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Virtual Engine a Tool for Truck Reliability Increase

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Abstract. The internal combustion engine development process requires CAD models which deliver results for the concept phase at a very early stage and which can be further detailed on the same program platform as the development process progresses. The vibratory and acoustic behaviour of the powertrain is highly complex, consisting of many components that are subject to loads that vary greatly in magnitude and which operate at a wide range of speeds. The interaction of the crank and crankcase is a major problem for powertrain designers when optimising the vibration and noise characteristics of the powertrain. The Finite Element Method (FEM) and Multi-Body Systems (MBS) are suitable for the creation of 3-D calculation models. Non-contact measurements make it possible to verify complex calculation models. All numerical simulations and measurements are performed on a Diesel six-cylinder in-line engine.

1. Introduction
In the powertrain development process several numeric simulation techniques have steadily gained in importance. The main target is design support; that is help for design decisions. With the increasing power of computers, accurate pre-calculations have become possible taking into account large number of effects and backward influences. First of all CAD models of Diesel in-line 6-cylinder engine are created. CAD models give basic geometric information about engine parts and can be used for a creation of FE models (e.g. crankshafts or engine blocks) or MBS rigid parts (e.g. pistons or piston pins). In the case of dynamic structural calculations the Finite Element Method (FEM) is ‘state of the art’. The calculation of the structural transfer behaviour of single components is efficiently possible in the frequency domain, giving consideration to a large number of degrees of freedom. Figure 1 shows FE models of main parts created on the basis of CAD models. The FE models of crankshafts or engine blocks are created in ANSYS. All FE models have uniform hexa element mesh and with exception in-line 6-cylinder crankshaft do not include small geometric details, for example, a radius on main bearing pin of a crankshaft. The uniform element size is suitable for dynamic solutions in time domain. The in-line 6-cylinder crankshaft includes small geometric details and is suitable for a stress-strain analysis.

2. Reduction of the models
Modal analyses can be performed in ANSYS and are not time-consuming, but for solution in time domain these models are very large and require reduction. The discretization of a flexible component into a finite element model represents the infinite number of DOF with a finite, but very large number of finite DOF [1]. The linear deformations of the nodes of this finite element model can be approximated as a linear combination of a smaller number of shape vectors, see equation (1).
\[
\begin{align*}
\mathbf{u} &= \sum_{i=1}^{M} \Phi_i \mathbf{q}_i \\
\end{align*}
\]

where

\(M\) … number of mode shapes, \(\Phi_i\) … mode shape, \(\mathbf{q}_i\) … modal co-ordinates.

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**Figure 1.** Diesel in-line 6-cylinder engine CAD and FE models

For reduction of FE models the Craig-Bampton method is used. The Craig-Bampton method separates the system DOF into boundary DOF, \(\mathbf{u}_B\) and interior DOF, \(\mathbf{u}_I\). Two sets of mode shapes are defined as follows [2]:

Constrain modes: these modes are static shapes obtained by giving each boundary DOF a unit displacement while holding all other boundary DOF fixed or Fixed-boundary normal modes: these modes are obtained by fixing the boundary DOF and computing an eigenvalue solution. The relationship between the physical DOF and Craig-Bampton modes and their modal co-ordinates is illustrated by the following equation:

\[
\begin{align*}
\mathbf{u} &= \begin{bmatrix} \mathbf{u}_B \\
\mathbf{u}_I \end{bmatrix} = \begin{bmatrix} I & 0 \\
\phi_{IC} & \phi_{IN} \end{bmatrix} \begin{bmatrix} \mathbf{q}_C \\
\mathbf{q}_N \end{bmatrix}
\end{align*}
\]

where

\(\mathbf{u}_B\) …. column vector of boundary DOF, \(\mathbf{u}_I\) …. column vector of interior DOF, \(I\) , 0 …. are identity and zero matrices, \(\phi_{IC}\) …. physical displacements of interior DOF in the constrain modes, \(\phi_{IN}\) …. physical displacements of interior DOF in normal modes, \(\mathbf{q}_C\) …. column vector of the modal co-ordinates of the constrain modes, \(\mathbf{q}_N\) …. column vector of the modal co-ordinates of the fixed-boundary normal modes.

