VIRTUÁLNY EXPERIMENT PRE URČENIE DYNAMICKÉHO ZAŤAŽENIA A ŽIVOTNOSTI MECHANICKÝCH SÚSTAV

VIRTUAL EXPERIMENT FOR DETERMINATION OF DYNAMIC LOAD AND DURABILITY OF MECHANICAL SYSTEMS

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Abstrakt

Cieľom príspevku je predstaviť metodiku virtuálneho experimentu pre výpočtovo efektívne určenie dynamického zaťaženia a prijateľný odhad životnosti kľukového hriadeľa, ktorý je najzaťaženejším prvkom spaľovacieho motora.

Doterajší prístup pri simuláciách modelu s tuhým blokom motora, v ktorom čiastočnú poddajnosť bloku motora reprezentujú pružné veká hlavných ložísk poskytuje v porovnaní so skutočnosťou len aproximáciu skutočnej interakcie kľukového hriadeľa s poddajným blokom motora.

Z porovnávacích analýz priebehu súčiniteľa bezpečnosti pre kľukový hriadeľ zo simulácie modelu s poddajným blokom motora vyplýva, že zavedenie modelu "dynamicky ekvivalentného bloku motora" s vhodne redukovaným spektrom modálnych vlastností poskytuje po overení reálnym experimentom vítanú alternatívu voči doteraz používaným modelom a je popri zachovaní dôležitých vlastností aj výpočtovo efektívna.

Príspevok je ukážkou nového inžinierskeho prístupu pri analýze životnosti kľukového hriadeľa integráciou nástrojov počítačovej podpory na efektívne utváranie modelov motora (Engine toolkit od MSC.Software) s reprezentáciou poddajných vlastností (modelovanie a vyhodnocovanie v prostredí MSC.Patran), na optimalizovanú analýzu napätosti (MSC.Nastran) a na odhad životnosti (MSC.Fatigue) na základe časovej histórie dynamického zaťaženia (MSC.ADAMS/Engine).

Prínosom modelu "dynamicky ekvivalentného bloku motora" je, že už v začiatočej fáze vývoja spaľovacieho motora, keď ešte nemôže byť k dispozícii detailný konečno-prvkový model bloku motora, umožní virtuálny experiment redukovať počet reálnych prototypov potrebných na overovacie testy.

Kľúčové slová: virtuálny experiment, dynamické analýzy, FE analýzy, odhad životnosti kľukového hriadeľa

Abstract

Aim of our paper is to introduce the computational effective method of virtual experiment and its application for determination of dynamic load and acceptable durability assessment of crankshaft as most loaded component of combustion engine.

Existing approach of simulation with rigid engine block model with some flexibility represented by compliant bearing cups is only approximation compared to the real interaction of crankshaft with a flexible engine block.

From comparative analyses of crankshaft safety factor course yield that the introduction of a "dynamically equivalent engine block" model with proper reduced spectra of modal

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properties could offer after assessment by real experiment a welcome alternative to the hitherto indicated modeling methods, because it maintain the most important dynamic properties and it is computationally efficient providing acceptable accuracy of results.

This paper is a demonstration of new engineering practise for durability assessment of the crankshaft based on integration of computational tools for efficient engine modeling (Engine toolkit developed by MSC.Software) with representation of flexibility (FE pre and postprocessing in the MSC.PATRAN), optimized stress recovery (MSC.NASTRAN for FE analyses), and automated durability design (MSC.FATIGUE for fatigue life estimation) based on time course of dynamic load (multibody dynamic analyses in the MSC.ADAMS/Engine).

The benefit of introduction of a “dynamically equivalent engine block” model yet in the early stage of combustion engine development, when no finite element model for the engine block exists, it is possible to reduce the number of real prototypes devoted for experimental tests.

Keywords: virtual experiment, multibody dynamic analyses, FE analyses, fatigue life estimation of crankshaft.

