VISUALIZATION OF ELASTIC BODY DYNAMICS FOR AUTOMOTIVE ENGINE SIMULATIONS

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ABSTRACT

Simulation of engine dynamics is a well established field of work in the automotive industry. We have worked closely with one of the companies developing industry-leading software for dynamic simulation of cranktrains to improve the model creation in their product. We have extended the modeler with a 3D preview of the engine which enables users to view a more direct representation of the design, thereby improving the pace and efficiency of their work. The data sets resulting from the simulation are vast. Previously, analysis could only be performed using 2D charts only. As a result of our co-operation it is now possible to inspect the simulation results in an interactive 3D visualization envionment.

KEY WORDS

Applications, engine dynamics, interactive visualization, iconic visualization, automotive industry

1 Introduction

Simulation and visualization of its results are gaining more ground in modern engine design. It is much faster and cheaper to create a virtual model of an engine and run a computer simulation than producing a physical prototype for testing purposes, even though prototype production and testing is still, and will remain, common in engine production. Proper visualization techniques can provide better insight into the behavior of the engine and facilitate the development of more advanced designs.

Our partner company AVL [1] offers a comprehensive set of simulation software for engine design in its *AVL Workspace* product. The suite incorporates software to simulate timing drives, hydraulic systems and gas flow in combustion chambers. It also includes *AVL Excite*, a software tool for simulation of vibration, fatigue and acoustic phenomena in power units. Its primary field of application is simulation of crankshaft dynamics, engine acoustics and performing thermo-elastohydrodynamic bearing calculations.

To aid in the analysis of the vast amount of data resulting from the simulation AVL Workspace offers two applications. *AVL Impress Chart* can present traditional 2D charts and diagrams, while *AVL Impress* is an interactive 3D visualization application. Both applications can process data from various simulators of the AVL Workspace.

First, this paper introduces AVL Excite to make the reader familiar with its workflow and some of the terms used in the software. We show how adding a 3D view to the existing 2D engine model in Excite can improve usability of the application and the productivity of engineers. A comparison of the 2D and 3D views used while building the simulation model is presented. Then the powerful tools we offer to visualize simulation results of Excite are demonstrated. Finally the possible directions of future work in this application domain are outlined.

2 Excite Simulation Software

Excite's simulation method outlined in [2] is based on the concept of a special multi-body system: linear elastic bodies (crankshaft, conrod, etc) connected by joints (bearings, dampers, etc) featuring essentially non-linear behavior. The interaction of the crankshaft's global motion (overall rotation) with the vibration of its parts is taken into account. The resulting non-linear inertia forces like gyroscopic effects are also handled in the simulator.

In the following sections we provide a brief overview of the typical workflow of a user working with Excite before the 3D view was implemented.

The engine components in Excite are defined via finite element (FE) meshes which are built from 3D CAD models. The users take these meshes as input. CAD modeling is not a feature of Excite.

First, the meshes are prepared for the simulation in a process called *condensation* [3]. Then the engine's logical simulation model is created using a 2D editor. The simulation is run and the results are evaluated. If the engineer is not satisfied with the results he or she goes back to the model editor and adjusts the parameters. Sometimes it is necessary to go back to the CAD model modifying its design if the crankshaft proves to be too weak, for instance.

2.1 Mesh Preparation

The FE mesh of an engine block, for example, may consist of several hundred thousand elements. Running forced response analysis in time domain on a structure with so many degrees of freedom would be intolerably slow on current
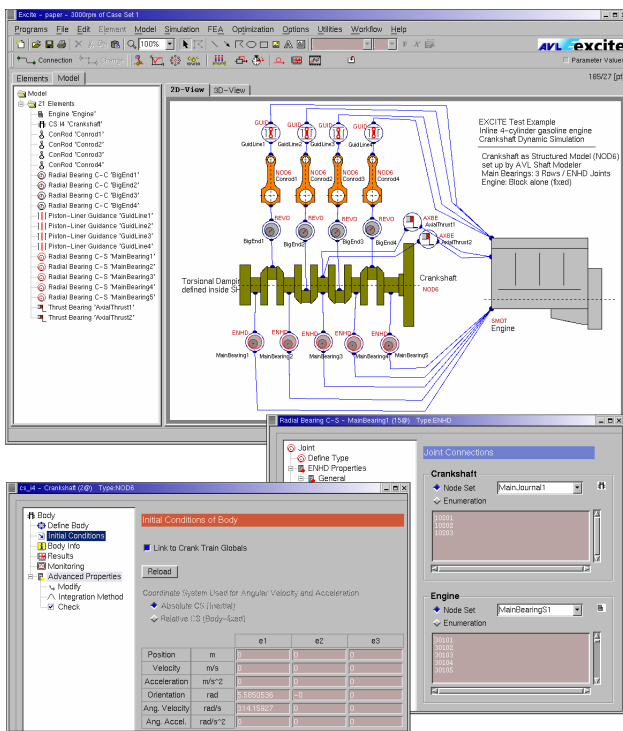
Figure 1. Block model of a 4 cylinder inline engine in Excite. The property dialogs of the crankshaft and a main bearing are also shown.

