Mechanical Simulation in the Engine Development Process: Part II = Coupled Analysis of Engine Subsystems

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Summary

The continuously increasing requirements regarding product quality while controlling the cost combined with the increase in computer hardware and software performance leads to a fast expanding usage of simulation techniques. In the mid term the objective is to substitute a hardware prototype with a virtual prototype.

In order to achieve this goal, it is required that the thermo-dynamic processes as well as the engine mechanics are considered to the highest level of accuracy. To support the different calculation disciplines several numerical simulation methods such as the finite element method (FEM), the multi body dynamics simulation method (MBS) and the computational fluid dynamics simulation method (CFD) have been proven. The tools, which utilize these methods, are so called multi purpose software packages designed to be applied to a variety of engineering problems. With regard to the engine mechanics calculation the combination of FEM with MBS through modal condensation appears to be the most effective approach. With that, it is possible to accurately predict engine component behavior as well as their interaction with other components and systems.

When analyzing the current use of CAE methods in the engine development process, it becomes apparent that simulation models have different levels of refinement according to the development phases. Very often these models are not compatible in terms of modeling method and do not share the same data model. Also, the data exchange with suppliers, which should be involved very early in today’s processes, is very challenging.

Additionally, the engineers have to have in depth knowledge of numerical methods beside their engine expertise, which leads to long adoption periods as well as an overall error prone process. The implementation of engine specific simulation modules in existing multi purpose software packages presents a solution to these problems. With this approach an interface between the development engineer and the powerful numerical simulation program has been created.

The requirements mentioned above were the corner stones for the development of the engine mechanics software: **ADAMS/Engine powered by FEV**. This paper contains an exemplary description of the major capabilities of this software. In particular it focuses on the crank train, the valve train and the timing mechanism.

1 Introduction: CAE in the Engine Development Process

There are a number of reasons to use CAE methods in the modern engine development process. Foremost the need to cut cost increases the usage of virtual testing versus costly hardware testing.

Another important argument is the fact that certain characteristics of the system cannot always be measured without influencing the system. In a first step the characteristics, which can be measured with relative low effort, may be used to correlate and to verify the validity of the calculation models. In return these models deliver a large number of characteristics who's measurement would be too time consuming and costly in the frame of a regular development project.

Since hardware prototypes are not available early in the design process especially in the „pre-prototype phase“, the usage of virtual prototypes is required and represents the most important scenario. During this period the results from calculations and the engineering experience of the designers are the only basis for design decisions, which influence the entire design process until production [1]. The more innovative the design is the less engineering expertise is available; hence the importance of the calculation increases dramatically in the concept phase. During the last years the significance of new concepts with respect to the engine mechanics has reached a new level as shown by the introduction of engines with variable compression ratio and valve trains with variable timing.

According to the application it is possible to distinguish between predictive and validated simulation models. The predictive models should deliver results based on physical input parameters early in the process, when no hardware prototype is available. The validated models are first validated against measured data using data deviating from the physical input data. These models are usually used in the detailed design phase, such that the requirements on model accuracy are much higher. In general, models with increasing levels of refinement are necessary during the development process [2].

Depending on the need to consider the interaction between models a modular approach is required. Component level analysis as well as subsystem and full system analysis must be possible. The modularity is also important to support the communication between the different areas of responsibility in the development process and to enable the focused analysis in these areas. The trend to out-source more of that development responsibility to suppliers further underlines this demand. The following main requirements for CAE software in the engine development process can be derived from the points mentioned above:

- Open and extensible
- Easy to use
- Multiple levels of refinement
- Modular

The common practice is to use different simulation tools during the different stages of the development process. While simple engineering judgment tools are used during the concept phase more complex programs are used towards the end of the design cycle. The data exchange between the tools is particularly difficult since no standard has been declared.

During the development of the engine simulation software ADAMS/Engine powered by FEV all the requirements mentioned above have been considered. In particular the focus was on the entire process rather then on partial areas of the process.

