each solution is presented by a point. Each point contains all parameters (variables) chosen for the optimization process. In a result, a mechanical engineer can choose a suitable solution (a combination of parameter values) according to the requirements and his own consideration and he can adapt the component design for further research.

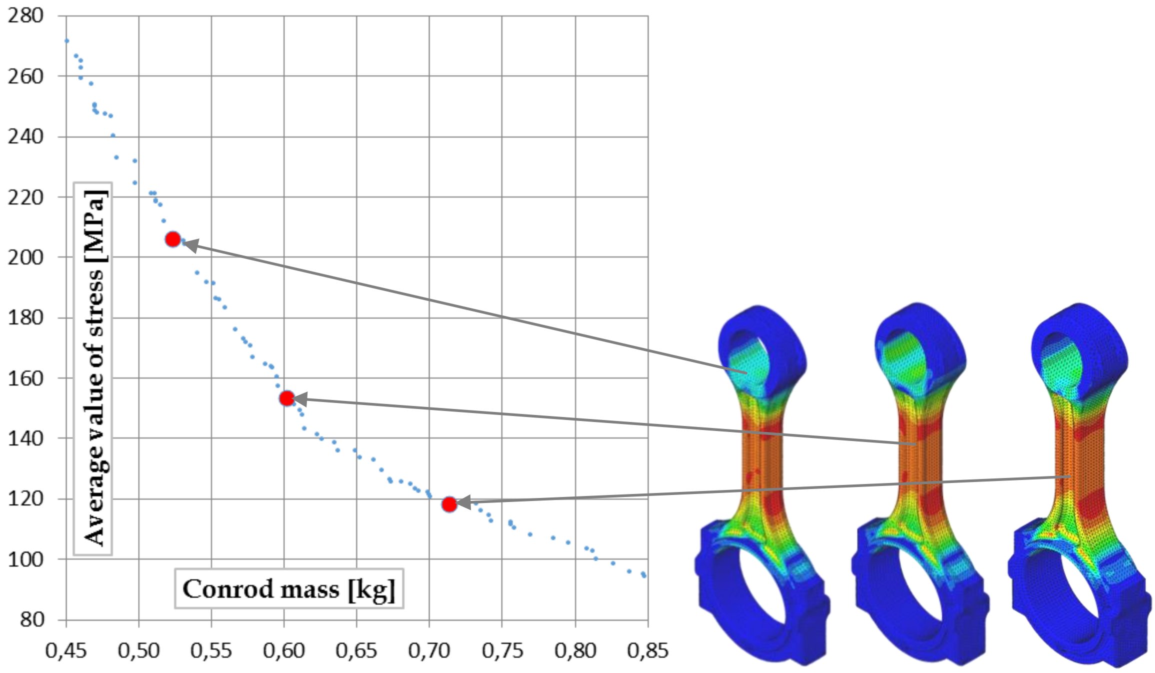

Fig. 6. *The output from the design optimization process - Pareto set and different connecting rod design according to the selected design-point.*

5. Conclusion

The discussed topic is very extensive. The main goal of this article is to present a possible workflow or method for early stage design of the cranktrain of an internal combustion engine and to prepare an experimental field for further research. The main idea of the design process is based on using of a system of parameters, which presents the cranktrain system as well each separate component.

This fact allows combining different designing and simulation processes by using of different software tools at the same time – to design and optimize the system from several aspects according to the demanded technical requirements. All of this is ensured by DASY - Design Assistance System - a powerful and flexible software tool, which allows obtaining a suitable and optimal solution of the engineering design task in an appropriate period of time.

List of symbols and abbreviations

DASY	Design assistance system
FEM	Finite element method

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