The generalized stiffness and mass matrices corresponding to the Craig-Bampton modal basis are obtained via a modal transformation [3]. The orthogonalized Craig-Bampton modes are not eigenvectors of the original system. They are eigenvectors of the Craig-Bampton representation of the system and as such they have natural frequencies associated with them. The FE models of crankshafts and engine blocks are reduced to the number of boundary nodes selected by the user [3]. Their number is selected according to the application of constrains of the model. Loads are applied on these nodes only. The reduction of FE models from ANSYS into ADAMS is executed from ANSYS [1]. The parameters which influence the accuracy of the reduction are the number and location of the boundary nodes and the number of first modes considered during the reduction. These parameters can be
validated, for example, by computing FE model with constraints in ANSYS and separately in ADAMS and by subsequent comparison of the results.

3. Interaction between reduced Models

Slide bearings are used in the case of 6-cylinder in-line Diesel engine. The numerical solution of the equation of the motion in time domain with integration time step corresponding crank angular displacement 0.01° requires effective calculation of the hydrodynamic reaction of a radial slide bearing. The procedure derives from the Reynolds hydrodynamic equation [2]. The solution of hydrodynamic radial and axial slide bearings is implemented in ADAMS, where loads are obtained from a precalculated oil film reaction force database [3]. The Reynolds differential equation cannot be solved analytically and some numerical methods must be used. When hydrodynamic bearings are modelled, it can choose to include or exclude misalignment effects by using the following methods:

- For the two-dimensional method neglecting misalignment - an empirical analytical equation is used. This approach, which is similar to the impedance method, is the most efficient way to model hydrodynamic bearings.
- For the three-dimensional method accounting for misalignment - the Reynolds equation must be solved explicitly. To keep the simulation effort in a reasonable range, you must decouple the hydrodynamic solution from the dynamic solution of ADAMS/Solver. During the dynamic solution, ADAMS/Solver [9], subroutines do the database access and the necessary analytical steps (coordinate transformations, and so on) [1].

The component outputs give the following results: forces, velocities and displacements. The creation of a nonlinear FE model of roller bearing is a first step; however, MBS using the simpler model has to be created.

4. Interaction between reduced models

The solution of the complex model in time domain runs in ADAMS[9]. Major parts, for example a crankshaft and an engine block, are solved as flexible parts [4]. The other parts are solved as rigid. Gas forces on pistons and a torsional damper are added in ADAMS as well. Some temperature elements for dependency on temperature are defined. The first temperature element defines the dependency of the oil temperature in bearings on the engine speed, and is referenced by a viscosity element that describes the dependency of oil viscosity on oil temperature. The oil viscosity is then necessary to describe the behaviour of hydrodynamic bearings. The second temperature element defines the dependency of the torsional vibration damper temperature on engine speed, which is referenced again by the torsional damper. The solution is very complicated and requires a great deal of computer time [4].

The numerical solution of the equation of the motion in time domain runs with integration time step corresponding to a crank angular displacement of approximately 0.01°.

5. Diesel in-line 6-cylinder engine cranktrain

Accelerations, velocities and displacements of all parts, both rigid and flexible, can be obtained from the ADAMS solution. Length or torsional deformations and stresses of flexible parts can also be obtained in ADAMS. One of the major problems is the torsional vibration of the crankshaft [8]. Tab. 1 presents critical engine speeds it can be determined from the first torsional natural frequency. The comparison of calculations and measurements is still a decisive quality criterion in the CAD environment. Non-contact measurements with laser Doppler vibration meters make it possible to verify complex calculation models. In-line 6-cylinder measurement was performed on an experimental engine. The use of viscous torsional vibration damper significantly reduces the vibration and the stress level. Rotational accuracy of valvetrain is the next problem [5]. The reduction of torsional vibrations decrease rotational accuracy and positively affects the combustion process [8]. The viscous torsional vibration damper decreases axial vibration of the crankshaft pulley. An acceleration sensor was used for crankcase sump vertical and longitudinal vibration measurement. The reduction of the vertical acceleration of the in-line 6-cylinder engine crankcase soup centre is more than 90 percent at nominal
engine speed [6]. The solution of reduction the complex model in time and frequency domain runs in ADAMS. Major parts are solved as flexible parts; see Figure 2[2], [7].