The conflict between the requirement for extendibility and openness on the one side and user friendliness on the other was solved by separating topology and data. While standard users can make quick and simple changes to the data then applied to existing templates, expert users can develop entirely new concepts quickly by utilizing the predefined components and templates. In this way the capabilities of special purpose software and multi purpose software have been ideally combined.

The existence of the clearly defined data model also enables the exchange of data between the different internal and external participants very efficiently. Through the usage of „communicators“ it is possible to combine a number of subsystems such that the modularity of the models is guaranteed. This allows the user to focus on the component analysis, subsystem and full system analysis using the models in the one environment.

Attention has been paid to the implementation of different modeling approaches for components representing different levels of refinement. The modeling approach can be changed quickly without changing the topology model. Following the usage of ADAMS/Engine powered by FEV in the engine development process is described with examples.

2 Application Examples

2.1 Layout and design of the Valve Train

Choosing the right model resolution according to the target of the simulation is crucial during the development of the valve train to achieve a good balance between simulation time and model accuracy. For instance when studying the fundamental functionality of a valve train under consideration of the valve closing velocity or the pressure between the cam and the follower, detailed models of the components such as the hydraulic lash adjuster or the valve spring have to be used in the frame of a single valve train analysis. This type of model can also be used to determine loads in the system for subsequent durability and acoustical analysis. It is possible to change the level of refinement of a component to the highest level of detail, if the improvement of a particular component is the main objective of the valve train simulation. In that case only the data of this component have to be adjusted, while all other model data remain unchanged. Based on the valve spring example this process is explained in more detail below.

2.1.1 Valve Spring Models

Several component models representing different levels of refinement are included in the software and described hereunder.

2.1.1.1 Dual-Mass-Spring Approach

The dual-mass spring approach represents the lowest level of refinement. For instance, it is appropriate to use this model, when the valve train is used as the excitation mechanism in a larger assembly that includes a timing mechanism. To consider some of the mass effects on a larger system, the spring mass is distributed into two masses. The distribution ratio may be adjusted according to experience. The masses are connected via a force with a function representing the nominal (static) stiffness characteristic of the spring. Figure1 shows the schematic representation of this model in ADAMS/Engine. This model does not consider any internal dynamics of the spring and is therefore not suited for the dynamic investigation of a valve train.

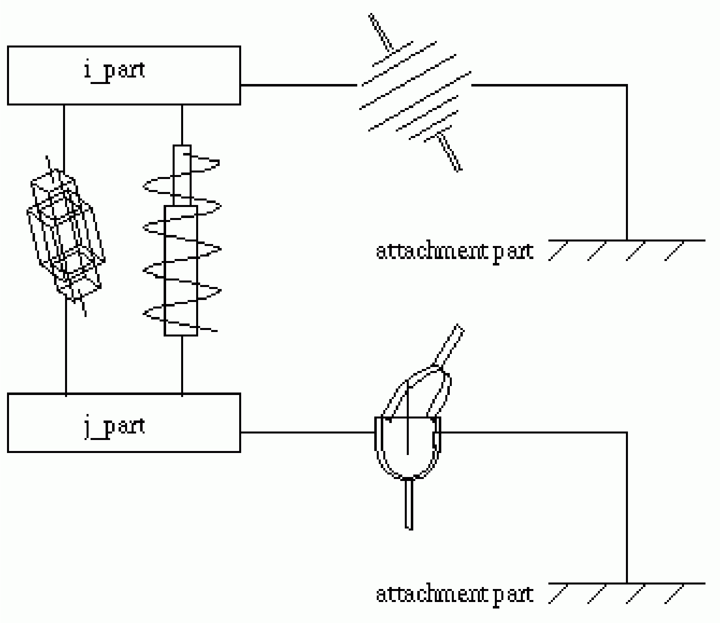


Figure 1: Dual-mass-spring Approach

2.1.1.2 Multi-Mass-Spring Approach

The multi-mass-spring approach, which is used to obtain the forces under dynamic conditions, is based on the discretization of the spring. The model parameters are derived from physical properties, such as wire dimensions and material properties.