Figure 2. 3D view of the same 4 cylinder engine. Half of the engine block is clipped to make the inner parts visible.

hardware. Therefore the meshes go through a condensation process before simulation.

It is important to understand that the Excite simulator works only with the *condensed meshes*, not with original FE meshes. The result is much faster simulation which produces results that are still valid for the entire structure – provided the condensation was correct.

Condensation is performed in third party software (ABAQUS [4], MSC.Nastran [5], etc). The condensation process chooses a subset of the nodes of the mesh which represent the body. It also creates mass, stiffness and damping matrices which describe the dynamic properties assigned to these nodes. The resulting reduced model and the matrices define the bodies in the simulator.

2.2 Building the Simulation Model

The user builds a 2D block model of the simulated engine. The Excite user interface is shown in Figure 1. There is a tree view of elements that can be inserted into the workspace. Properties such as initial position and mesh files can be specified in popup dialogs for each component.

Joints connect two groups of nodes between two bodies. The connected bodies can be selected by clicking them. Depending on the types of bodies, Excite can usually offer the appropriate joint types automatically. For instance, if the crankshaft and the engine block are connected then the
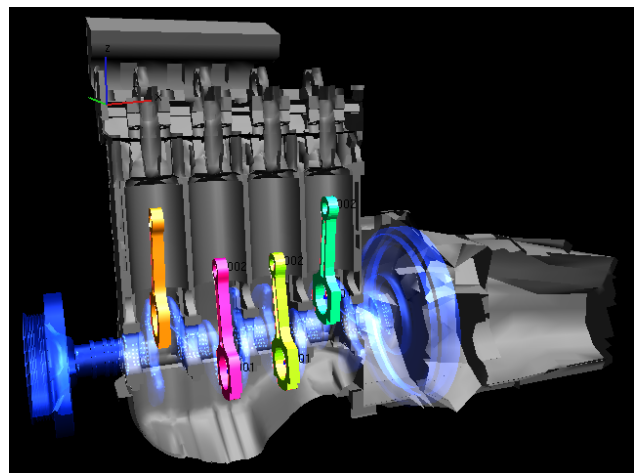
joint is likely to be a main bearing.

The nodes of the meshes that the joint connects can be specified in the joint's property dialog. The nodes are identified by *node IDs* (numbers), for example: "connect node 2 of the crankshaft with nodes 10,11,12,13 of the block". The joint's physical model (stiffness, damping, etc) is also defined in its property dialog.

The user can also create *node sets* that contain nodes which can be used in joints. For example, the nodes of the engine block that can come in contact with the crankshaft can be put in sets called "MainBearing1", "MainBearing2", etc, for each main bearing, respectively. Excite can find potential joint nodes automatically and create these node sets. For example, the user can define something like "connect MainBearing1 (block) to MainJournal1 (crankshaft)" and Excite will automatically list the node IDs of the two node sets.

There are over 20 different joint types in Excite depicted by specific icons in the block model, each defining a specific physical model in the simulator.

2.3 Simulation

After all bodies and joints are created, additional information about the crank train, external loads and boundary conditions (oil type, etc) are input. The user then runs the simulation. Depending on model complexity and the length of the simulated interval this may take several hours.