![FE Model - Frequency domain](image)

**Figure 2.** Assemble of a virtual engine with flexible and rigid parts

The torsional vibration order analysis of the pulley of the Diesel in-line engine with and without a damper is presented in Figure 3 [5], [7].

![Assemble Computed torsional vibration order analysis of Diesel in-line 6-cylinder engine](image)

**Figure 3.** Assemble Computed torsional vibration order analysis of Diesel in-line 6-cylinder engine
Table 1. Critical engine speeds.

| Order | Computation $n_{KRiT-C}$ [min⁻¹] | Measurement $n_{KRiT-M}$ [min⁻¹] |
|-------|----------------------------------|----------------------------------|
| 3     | 4800                             | 4750                             |
| 6     | 2400                             | 2370                             |
| 6.5   | 2215                             | 2188                             |
| 7.5   | 1920                             | 1896                             |
| 9     | 1600                             | 1580                             |
| 12    | 1200                             | 1185                             |

6. Conclusion

Internal combustion engine simulation is a very complex problem consisting of many partial issues. The simulation of cranktrain dynamics is a central module of the virtual engine. New calculation methods are necessary to achieve more accurate results that allow a design that is nearer to the mechanical limit. The combination of ANSYS and ADAMS [9] provides a powerful implement for virtual engine design[5], [7]. With the increasing power of modern computers the new techniques will replace the traditional methods. Applied viscous torsional vibration dampers with extremely high viscosity silicone fluids are effective means of modern engine vibration and noise reduction[6]. Computational models of the Diesel in-line 6-cylinder engine were developed and verified by measurement on existing prototypes of engines and help to increase truck engine reliability. The paper contains partial methodology which was used in the construction of engine which has been tested and is ready for production. We expect its use as a propulsion unit of special vehicles.

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References

[1] SHABANA, A. Dynamic of Multibody System. Second Edition. Cambridge University Press. Cambridge, UK, 1998. ISBN 0 521 594464
[2] NOVOTNY, P., PISTEK, V., STODOLA, J. Virtual Engine Tool for Ground Military Vehicle Reliability Increase. Advances in Military Technology. Vol. 1. No. 1, 2006 (p 49 - 69)
[3] SHIGLEY, J. E., MISCHKE, C. R., BUDYNAS, R. G. Mechanical Engineering Design. New York. McGraw Hill Companies, 2004
[4] PISTEK, V., NOVOTNY, P., STODOLA, J. Virtual Engine Tool for Ground Military Vehicle Reliability Increase. 10th European Armoured Fighting Vehicle Symposium. Shrivenham. UK, 2005
[5] STODOLA, J., STODOLA, P. Virtual Design of Ground Armored Vehicle. International Conference Transport Means 2009. Kaunas Lithuania. ISSN 1822–296 X (p 43 – 46)
[6] FURUHAMA, S., TAKIGUCHI, M. Measurement of Piston Friction Force in Actual Operating Diesel Engine. SAE Technical Paper 790855, 1979. Doi: 10.4271/790855
[7] NOVOTNY, P., BREZNICKA, A., STODOLA, J. Virtual Engine - Tool for Military Truck Reliability Increase. International conference Armament and Technics of Land Forces 2016. Liptovsky Mikulas, 2016. IBSN 978-80-8040-537-3 (pp 169 – 180)
[8] ROSS, D. Vibrations and Noise due to Piston-Slap in Reciprocating Machinery. Sound and Vibration., 2, 1965 (pp1 32 - 146)ADAMS [online]. [cit. 2016-11-7] Available from>http://www.mscsoftware.com/product/adams
[9] ADAMS [online]. [cit. 2016-11-7] Available from>http://www.mscsoftware.com/product/adams