Valve Train Design and Calculation for High-Performance Engines

Camshaft Design System is a computing programme for the design of different types of valve trains. Starting from the related acceleration curve of the valve, which is mapped as a spline, the cam profile is calculated using the valve train geometry.

The cam profiles are especially suitable for subsequent dynamic simulation calculations

The purpose of the system is the development of high-quality valve acceleration curves that comply with the hydrodynamic fringe conditions of the charge cycle while providing an oscillation-attenuated valve train that is subjected to as little dynamic stress as possible. The cam profiles obtained with this approach are also especially suitable for subsequent dynamic simulation calculations, e.g. using the multibody simulation programme RecurDyn from FunctionBay, because, due to the particular spline approach, they do not display numerical noise in the calculated acceleration curve.

Camshaft Design System (CDS) is applied in almost all areas of engine development: car series development, large diesel engines and all areas of motor racing, as well as by system suppliers, in research and teaching. As conventional design soon comes up against limiting factors, special design tools have been developed for valve trains in high-speed engines.

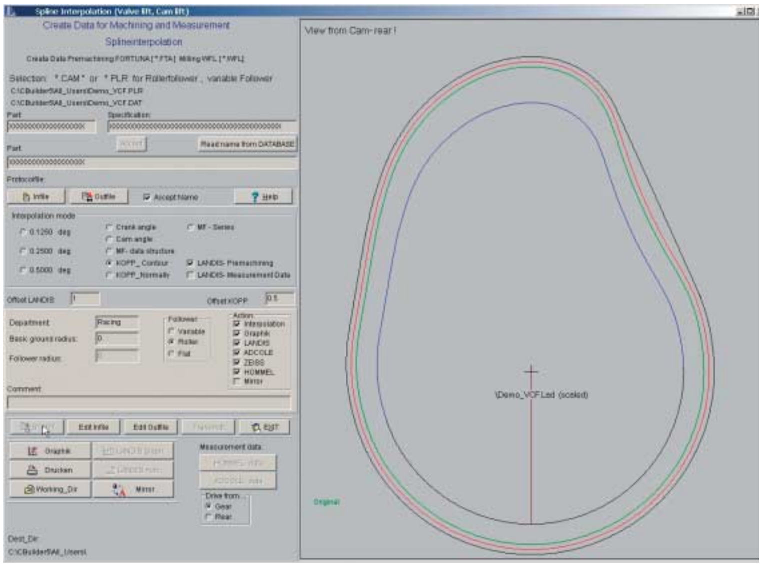

Figure 1: Camshaft Design System is applied in almost all areas of engine development.

System Architecture

The flexibility and adaptability of CDS is due to the modular structure of the programme, which is made possible by programming with the Borland C++ builder for the Windows operating system. New requirements can be integrated without problems and custom adaptations can be performed without loss of time. A special module, for example a new type of valve train, can be integrated without requiring the new installation of the system.

The Design of the Acceleration Curve

The Hertzian stresses of a valve train depend mainly on the forces of inertia and therefore directly on the acceleration of the parts involved. Therefore, the design of the valve train in the CDS system starts with the layout of the related valve acceleration curve, Figure 2.

By generating the acceleration function with any number of spline nodes, any required characteristic can be obtained. This acceleration curve can simply be optimised and adapted by shifting the nodes with the mouse pointer or the navigator. In this way, the acceleration curve can be changed quickly without loss of accuracy. The dynamic opening and closing behaviour of a valve train is decisively influenced by the ramp in the acceleration curve. For this reason, the length and height of the ramp can be specified. Which shape of ramp is used depends on the type of valve train and the conditions of service. To take care of this, the ramp shape can be freely defined by the user. During the computation, the spline nodes characterising the ramps are automatically scaled to the required height to obtain the ramp lift. If the valve lift needs to be changed, a central spline node (green) is defined. If this spline node is enabled, the valve lift width can be set with the slider

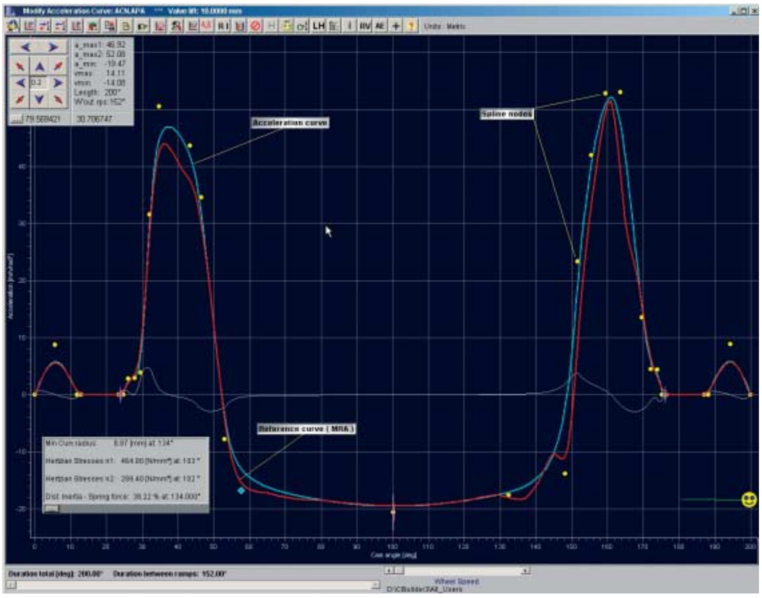

Figure 2: Graphical user interface for the modification of the acceleration curve.

that is visible in the lower left part of the screen. The curve extends or shrinks accordingly. The acceleration curve and the ramp shape do not change.