The simulation is usually run for 3-4 engine cycles which equals 6-8 complete revolutions of the crankshaft. The simulator output is directly available for the condensed mesh nodes only. Using the information from the condensation process the data can be recovered for the entire FE mesh. The resulting data files often exceed 1 GB, since they include displacement, velocity and acceleration, at each mesh node for each discrete time step.
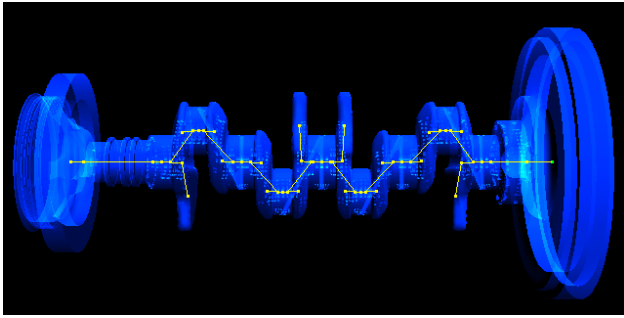
Figure 3. Condensed mesh of the crankshaft used in the simulator. The transparent FE mesh is also shown as context.

This huge amount of data can be evaluated in traditional 2D diagrams and in AVL Impress. The features of Impress related to Excite visualization are detailed in Section 5.

3 Introducing the 3D View in Excite

Looking at the above workflow it appears that the users could only see a 2D block model of the engine. They had no opportunity to view the 3D model before a simulation run. This raises at least 2 issues which may slow down the work with Excite:

- The initial conditions (position and orientation) of bodies are input in dialog boxes without immediate feedback showing the actual position in 3D space relative to the other elements.

- Without a 3D view the user has no way to localize a node. Errors stemming from incorrectly specified node IDs for joints are very hard to track down when you cannot see the actual joint and the nodes it connects.

To address these problems we implemented a 3D view of the engine model in Excite in addition to the existing 2D block model. The topology of the model can be conveniently defined in the 2D view while certain tasks are easier to carry out in the linked 3D view. The user may switch between the views at any time while building the simulation model. The following sections describe how components of the 3D model view are implemented.

3.1 Bodies

Bodies are the structural components of the Excite model. Bodies naturally appear at their defined initial position and orientation. Each body has its local coordinate system which is also indicated. The axis of rotation is highlighted in a different color. Each body can have two associated meshes: the FE mesh and the reduced one.
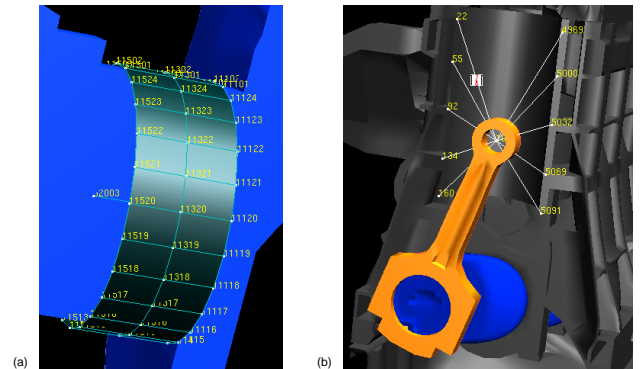

Figure 4. (a) One of the main bearings of the engine. Part of the crankshaft is clipped to reduce occlusion. The IDs of the connected nodes are shown. (b) Piston-liner contact. The piston itself is hidden to reveal the connection.

3.1.1 FE Mesh

This is the FE mesh that was used as input for the mesh simplification process. One should not forget that the Excite simulator does not work with this mesh, it is used solely for the 3D view. Surface and/or wireframe FE meshes can be drawn, again in various colors. Occlusion is a major issue in this context, since practically everything (crankshaft, conrods, etc) that is of interest to the engineer is contained. Furthermore, joints usually represent contacts between bodies thus these bodies almost always obscure them. We offer four means of reducing occlusion of FE meshes:

- The outermost layers of FE meshes can be removed one-by-one temporarily, much like peeling an onion. This allows investigation of the inner elements.
- An arbitrary clipping plane can be applied to each FE mesh. The elements in one half-space are not rendered. This can be used to remove half of the engine block, for instance, allowing an exploded view of the engine. The plane can be rotated and slid along its normal.
- An arbitrary intersection plane can also be applied. Only elements that intersect the plane are rendered. As with the clipping plane, this plane can be also rotated and slid along its normal.
- There can exist arbitrary groups of FE elements which can be hidden or rendered in different colors. If the FE mesh file contains such groups (*cell sets*) those are read automatically. In addition there are numerous powerful ways of defining or editing sets in the 3D view.

