DESIGN ASSISTANCE SYSTEM APPLICATIONS FOR SIMULATION OF IC ENGINE DYNAMICS

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SHRNUTÍ

Design Assistance System (DASY)^[1] umožňuje použít přístup, kdy konstruktér/výpočtář potřebuje propojit všechny aspekty návrhu pro dosažení optimálního řešení. Tento článek je zaměřen na prezentaci vybraných výpočetních metod a jejich integrace do DASY. Metody kombinují CAD konstrukční návrhy součástí spalovacího motoru s modely pro výpočet dynamiky klikového a rozvodového mechanismu. Výpočetní modely jsou řešeny v komerčním softwaru nebo přímo v DASY. Koncept pro navrhování zdvihové křivky ventilů je představen jako zástupce metod, které mohou být řešeny přímo v DASY pomocí Gauss-Newtonovy iterační metody. Vyvinuté koncepty mohou být dále začleněny do modelu celého motoru nebo vozidla díky blokové struktuře DASY.

KLÍČOVÁ SLOVA: DASY, DESIGN ASSISTANCE SYSTEM, KLIKOVÝ MECHANISMUS, ROZVODOVÝ MECHANISMUS, ZDVIH VENTILU

ABSTRACT

A Design Assistance System (DASY)^[1] offers methods that can be applied in the situation where a designer needs to interconnect all aspects of a design to achieve an optimized solution. This article is focused on the presentation of selected computational methods and their integration into DASY. The methods combine a CAD design of combustion engine components with the computation of crank train and valve train dynamics. The computational models are solved using commercial software or directly in DASY using a built-in solver. A concept for the designing of a valve lift curve is introduced as an example of methods that can be solved directly in DASY using the Gauss-Newton solver. The developed concepts can be further incorporated into a model of a whole engine or vehicle thanks to the block structure of DASY.

KEYWORDS: DASY, DESIGN ASSISTANCE SYSTEM, CRANK TRAIN, VALVE TRAIN, VALVE LIFT

1. INTRODUCTION

EU targets for the period after 2020 are aimed, among other things, at an 80% energy consumption reduction for passenger urban transport. There is no easy way at the vehicle design level to resolve such an ambitious demand. The combination of existing knowledge and new solutions based on a holistic approach to vehicle design is the only possible way. The design process consumes a large amount of computational power and human resources. It would clearly be helpful to have tools that can assist in the design process, decrease the required effort and reduce time to market.

The Design Assistance System (DASY) is being developed as a tool for use in designing new vehicles or their parts with the

capability of incorporating knowledge gathered over time into comprehensive models covering all areas of vehicle design. The newly developed methods included in the vehicle design process can be executed using built-in solvers in the DASY. Using a holistic approach increases the size of a task that often has conflicting objectives. It is therefore necessary to select a compromise solution which is the result of optimization. Integrated software in DASY using a genetic algorithm is an appropriate tool for solving optimization problems.

The GT SUITE software package is currently a comprehensive tool for the simulation of internal combustion engines, transmissions and vehicle dynamics. This tool was chosen for solving crank

train and valve train dynamics. Input parameters for calculation are obtained from CAD models of the mechanisms via the built-in DASY plugin. This plugin also allows the modification of CAD models based on the results of calculations. This feedback automates the design process of the mechanism parts.

The DASY method for valve lift curve design is based on the valve acceleration proposal, which is designed to respect zero conditions of lift, velocity and acceleration at the beginning and end of the valve displacement while allowing the user to specify some parameters, in particular the maximum valve lift, and both minimum and maximum valve acceleration.

2. DESIGN ASSISTANCE SYSTEM

The Design Assistance System features a descriptive model definition, numerical solvers and optimization algorithms. Any model in DASY is described with available knowledge, and the definition of input and output parameters is separated from the model definition. This allows swapping of input and output parameters. It solves both direct and reverse design tasks.

A model in DASY2 is represented by a set of blocks linked by connections. Each block contains a set of equations that define its sub-model. A sandbox approach is used for each block, which means that parameters used in the equations of a block are accessible by this block only. A connection is used to connect the parameter of one block with the parameter of a second block. A connection provides a bridge between two separate block sandboxes. Connected parameter values are assumed to be equal. This approach allows implementation of any model with blocks, representing sub-models, and connections that will connect the output state parameters of one block (sub-model) to the input state parameters of another block (sub-model). With such a descriptive definition any knowledge about the model can be used without the strict separation of input and output parameters.