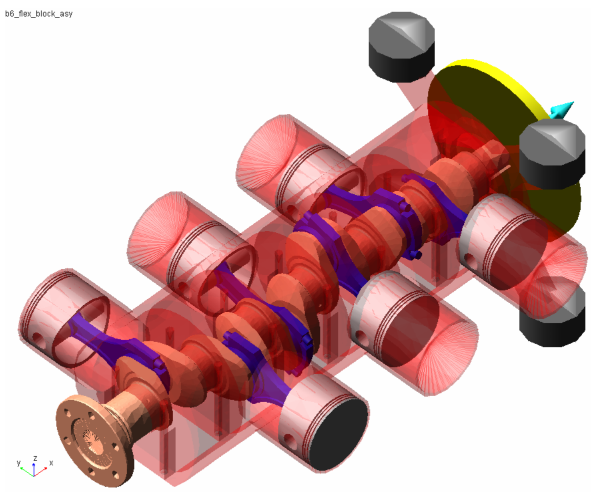

Fig.1 The model of horizontally opposed six-cylinder engine with flexible crankshaft and flexible engine block

INTRODUCTION

The primary objective is to develop a set of engine block models (rigid, flexible, and “dynamically equivalent”) with flexible crankshaft, then compare the results from dynamical and consequent fatigue analyses and confirm that “dynamically equivalent engine block” model will promote high-fidelity and efficient simulation over operating engine speed. For purpose of our research was used the engine toolkit ET developed by MSC.Software for efficient engine modeling (Fig.1), optimized stress recovery and automated durability design based on collaboration of computational tools: MSC.ADAMS (multibody dynamic analyses), MSC.PATRAN (FE preprocessing environment), MSC.NASTRAN (Solver for FE analyses), and MSC.FATIGUE (fatigue life estimation). The engine toolkit ET support MSC.NASTRAN modeling for user-friendly and fast generation of the *.mnf file (modal neutral file) necessary for dynamic analyses in the MSC.ADAMS/Engine, reduce CPU-time and disk space by limiting transient states and output in MSC.ADAMS/Engine for a user-defined range of crankshaft revolutions in rpm and enable instant deformation and stress recovery by MSC.NASTRAN with a minimum of disk space requirements. Within the process chain on Fig.2 the engine toolkit (ET) is reading the bulk data deck *.bdf, generates the nodes and the corresponding RBE3-elements and writes them to the file *.rbe, which is inserted into the *.dat file.

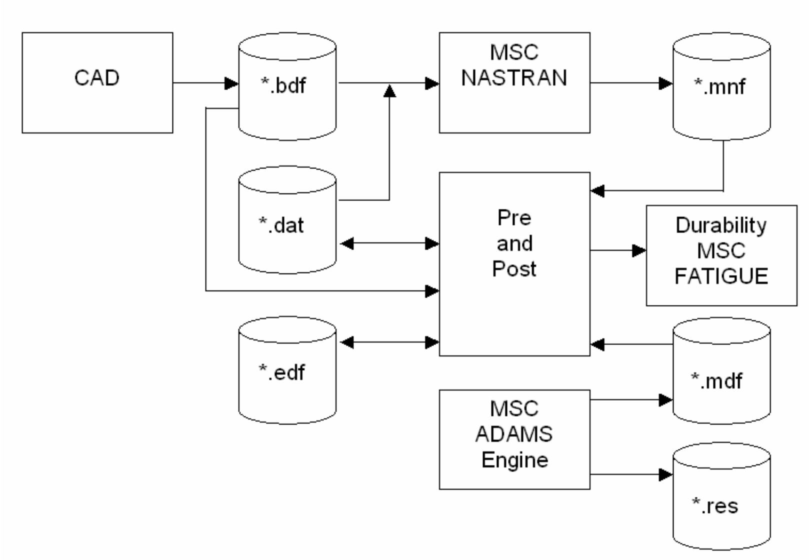

Fig.2 The process chain of computational tools collaboration

The hot spots with critical stresses in crankshafts are usually around the bearing surfaces. The toolkit reads bulk data *.bdf, extracts data from the *.edf file and outputs a number of subregions as MSC.NASTRAN bulk data file containing the elements, grids and properties.