Transparency can be combined with any of the above tools.

Figure 2 demonstrates two of these methods in order to provide a good view of the whole engine. Half of the block is clipped away and the crankshaft is drawn transparent.

3.1.2 Condensed Mesh

As described in Section 2.1, this is a reduced mesh, consisting of nodes and optional line segments connecting them. This mesh is taken as input in the Excite simulator. Nodes, beams and node ID labels of condensed meshes can be shown or hidden from the property dialog and their colors can be customized. Figure 3 shows the reduced mesh of the crankshaft.

3.2 Joints

It is worth mentioning that joints cannot be represented as easily as bodies because they differ fundamentally: there is no mesh associated with them. They merely describe the non-linear contacts between meshes.

In the 3D view the joint is represented by a glyph and a lines that connect the actual nodes of the bodies. For some specific types (bearings, belt and gear drives) 3D glyphs have been incorporated. For others icons from the 2D view are displayed besides the nodes. Users can optionally enable node ID labels and customize colors of each component of the joint visualization.

In Figure 4 (a) a main bearing can be seen. In this image the ring is a glyph that indicates the diameter and the width of the bearing. Figure 4 (b) shows a piston-liner guidance. The beams indicate how nodes of the engine block are connected to the piston pin for simulation. The yellow labels show IDs of the connected nodes.

3.3 Interaction with the 3D View

It is possible to hide or drag components that are temporarily out of the user's interest in order to reduce occlusion. Dragged objects can be returned to their original position by a single click. It is worth mentioning that the *initial conditions* of components in the simulator are not changed when the bodies are dragged. The view can be panned, rotated and zoomed as desired.

The current display settings of all bodies and joints can be stored in the list of *user-defined views*. These display options are saved with the project and can be restored with a single mouse click at a later time.

4 Comparison of the 2D and 3D Views

It is natural to ask why we have kept the 2D block model editor when there is a new 3D view. We compare the two views in more detail in this section.

The 2D block model editor provides good representation of the logical structure of the model. Engineers can clearly see how the components are connected to each other. Different bearing models can be easily indicated by annotations. Occlusion is usually not a problem or it can be resolved easily. The users of Excite at various companies in the automotive industry are already familiar with this view.
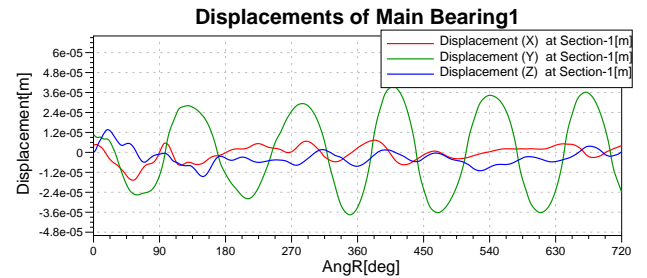

Figure 5. X-Y-Z components of the displacement of one main bearing section over a full engine cycle in a 2D diagram.

On the other hand there is no impression of actual positions of components in 3D space. Errors in the specification of initial conditions of bodies are hard to find because one must try to comprehend the 3D positions from numeric data in the property dialogs. The nodes used in the joints are identified by numeric labels and there is no way to see their actual locations. If nodes in joints are listed incorrectly this is impossible to find with the previously existing tools in Excite.

Adding the 3D view opens new possibilities. Relative positions of components in 3D space are clearly seen which makes it possible to discover errors in the initial conditions more easily. Misplaced components, mismatching crankshaft and block meshes are very easy to find. Joint nodes are drawn at their actual positions, thus incorrectly specified ones are easily spotted. Defining node sets (big end of a conrod, for example) becomes intuitive: instead of listing numeric node IDs one can simply click the nodes to be included.

Unfortunately the 3D view has some drawbacks compared to the 2D one. The actual FE meshes may add too much detail which obscures the logical structure of the engine. Furthermore, a useful 3D view cannot be offered when FE meshes are not available. Sometimes this can happen, because the simulator only needs the condensed meshes for its operation.