A DASY model structure consisting of blocks and connections allows almost effortless structural changes. However, under the cover it is a system of non-linear algebraic equations collected from all blocks with respect to the connections. Before solving this system some simplifications can be made, such as merging parameters that are connected, substituting known parameters with numbers, and performing algebraic operations on numbers. Substitution of known parameters is recurrent and goes through following steps:

1. Substitute all parameters that are defined as known with numbers.
2. Perform computations of algebraic operations and functions on numbers, where possible.
3. Analyze the system of equations to find parameters that became known after simplifications in steps 1 and 2.

4. If new parameters were defined as known in step 3 – go to step 1. If no new parameters were defined as known in step 3 – simplification complete.

If, after all possible preliminary simplifications, some equations remain unsolved, a numerical solver should be used to solve this system. Two numerical solvers are incorporated in DASY2:

- Gradient descent solver with variable step,
- Gauss-Newton solver with variable step.

Usually the modified Gauss-Newton solver is preferred, because it is one of the most robust gradient-based methods.

Integration with CAD is achieved using special CAD system plugins. So far plugins interacting with CATIA and Pro/Engineer have been developed. A plugin is a communication interface between DASY and the corresponding CAD system. It allows generalization of interaction with CAD and provides one convenient interface to interact with all supported CAD systems. Using this approach it is possible to read and write parameters from/to a CAD model. It is also possible to read all available inertia properties. If some parameters or inertia properties are read from a CAD model, then this model will be involved in the solution process described in previous section. If parameters are only written to a CAD model – it will be updated after computation is complete.

A CAD model in DASY is represented as a CAD block, which can be connected to other blocks using regular connections. This ensures that CAD models are always updated with the latest parameter values and allows us to use all available data from CAD models in computation and/or optimization.

3. MODELS OF ENGINE DYNAMICS IN DASY

3.1 CRANK TRAIN MODEL

The crank train model shown in Figure 1 is typically used to determine the load of the crank train parts. Calculations are performed to check the bearing and crankcase load. Using this model the calculation of mechanical efficiency and loading conditions for FEM analysis can be performed. The model consists of rigid bodies without friction. The model's input parameters are geometric dimensions, centers of gravity, masses and moments of inertia. These parameters are loaded into DASY directly from the Pro/E models in which they are modeled using the built-in plugin. In the DASY model the parts are presented as blocks (CAD Crank, Piston CAD, CAD Con. Rod) for which the model parameters can be set thus changing its dimensions, or they can just be read as an input for the solver. The numerical values of the parameters are recalculated to appropriate units in DASY block Conv1. The parameters are connected with the Input/

FIGURE 1: Crank train DASY model.

OBRÁZEK 1: Model klikového mechanismu v DASY.

Output block, where the parameters are written in the input file for the GT-SUITE solver. GT-SUITE solver involves a 5th-order explicit Runge-Kutta integration scheme for solving the system of differential equations. Changes in the model parameters in the DASY blocks are carried in both directions along the connections between blocks. Based on the results read from the GT-SUITE output file, the design of the crank mechanism parts in Pro/E models can easily be changed via connections to their input parameters thus closing a loop in the design process.

Detailed CAD models of the mechanism parts are not necessary in the conceptual design phase of a new engine. Using simplified parameterized models that were created by changing the parameters of conceptually similar engines accelerates the acquisition of input data for further calculations.

A crank train mechanism model is typically used to determine the loading of its parts, which are then analyzed by FEM. A connecting rod is loaded in both compression near TDC of the expansion stroke and tension at TDC during the cylinder charge exchange. The FEM model also takes into account the effects of the connecting rod angular acceleration, angular velocity and linear accelerations. Solving the dynamics of a rigid mechanism in GT Crank provides these values for the FEM calculation.

Some results from the crank train model are important for the design of other engine parts. Calculation of the connecting rod big end rotation around the axis of the crankshaft provides

a design parameter for both width and height of the engine crankcase. The connecting rod angle affects the depth of liner embedment into the engine crankcase. These outcomes are important as they enable clashes to be eliminated whilst still in the conceptual engine design phase, and they can be linked in DASY with the relevant input design parameters of the engine, usually with the dimensions of the crankcase and the cylinder block of the engine.