To capture the internal dynamic effect often referred to as spring surge, the valve spring is modeled via a series of masses coupled with spring dampers. All masses represent a segment of the spring wire. Every winding is usually split in 4 – 8 segments. The torsional stiffness of each wire segment is used to determine the equivalent translational spring stiffness, such that the stiffness may vary depending on the diameter or change in cross section. The damping represents the material damping.

To include the nonlinear behavior of the spring caused by the changing number of active coils during compression, it is necessary to consider the interaction between the coils. This is done via additional nonlinear contact forces, which are dependent on the approximation of the appropriate parts. Due to the presence of nonlinear contact forces, it is also possible to consider coil clash.

Figure 2 shows the schematic representation of the model, as implemented in ADAMS/Engine [3].

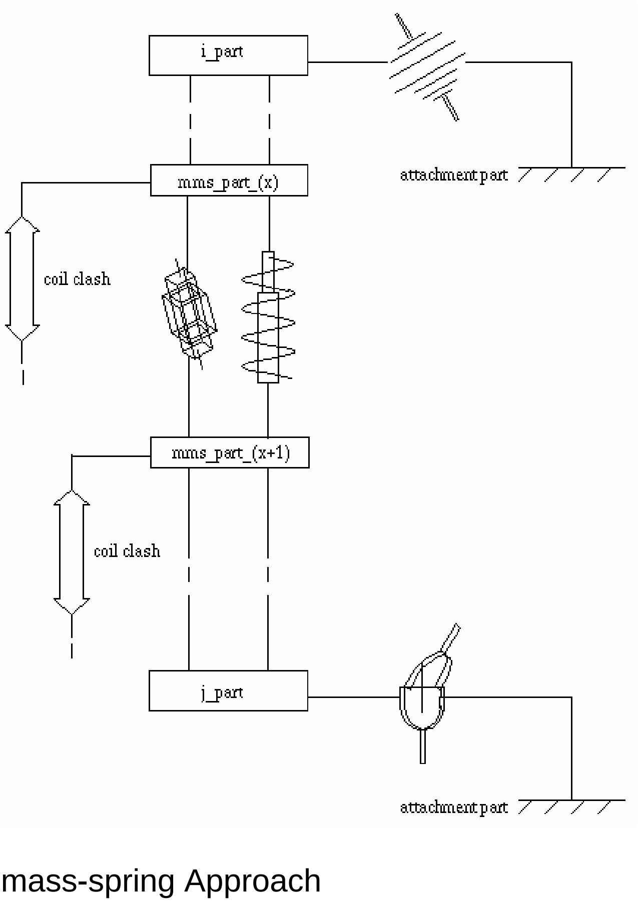


Figure 2: Multi-mass-spring Approach

Figure 3 shows the correlation between test and simulation in terms of stiffness and frequency characteristic. Further validation can be found in [2].

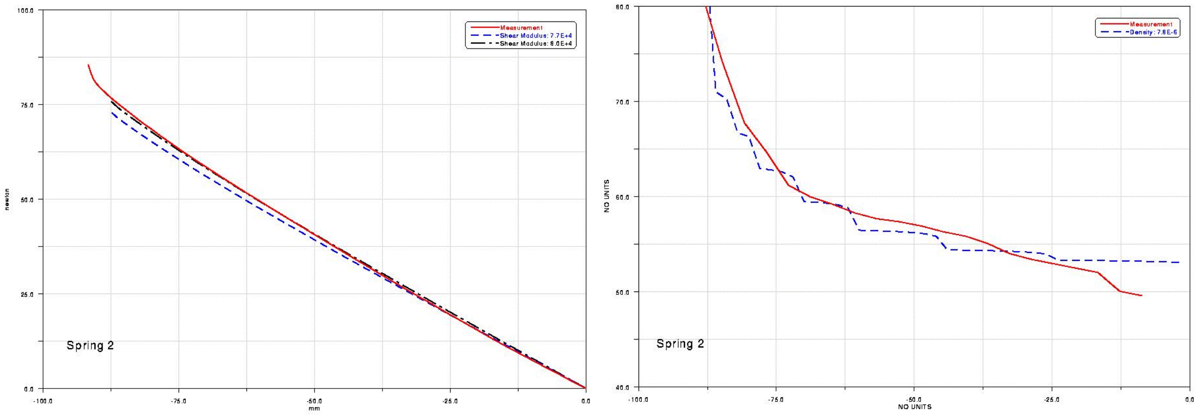


Figure 3: Correlation between component test and simulation

2.1.1.3 Flexible-Body-Spring Approach

The highest level of refinement for the spring component is achieved through flexible bodies. This model is particularly suited for the component responsible, since it allows studying the influence of the spring on the system in great level of detail.