A pointer tool that directly shows the area conditions in the first integral of the curve is visible in the lower right of the screen. Correct surface compensation is important to avoid partial lifting or exceedingly large deformation during cam rotation.

From the valve law of motion generated in this way, the cam profile is calculated by linking it with the valve train geometry. The valve train geometry can be generated with a few parameters in an input screen. This makes the geometry easy to vary and optimise.

The generated cam profile features high numerical quality, which is very important when using it for dynamic simulation. On the other hand, a profile of this kind can only be obtained from a valve law of motion that complies with the same numerical requirements. The spline method by which the valve lifting curve is calculated offers, by the way of 2nd derivative of the valve law of motion (acceleration), all possibilities to obtain the required numerical quality.

For a direct assessment of the effects of modifying the valve acceleration and valve train geometry, the CDS system provides a large number of standard values for valve train analysis and assessment of the producibility of the cam. For example, the distance inertia spring force (if available), the negative curvature radii, Hertzian pressure and the lubricating film thickness at the cam contact surface are calculated as parameters of the dynamic behaviour and displayed in a window. All steps of the optimisation process with the typical characteristics can be viewed in summary in the development history and restored if necessary. This supports the systematic optimisation with automatic documentation.

A description of the complete functionality of the system is not possible within the scope of this article. However, it should be noted that other interfaces with CAD systems, for quality control and testing, which ensure the homogeneous nature of the subsequent processes are available.

The interface to manufacturing and quality control generates data for the grinding and measuring machines in the required format

Manufacture and Quality Management

The interface to manufacturing and quality control generates data for the grinding and measuring machines in the required format. The following grinding machines are supported: Kopp, Schaudt, Fortuna, and Landis, and the measuring machines: Adcole and Hommel.

Influencing the Dynamic Behaviour

The dynamic behaviour of a valve train depends very much on the stiffness and attenuation of the parts of the valve train and the

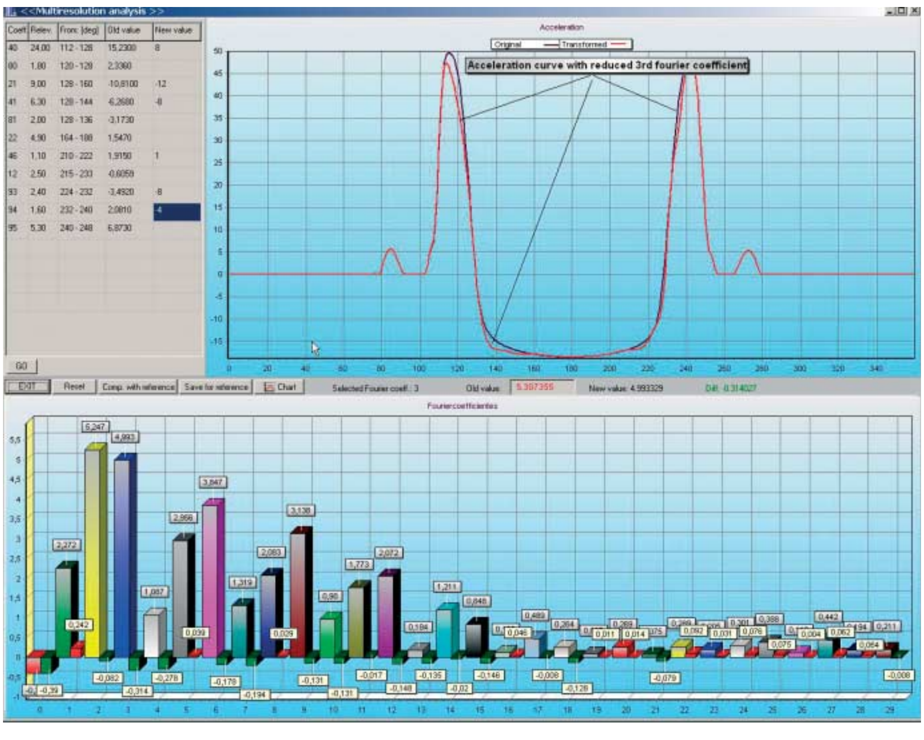

Figure 3: Multi-resolution analysis.

The shape of the valve acceleration curve can excite frequencies in the range of the natural frequencies of the valve springs

points of contact and joint. Because the valve spring is the part with the least hardness and the lowest natural frequency, its effect is especially high. For example, the shape of the valve acceleration curve can excite frequencies in the range of the natural frequencies of the valve springs. The orders excited by the valve acceleration are displayed by means of so-called multi-resolution analysis (MRA), Figure 3.