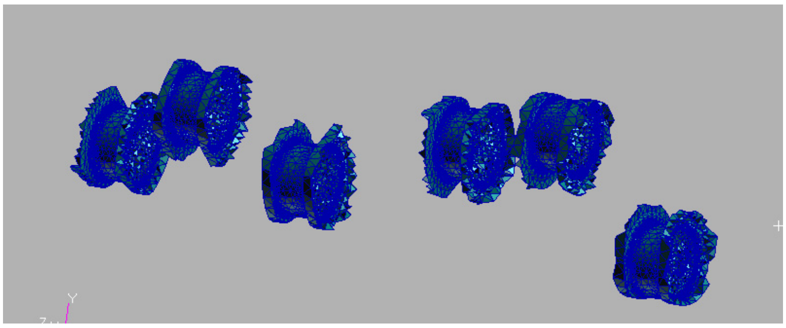

Fig.3 The hot spots for crank pins of the crankshaft.

The *.mtx file contains all orthogonal modes (including the rigid body modes) for all nodes. The toolkit retrieves first the translational components of the orthogonal modes, followed by the rotational components. Successful executions of the *.dat by MSC.NASTRAN will result in the creation of *.op2 files, which are needed later for the durability prediction.

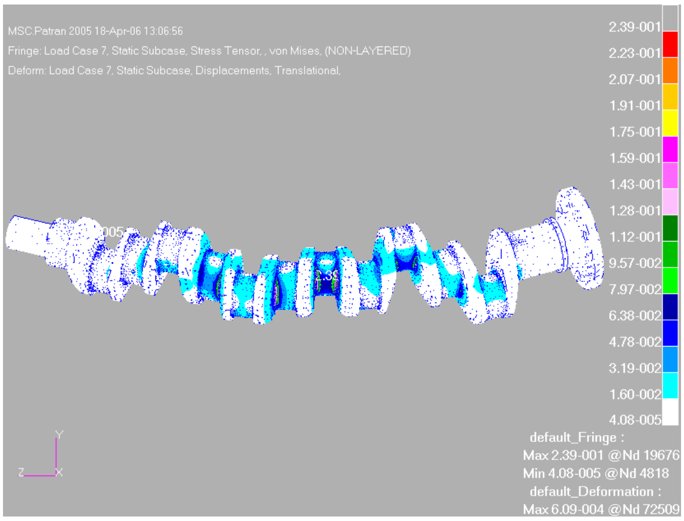

Fig.4 The modal stresses at first normal mode of flexible crankshaft

STRESS CALCULATION OF THE CRANKTRAIN

The flexibility of main bearings is combined with global bending line of the crankshaft in a flexible engine block with appropriate reduced modal content. During dynamic simulations a resonances may occur, so each mode shape should be selectively damped by a value proportional to the frequency. The normal modes are assigned a low material damping, while the constraint modes required a higher damping value due to necessary static corrections.