Nonlinear effects, such as coil-clash and surge, exclude the usage of a plain modal representation. Nonetheless, the modal approach has some merits. The number of equations to be solved is minimal, thus the computational effort is small. The introduction of non-linearity into the model is required for this model to be valuable for valve train simulations. The effect of the spring on the valve train is the main concern; therefore performance has a high priority. This led to the development of a two-stage model as described in [4]. Following is a brief description of the fundamentals of this approach.

The detailed model, which consists of three to five flexible bodies per winding, considers the geometric non-linearity, as well as the interaction between windings, thus governing the non-linearity in stiffness and frequency. The model also captures buckling and all other three-dimensional effects. The flexible bodies are auto-generated, as shown in figure 4 on the left side.

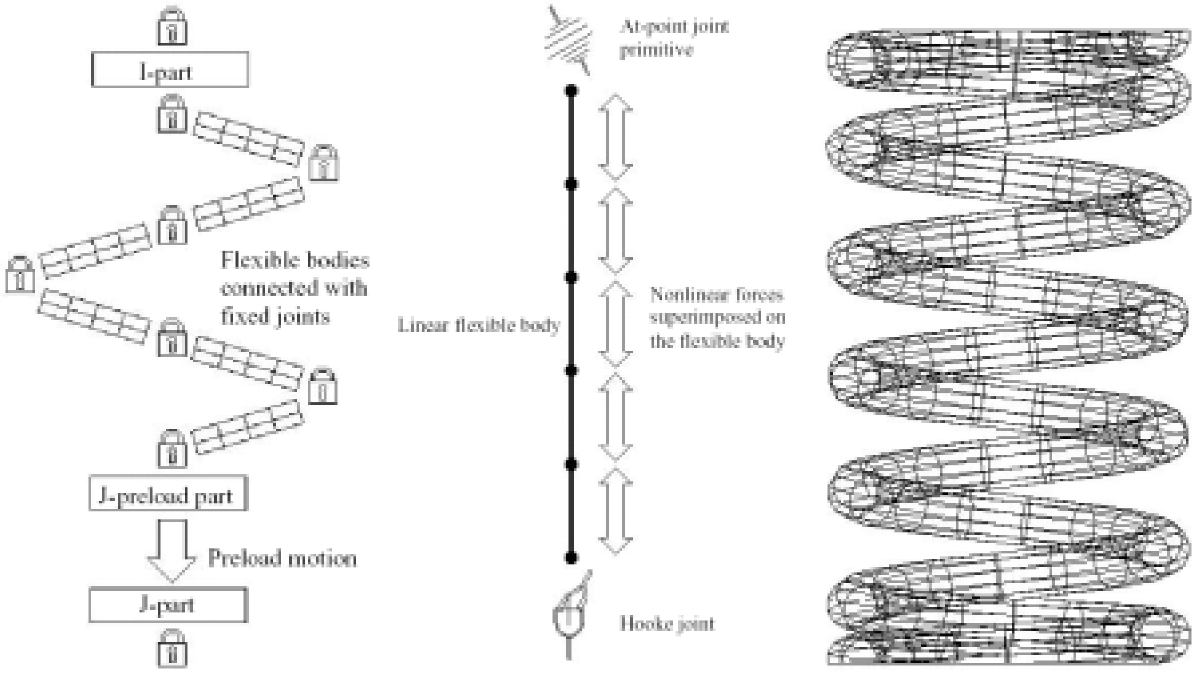


Figure 4: Flexible body model, equivalent model and representation

The equivalent model consists of one flexible body, which only represents the linear, longitudinal portion of the spring model. Forces between certain nodes are superimposed to introduce the non-linearity determined by the detailed model. To generate the equivalent model, the results of a quasi-static compression of the detailed spring are required. Figure 4 shows the schematic model (center) and the ADAMS model (right).