3.2 VALVE TRAIN MODEL

The valve train model, shown in Figure 2, is usually used to determine dynamic behavior of the valve train components. The GT-SUITE model includes these flexible parts: a rocker arm, a camshaft, a different-pitch cylindrical valve spring and a valve. The "Contact2D" part[3] is used to model 2-dimensional contact between the rocker arm, the cam, the valve and a rocker arm pivot. Contact geometry information must be specified for each part. Curves of arbitrary shape, arcs or lines can be specified as the contact geometry on each connected part. There is an option for contact stiffness and damping definition based on a contact tribology model. Either just a Hertz analysis or a full Hertz/EHD analysis can be performed. The output of this analysis comprises a number of useful tribological quantities such as oil film thickness, Hertz stress and deformation. Hydrodynamic and boundary contact friction forces/power loss are also calculated. A RevoluteJoint object models a roller movement. This object

FIGURE 2: Valve train DASY model.
OBRAZÉK 2: Model rozvodového mechanismu v DASY.

enforces zero relative displacements between the connected bodies at the connecting points. It calculates friction torque and friction power loss based on the combined effects of dry and viscous friction. Constraint forces between the two connected bodies are also calculated. A Helical Spring object models the valve spring; its attributes are spring geometry data, mass and initial stiffness. The spring model uses detailed coil geometry (local coil height) data to extract inter-coil (clash) distances used for modeling coil clash and loss of active coils. Number of masses per coil determines the number of degrees of freedom to be used in the spring model. One mass per coil is used in the model as it is a compromise between physical spring representation and simulation time. The valve train model involves the GT-SUITE built-in solver, the implicit integrator Radau 2A (3-stage). The valve train model is mainly used for vibration analysis of the mechanism that causes a deviation from the valve lift curve design. The suitability of component designs, in particular the valve spring, can be verified by this model. The parameters of the spring design can be modified based on the results from model calculations. The used CAD model of the engine[2] is parameterized and it enables changes to be made, for example, to its cylinder head design or other parts adjacent to the valve train via connections in the DASY model. The influence of the

proposed valve lift curve on the dynamic behavior of the valve train can be analyzed. Checking for any collision between the piston and valve in the existing engine structure can easily be achieved by combining both the crank and valve train models in DASY. The default requirement is the camshaft axis distance from crankshaft axis of rotation. This data is available from an existing CAD model of the engine and the clash analysis can be performed for various valve timing data.

4. DASY METHOD FOR VALVE LIFT CURVE DESIGNING

In general, a valve lift proposal has more optional parameters than constraints and therefore the selected calculation method will determine how much demand will be placed on the user experience in terms of setting up the correct values of optional parameters for achieving the desired valve lift. The main motivation for the development of computational methods was to reduce the number of optional parameters to a minimum, ensuring the solvability of systems of equations. The method for designing valve lift curves is based on the proposal of the valve acceleration, then valve velocity and valve stroke is calculated by

Parameter	Meaning
aB	acceleration during valve opening
xAD	angle of section AD
xDE	angle of section DE
vD	velocity during valve opening
xEF	angle of section EF
aF	valve acceleration at point F
kFG	the slope of the line between points FG
kGH	the slope of the line between points GH
aH	maximum valve acceleration
vJ	maximum valve velocity
aL	minimum valve acceleration
xL	angle of half valve stroke
uL	maximum valve lift

FIGURE 3: Layout of the valve acceleration proposal.
OBRÁZEK 3: Schéma návrhu zrychlení ventilu.

TABLE 1: List of optional parameters of the valve acceleration proposal.
TABULKA 1: Seznam volitelných parametrů zrychlení ventilu.

integration of the valve acceleration as a function of camshaft rotation. The valve acceleration proposal is designed with respect to the zero conditions of stroke, velocity and acceleration of the valve at the beginning and at the end of the valve stroke. These conditions are permanent. There are just some conditions applied to the valve acceleration; the other conditions can be applied to the valve velocity or to the valve stroke. The main parameters applied to valve acceleration are its maximum and minimum values. The maximum value of acceleration affects the forces of the valve train and these forces are related to the dimensioning of valve train parts, particularly the rocker arms, push rods, tappets, bearings, etc. The minimum value of the valve acceleration affects the valve spring design.