It is obvious that the two views complement each other. Both have features that are crucial and missing from the other one. Therefore we decided to retain both views and allow the user to choose the view that is more suitable for the specific task.

5 Evaluation of Simulation Results

The user has basically two possibilities to analyze and evaluate the simulation result data. AVL Workspace offers Impress Chart to generate 2D charts and diagrams like the one shown in Figure 5. Interactive 3D visualization and animation is available in AVL Impress. Both applications can process data from other simulators of the AVL Workspace. The capabilities of Impress regarding visualization of timing drive simulation data from AVL Tycon are already pre-
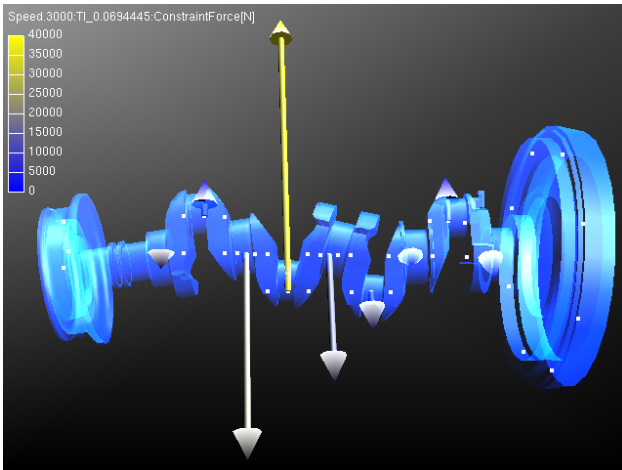
Figure 6. Distortion of the crankshaft under load. Deformation is magnified by two orders of magnitude. The arrows indicate the constraint forces at the nodes of the reduced crankshaft mesh.
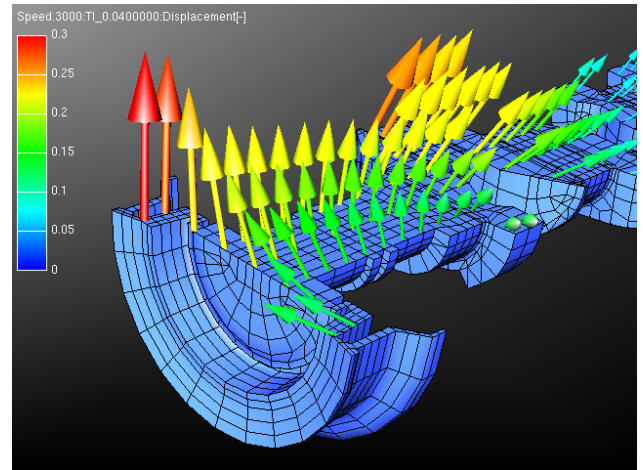

Figure 7. Arrows depicting displacement on a cross-section of the crankshaft. The displacement data available at all nodes is resampled to a grid of lower resolution to reduce visual clutter.

sented in [6]. However, in this section we concentrate on the Excite specific features of Impress which are related to our work.

After the simulation has finished the user can load data of all or only selected time steps of the simulation. The condensed meshes and FE meshes of the components are loaded and displayed. Naturally, all the tools described in Section 3.1.1 are available to reduce occlusion of FE meshes.

5.1 Deformation of Bodies

In order to create a good impression of how engine components are deformed under loads, the deformation of the meshes can be magnified. The global motion (overall rotation) of the crankshaft can be turned off and only the vibration component shown to allow exact comparison of the crankshaft's deformation at various crank angles.

In Figure 6 the distortion of the crankshaft is emphasized by a magnification of two orders of magnitude. Compare this to the original shape as shown in Figure 3.

5.2 Glyphs

Glyphs have been used extensively to visualize physical attributes [7] [8], especially when the data is inherently discrete [9] [6]. Many of the attributes stemming from the simulation are vectors. Velocities, accelerations, forces can be visualized very intuitively by arrow glyphs positioned at the nodes of the condensed mesh.

In Figure 6 the arrows show the constraint forces on the crankshaft. As detailed in the next section it is possible to create arrow glyphs on surfaces of the FE meshes, too.

5.3 Surfaces and Cross-sections

When bodies have FE meshes, the user has more options to visualize certain attributes.