The models are auto-generated based on design parameters such as wire dimensions, wire centerline path, and material properties.

2.1.2 Application of the spring in the Valve Train

The detailed model can be used for quasi-static compression tests in a virtual test rig or in dynamic mode in a single valve-train simulation. The equivalent model should be used for simulations of single or complete valve trains. As mentioned above the model exists in different levels of refinement and the exchange of data between the different levels of refinement has been a major focus of the development. During the development process the system responsible engineer sets the boundary conditions for the component responsible engineer such that he/she can design the spring. The spring can then be passed back for the system integration in form of data and the performance of the component within the system can be studied. Figure 5 shows the result of a quasi- static compression test in terms of force and torque over displacement. Now it is possible to determine if the spring satisfies the system requirements in terms of stiffness characteristic for example.

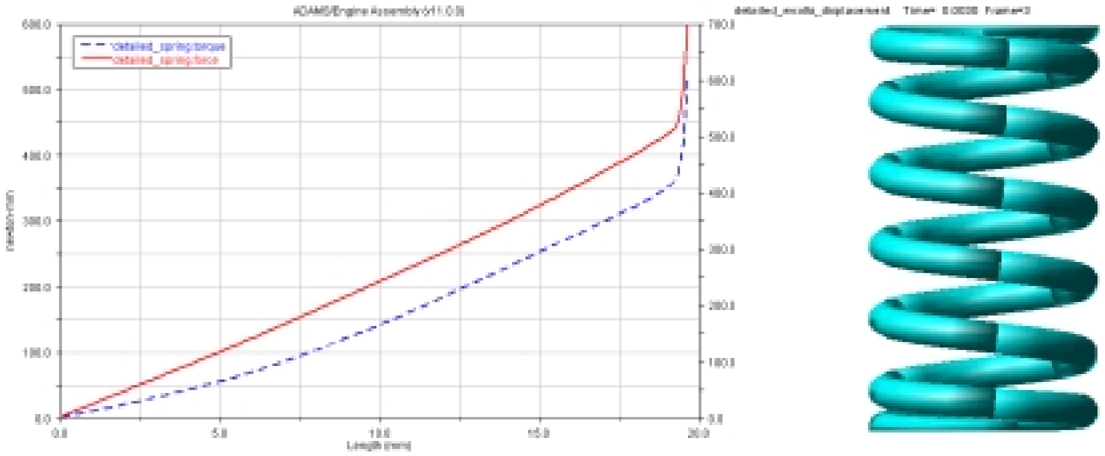


Figure 5: Force and torque versus displacement

Now it is possible to derive the equivalent spring for a single valve train simulation. This simulation is very efficient with reasonable level of accuracy from a system perspective. As previously mentioned the detailed spring can also be used in a single valve train analysis. Figure 6 shows the comparison of the results from the two models in terms of valve acceleration.