The valve acceleration proposal, see Figure 3, is divided into 11 sections in which the acceleration varies linearly. Table 1 summarizes the optional parameters which can be chosen by the user. The approach satisfies the fundamental law of cam design that states "The cam-follower functions must be continuous through the first and second derivatives of displacement (i.e. velocity and acceleration) across the entire interval". The result of this law is that the jerk function must be finite across the entire interval[4]. The presented model complies with the cited law. Valve acceleration proposal is described by a linear function in each section. The equations for valve velocity and valve lift are derived by integrating these equations. Values at the end of a section are obtained by applying the boundary conditions.

General equations (1), (2) and (3) are given below:

$$a = a_{prev} + k(x - x_{prev}) \quad (1)$$

$$v = v_{prev} - a_{prev}x_{prev} + \frac{(a_{next} - a_{prev})(x_{prev} - x)^2}{2(x_{next} - x_{prev})} + a_{prev}x \quad (2)$$

$$s = s_{prev} - \frac{6v_{prev}(x_{prev} - x)(x_{next} - x_{prev}) + (x_{prev} - x)(a_{next}(x_{prev} - x) + a_{prev}(-3x_{next} + 2x_{prev} + x))}{6(x_{next} - x_{prev})} \quad (3)$$

These equations are applied to each section together with the constraints shown in Table 1. The DASY model is shown in Figure 4.

The DASY model for calculating the valve stroke consists of three blocks. The first block, "Inputs", contains the input parameters entered by the user according to Table 1. Block "Equations" contains a list of equations describing the task. Block "Acceleration/Angle Outputs" writes the calculated valve acceleration with respect to cam angle into the file read by the Matlab software. The Matlab model is used for integrating valve acceleration and valve velocity to calculate the valve stroke. Resulting SVAJ diagrams are shown in Figure 5.

The DASY model is useful for rapid conceptual valve lift design. The resulting valve lift curve is well suited for thermodynamic calculations in the valve timing optimization. The set of multipliers is used for changing valve lift curve parameters, primarily cam angle and valve lift, in these calculations. This process can generate unrealistic valve lifts in terms of their acceleration. Acceleration of the valve is a critical variable in the design of valve train elements and is therefore limited by the permissible values. The DASY model gives a quick overview of the links between displacement, velocity and acceleration of the valve for users using the valve lift curve primarily for thermodynamic calculations.

5. CONCLUSION

This article introduced concepts for using DASY to calculate the dynamics of the crank and valve trains. In these concepts DASY is used for the two-way linkage of GT-SUITE models with CAD models, for managing independent parameters, and for executing GT-SUITE solvers. The verification of these concepts is an important conclusion. The integration of developed methods into more complex models can be realized based on these concepts. This opens up possibilities for combining thermodynamic and mechanical engine models in the future. The concept for designing of a valve lift curve uses DASY as a solver to provide a solution for a non-linear system of algebraic equations. The DASY solver is sufficiently robust for solving this type of equation and this work will continue by applying this method to the entire valve stroke. This method is useful, for example, in the designing of the valve strokes into engine braking systems. These systems usually require quite high valve strokes with a small cam angle, which results in high valve acceleration. Valve acceleration is therefore the parameter that has to be constrained in the design, and the presented method satisfies this requirement.

FIGURE 4: Block diagram of the DASY method for valve lift curve design.
OBRÁZEK 4: Blokové schéma metody návrhu zdvihové křivky v DASY.

ACKNOWLEDGEMENT

This work was supported by:

- Technological Agency, Czech Republic, programme Centre of Competence, project #TE01020020 Josef Božek Competence Centre for Automotive Industry.
- EU Regional Development Fund in OP R&D for Innovations (OP VaVpl) and Ministry of Education, Czech Republic, project #CZ.1.05/2.1.00/03.0125 Acquisition of Technology for Vehicle Center of Sustainable Mobility.

FIGURE 5: SVAJ diagrams resulting from the DASY model.

OBRÁZEK 5: Výsledné průběhy zdvihu, rychlosti, zrychlení a následné derivate z DASY modelu.

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LIST OF ABBREVIATIONS

IC – Internal Combustion
 DASY - Design Assistance System
 CAD – Computer Aided Design
 GT-SUITE – Gamma Technologies Suite
 EU – European Union
 TDC – Top Dead Center
 SVAJ – Stroke Velocity Acceleration Jerk

SUBSCRIPTS

prev – previous value
 next – next value

SYMBOLS

x – cam angle, independent variable
 a – acceleration
 v – velocity
 s – stroke
 k – slope