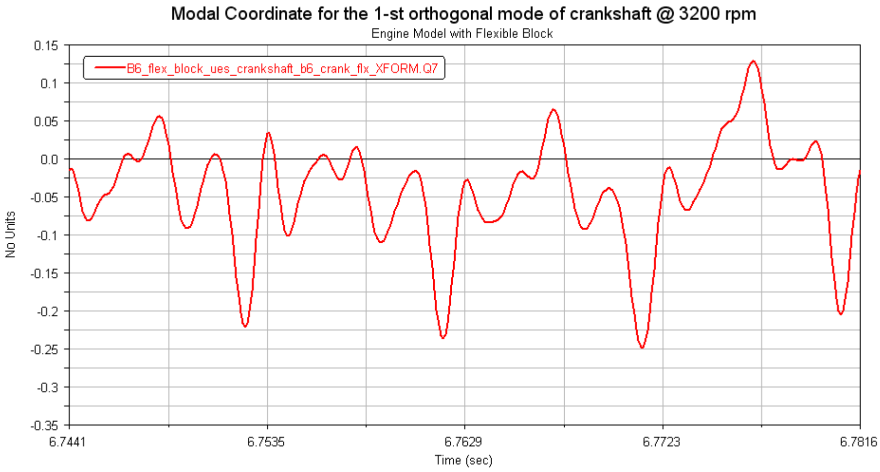

Fig.5 Time history of modal coordinate for the 1-st orthogonal mode of the crankshaft

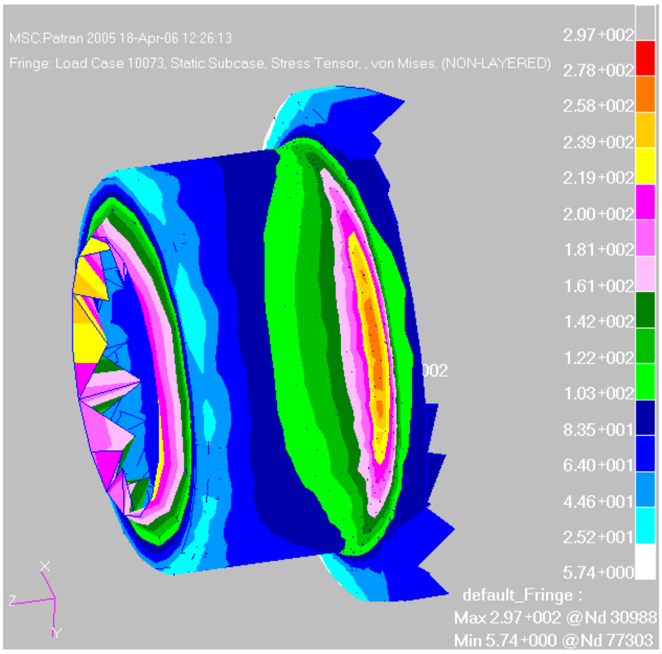

Fig.6 Von Mises stressess from MSC.Patran environment

MODALLY BASED DURABILITY ANALYSIS

The elastic deformation $\{x\}$ of all degrees of freedom is approximated by a linear combination of suitable modes. The so-called 'Component Modes Synthesis' turned out to be a reliable technique in order to determine such a set of modes [1,2]. The modal Craig-Bampton matrix $[\Phi_{CB}]$ containing orthogonalized component modes is used to import the elastic properties of a FE model into the MBS environment. This set of modes contains both, the FE structures static and dynamic properties and is a result of a FE analysis. The system DOFs are partitioned between internal and boundary DOFs, so the flexible body motion equation becomes

$$\{x\} = \left\{\frac{x^B}{x^I}\right\}\begin{bmatrix} [I] & [0] \\ [\Phi^C] & [\Phi^N] \end{bmatrix}\left\{\frac{q^B}{q^I}\right\} = [\Phi_{CB}]\{q\}.$$

Each deformation $\{x\}$ of a FE structure is related by 'modal coordinate' given as $\{q^i\}, i = 1,2,...,n$ to a clearly defined stress distribution. Consequently, each orthogonalized component mode (deformation) $[\Phi^i_{CB}], i = 1,2,,...,n$ corresponds to a clearly assigned stress distribution (modal stress) $\{\sigma^i\}, i = 1,2,...,n$. The concept of the modal stresses is analogous to the orthogonalized component modes. The resulting stress state of a FE structure is computed by a linear combination of modal stresses. The single stress shape's modal coordinate is the same as the modal coordinate of the corresponding component mode and a result of the MBS.