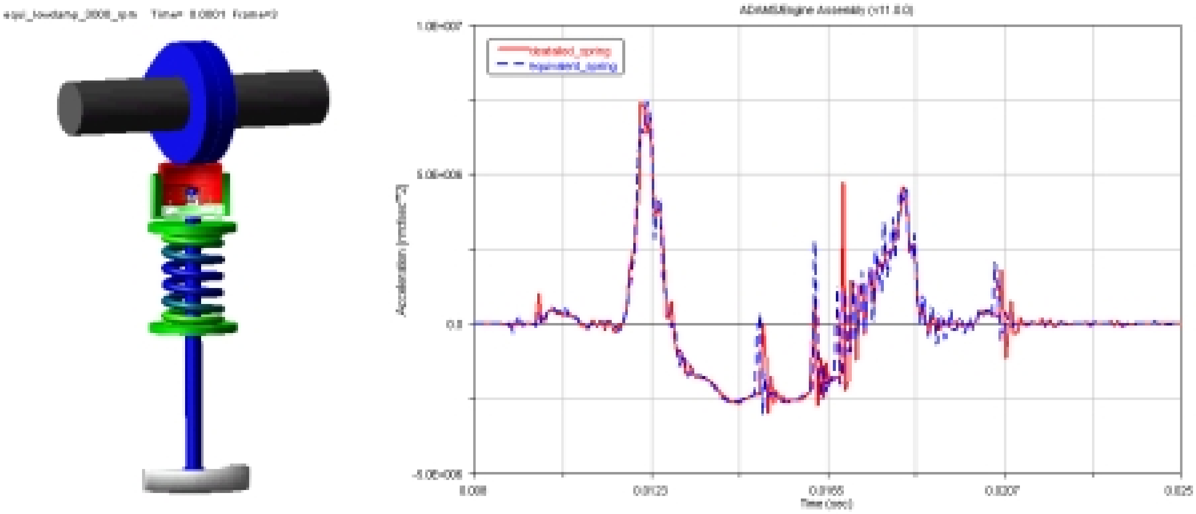


Figure 6: Comparison: Detailed versus equivalent spring model

In further analysis it is possible to investigate the influence of the lateral forces and the bending moments on the system.

Following it is explained how a minor change of the spring wire path without significant influence on the longitudinal stiffness has a large impact on the system in terms of valve guide loading. A typical rocker arm design as shown in figure 7 is the basis for this study.

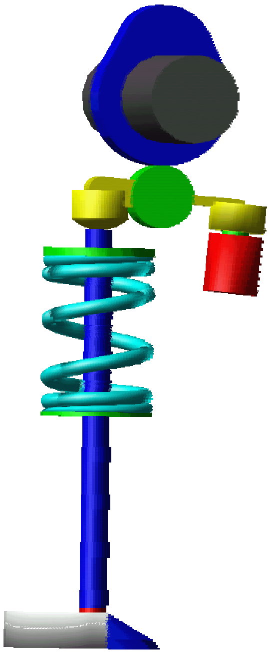


Figure 7: Single valve train with detailed spring

The lateral forces in the valve guide are shown in figure 8 for a simulation including a spring with 3.4 (solid line) and 3.5 (dotted line) active coils. On the left we see the force in the rotational plane of the rocker and on the right in the plane normal to that and parallel to the valve. On the left, the change in sign of the relative velocity between the rocker and the valve stem and with that of the friction force is clearly reflected. Remarkable is the difference in force level caused by the small difference between the wire paths and with that how the windings are starting to touch each other. Using this approach the component responsible can ensure that the spring behaves within given constraints. On the right of figure 8 a similar high difference in force level can be seen, which has a direct impact on the oil film in the valve guide.

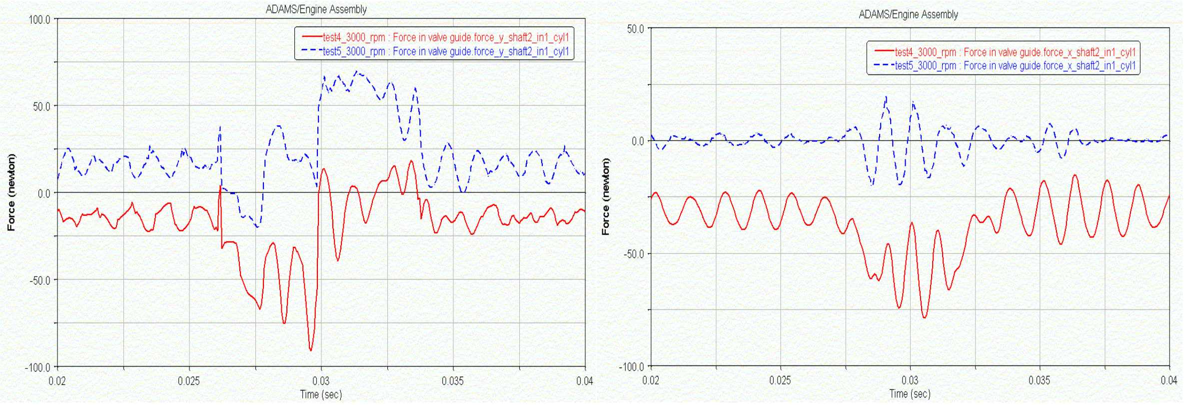


Figure 8: Lateral force in the valve guide for one revolution

The flexible body based models are well suited for the component design and integration.