It is possible to display any attribute using color coding on the surface of the FE mesh. For example, in Figure 8 the displacement of the surface of the engine block is shown. If parts of the mesh are hidden by the tools described in Section 3.1.1 then the surface of the remainder of the mesh is used.

Similarly, users can create planar cross-sections of the meshes and apply color coding to the referenced cells to display any attribute. The user can drag the plane through the mesh acting as probe.

Furthermore, vector attributes can be visualized by rendering arrows at each node of the surface or cross-section. In order to ease the visual clutter with FE meshes of many cells, the resampling tool proposed by Laramee [10] is adapted to our arrow rendering. As an illustration, note that there are fewer arrows than nodes indicated by the wireframe in Figure 7. Drawing arrows at each node would only clutter the view.

Finally, the cross-sections can be used as the reference plane of height fields (shown in red in Figure 9). Any attribute may be mapped to a user-defined height field.

5.4 Interaction and Animation

Any number of independent 3D viewing windows can be opened to allow comparison of data of different simulation cases. The view can be panned, rotated and zoomed as desired. The model can be animated using VCR-like controls. Even during animation the user can change the viewpoint, adjust properties of objects and create new surfaces or cross-sections. There is a movie director module
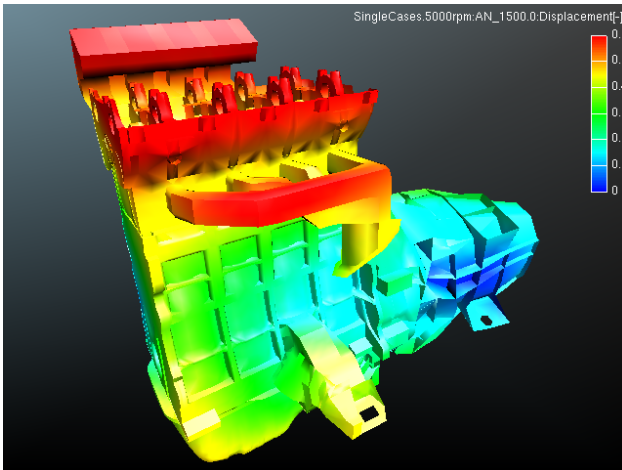
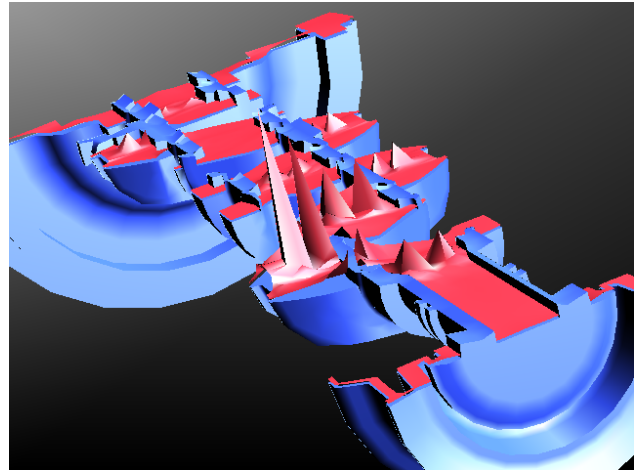Figure 8. Displacement of the surface of the engine block shown using color coding.

Figure 9. Stresses on the cross-section of the crankshaft visualized using a height field. Peaks highlight areas of high stress.

to facilitate creation of AVI or MPEG movies for presentations. Supplementary movies of engine simulations can be downloaded from our web page [1].

6 Conclusion and Future Work

This paper has shown how coupling a 3D view with an already existing 2D editor for defining the simulation models of engines can be achieved. The topology which is easily created in 2D is extended by a real geometric 3D view of the model. We have applied 3D visualization techniques to effectively depict simulation results of elastic body dynamics. The results of this work have been implemented in one of the leading software products for cranktrain simulation.

There are some shortcomings of our current implementation which we plan to address in the future. Currently, it is not possible build the model entirely in 3D, joints can only be defined in the 2D view. Our next goal is the implementation of a semi-automatic joint generation scheme: when bodies are dragged to a possible contact situation the joint nodes should be connected automatically by the software. We wish to invent intuitive glyph joints, too.

We also plan to implement a similar 3D view for the modeling of timing drives.

Acknowledgments

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