If all displacements $\{x\}$ of the nodes inside a body are known, a vector $\{\varepsilon\}$ containing the strains can be computed using a function matrix $[B]$ of geometry relating strains to deformations as linear operator

$$\{\varepsilon\} = [B]\{x\}.$$

For elastic properties the linear relation between strain $\{\varepsilon\}$ and a vector $\{\sigma\}$ of the resulting stress is given by the matrix $[E]$ of stress and strain relationship based on material elasticity containing Youngs modulus

$$\{\sigma\} = [E](\{\varepsilon\} - \{\varepsilon_0\}) + \{\sigma_0\}$$

where $\{\varepsilon_0\}$ is a vector of intrinsic strain, and $\{\sigma_0\}$ is vector of intrinsic stress. If all intrinsic contributions are zero, then considering a known time-history of the modal coordinate $\{q\}$ the stress distribution $\{\sigma\}$ at each time-step is given by equation

$$\{\sigma\} \cong [E][B][F]\{q\}.$$

REMARKS TO THE ANALYSES

The determination of dynamic load and acceptable durability assessment of crankshaft by integration of different computational tools require the knowledge of theoretical background from various disciplines and practical experience from modeling and management of analyses. For purpose of dynamic analyses is necessary to change default GSTIFF Solver. Optional HHT Solver can provide quick analyses with required accuracy of results if precise setting of integration step (HMAX, HMIN) and suitable adjusted ERROR will force the recovery of Jacobi matrix. Then Jacobian matrix remains stable at small step sizes, which increases the stability and robustness of the corrector at small step sizes.

The dynamical load accuracy is crucial for durability assessment, because the 20% increase of difference in dynamical load cause more than 200% decrease of fatigue life. From point of view of accuracy the method of setting critical damping on the very high frequency modes was also used.

Modal stress shapes in the *.xdb file viewed in MSC.Patran can be efficiently combined with the modal coordinates in the *.dac file from MSC.ADAMS/Durability for subsequent fatigue evaluations in MSC.Patran and MSC.Fatigue. This is the key in recreating the stress history at each node that will be used for rainflow cycle counting in the fatigue analysis algorithm. For factor of safety (FOS) analysis was used Dang Van criterion of muliaxial, high cycle fatigue analysis. The results on Fig.8 from factor of safety (FOS) analysis stored in the MSC.Patran database after postprocessing shows that equivalent engine block properties are acceptable.

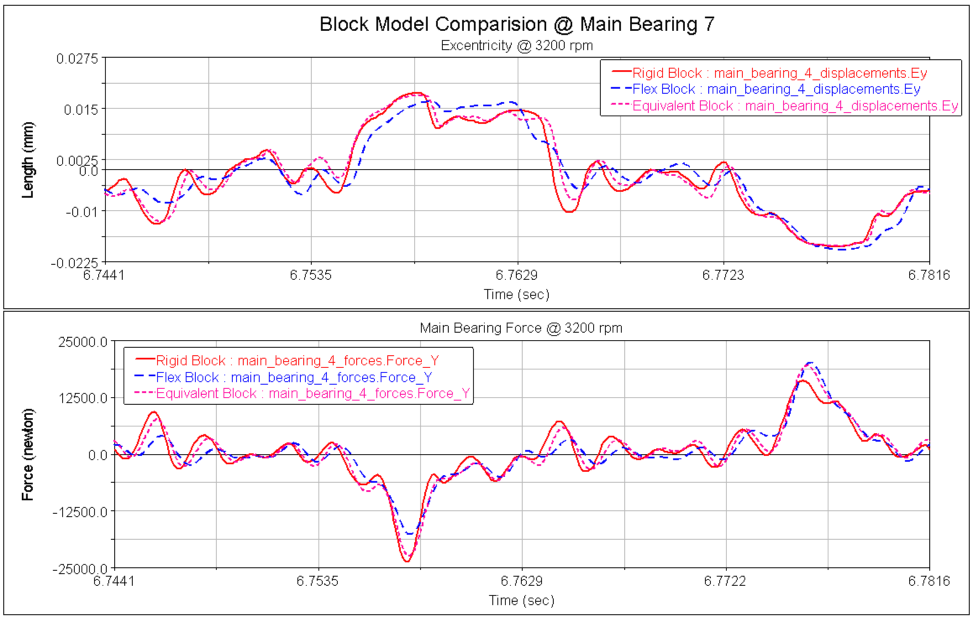

Fig.7 Comparison of displacements and forces in main bearing from rigid, flexible, and equivalent engine block models