After the detailed single valve train analysis follows the complete valve train analysis. This type of analysis is required for instance, when investigating the torsional behavior of the camshaft. Depending on the objective of the simulation the level of refinement for several components such as the spring should at least be reduced to use the equivalent model or even the dual-mass model for example.

2.2 Timing Mechanism

2.2.1 Chain Drive

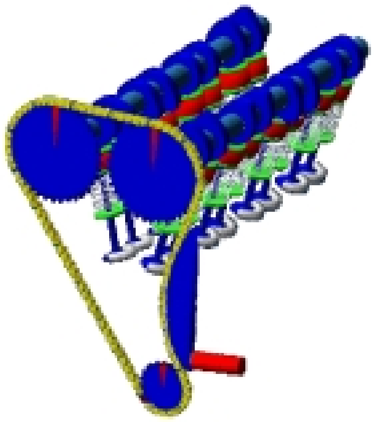
Also for the chain, the level of refinement should be adjusted to the task at hand. As mentioned before the software has been designed to make the switching between models while maintaining the topology easy for the user.

In case the chain serves as a coupling between the crank train and the valve train to determine the free forces of the system due the mass and inertia effects a simple constrained based representation of the chain is appropriate.

If the rotational vibration of the system is the major focus of the simulation a model with one spring per span may be sufficient.

If the dynamic response of the chain drive itself is the main interest in order to improve the tensioner device or to reduce the force level for better durability, a detailed model has to be used. The detailed model of the roller/bush chain and the toothed ("silent") chain consists of a part per link coupled with force elements. The force elements represent the longitudinal stiffness of the chain link and the friction force in the joint. Additionally there are force elements to represent the different contacts occurring between the links and the sprockets and between the links and the guides.

It is also possible to determine the bearing loads. Figure 9 shows a complete valve train combined with a chain drive. The model is excited at the crankshaft sprocket with a harmonic series function derived from test data and at the cam sprockets through the virtual valve train.



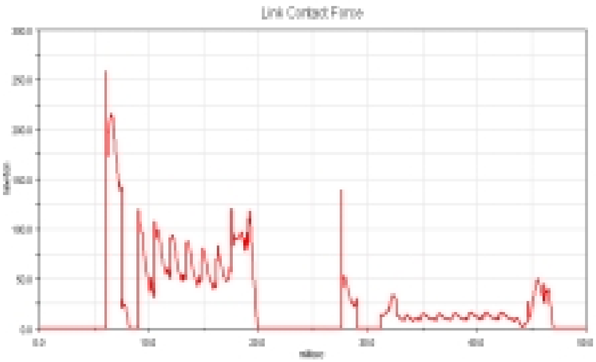


Figure 9: Chain drive combined with valve train and contact force between a link and sprocket and between a link and the guide.

The described chain models can easily be switched against each other within the environment without changing the model topology while inheriting the data.

2.2.2 Gears

Valve trains, accessories or balancing shafts may be driven with gears in the engine. Consistent with the other modules of ADAMS/Engine powered by FEV it is possible to adjust the level of refinement to the objective of the simulation.

For instance when calculating the free forces and moments of the engine a constrained based approach representing the gears is sufficient. This means that balancing shaft or the camshaft is directly constraint to the driving shaft with a constant ratio.

A force-based approach has to be used in order to study backlash effects or the influence of the gear tooth geometry on the vibrations in the system. These models also enable the user to determine bearing loads under consideration of the helix angle for example. Figure 10 shows an ADAMS model including valve train, timing chain and gear drive.