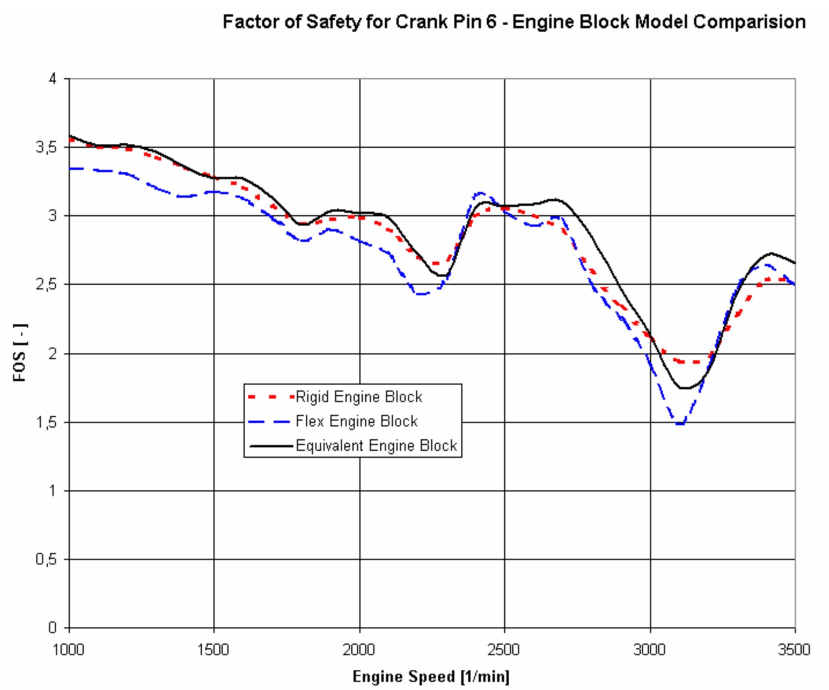

Fig.8 Comparison of factor of safety for models of rigid, flex and equivalent engine block

CONCLUSIONS

From point of view of existing continuation in the engines development considering about new concept it is necessary to take into consideration proven correlation of real and virtual prototype properties.

The application of method of virtual experiment requires knowledge about strain/stress variations for potential modeling methods of the engine block starting with rigid block, then model with bearing cup stiffness consideration and finally how to apply the modeling methods of flexible engine block. The introduction of a dynamically equivalent engine block could offer a welcome alternative to the previously indicated modeling methods, because it maintain the most important dynamic properties and it is computationally efficient providing acceptable accuracy of results.

Despite to benefits from engine toolkit ET frankly said the whole procedure is a fairly complicated business. On the contrary, the purpose of this article is to provide potential users with some appreciation of what is going on inside such canned routines, so that they can make intelligent choices about using them, and intelligent diagnoses when something goes wrong.

Integration of flexible properties of crankshaft with "dynamically equivalent engine block" model enables to capture inertial and compliance effect during dynamic simulations, study the influence of flexible crankshaft deformations and predict dynamic loads with greater accuracy for true durability of crankshaft assessment. In the further research the dynamic interaction of a crankshaft with engine block should be optimised from local point of view by introducing more advanced model of elasto-hydrodynamic bearing to achieve proper trade-off among computational effort, accuracy of results and reliability of durability prediction via multi-criteria optimisation approach.

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