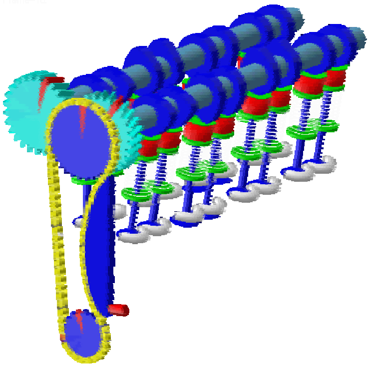


Figure 10: ADAMS/Engine model with timing chain, gear drive and valve train

Beside the aforementioned models additional models, which consider the tooth geometry in a higher level of detail, are included for spur gears. These models are suited for acoustical studies as well. The on-going development focuses on the expansion of this model to helical gears.

All models can be exchanged against each other without changing the model topology.

2.2.3 Timing Belt (toothed belt)

The timing belt or synchronous belt is another method to couple rotational systems in the engine.

Again, to compute the free forces of the system a constrained based approach is appropriate to use.

To investigate the belt vibrations and the internal forces of the belt a detailed model is required. This model consists of rigid bodies for the tooth and land segments of the belt coupled with a force element that includes the non-linear behavior of the belt material. Contact forces between the belt and the pulleys are included as well. These forces have non-linear stiffness laws and consider the friction at the contact location along the tooth profile. A number of tensioner devices are included in the software. With this model a number of design variations can be compared based on virtual tests with respect to durability and acoustical characteristic. Figure 11 (left) shows a timing belt model with two tooth pulleys and one deviation pulley attached to a mechanical tensioner device (not visible). In this case the model can be driven with a torque or a motion based on test data or data from previous analysis of the attached systems. On the right of figure 11 is a complete engine assembly including valve train, crank train and the timing belt.

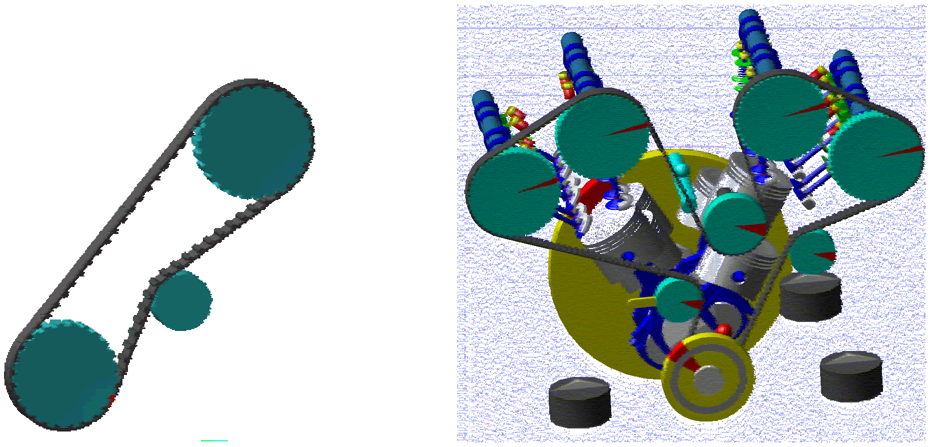


Figure 11: Timing belt and engine assembly including crank train, valve train and timing belt

3 Considerations and Future Work

During the development of ADAMS/Engine powered by FEV it was a main objective to reflect the complex processes in the engine development process into the software architecture. This means that during all development phases the model refinement can easily be adjusted in order to balance modeling accuracy against the computational effort according to the task at hand. Also it is possible to combine several subsystems to a full engine assembly due to the modular approach. The consistency of all modules makes this possible. Such a combined model is shown in figure 11.

The simulation of such complete models in low levels of refinement is feasible and recommended; for instance studies regarding the free forces and moments of the entire engine can be performed rather quickly. If higher levels of refinement are desired, the computational effort in a few cases exceeds the time available during the development process for such models to be a standard step in the process. On the other hand despite the high computational effort these models deliver results, which cannot be measured and therefore can be used for fundamental studies. Additionally it can be expected that the development of computer performance will continue with the same gradient so that the introduction of such a modular software approach is meaningful at this point in time.

In future modules the importance of flexible structures will increase further. Although the integration of flexible bodies is possible in principal already, the current development is focused on improving and automating the integration of flexible bodies in the crank train area in particular.

4 Literature

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