MRA coefficients

MRA establishes a correlation between the Fourier orders with their global action and the local effects of the MRA coefficients. This is very important because the natural frequencies of the valve spring change significantly with the valve lift. This makes it possible to assign frequencies from the spectrum of natural frequencies to local areas.

The lower diagram shows the Fourier coefficients that can be assigned to a frequency with reference to the speed of a camshaft. After selecting the Fourier coefficients that are to be modified, the MRA coefficients that effect the selected Fourier order are displayed in tabular format. The relevance shown in the table is a measure of the influence of the MRA coefficients on the selected Fourier order.

The third column of the table indicates the local range in which the MRA coefficient influences the acceleration function. The curve in the top diagram shows the local effect of the modified MRA coefficients on the acceleration curve. The MRA coefficients are selected in such a way that there is no effect on the ramp. The deviations of the Fourier orders from the original curve are shown in the lower diagram. After the end of the MRA, a reference curve is generated from the modified curve. The reference curve (red colour) is displayed in the development system. The acceleration curve is adjusted to the reference curve by shifting the spline nodes. Next, the calculation is performed again and the MRA is displayed. It may be necessary to repeat this procedure several times before the required result after the dynamic simulation is obtained. At this time, the calculations are exclusively made on the valve lift curve.

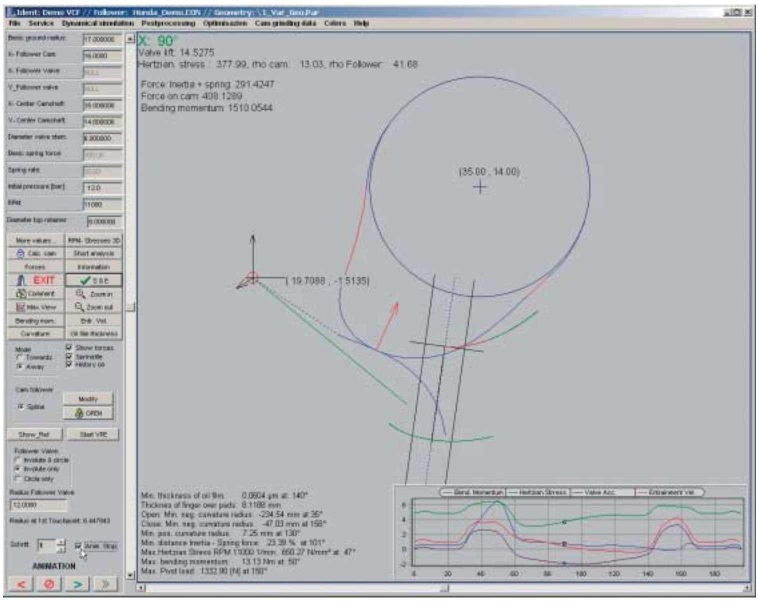

Figure 4: Valve train: finger follower with variable follower contours.

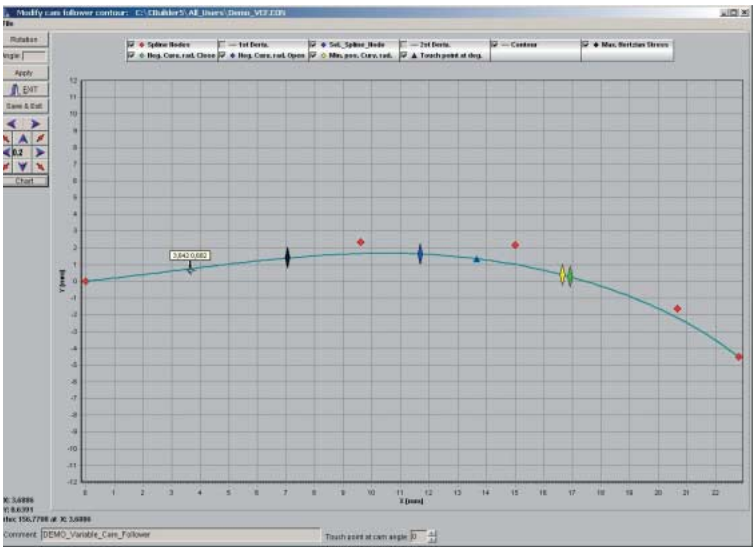

Figure 5: Graphical user interface for the manipulation of the follower contour spline.

Finger Follower with Variable Follower Contours

The speeds of the engines used in Formula 1 racing cars cannot be obtained with wire springs. These very high speeds produce extremely high forces of inertia. The compressive forces at the cam profile and the cam follower as well as the deformation forces acting on the valve are correspondingly high. Consequently, it was necessary to develop a valve train concept that allowed minimisation of the compressive forces at the cam and the transversal forces at the valve, Figure 4.

Follower contour at the cam end: Generally, the contour of the cam follower is characterised by a circular arc, which is sufficient for the conventional valve train. If the circular arc is substituted by a spline, it is possible to assign different curvatures to the follower. The calculation of a cam profile with such a follower contour cannot be accomplished with conventional methods. Therefore, a new method of calculation for a variable follower contour had to be developed. If the follower contour

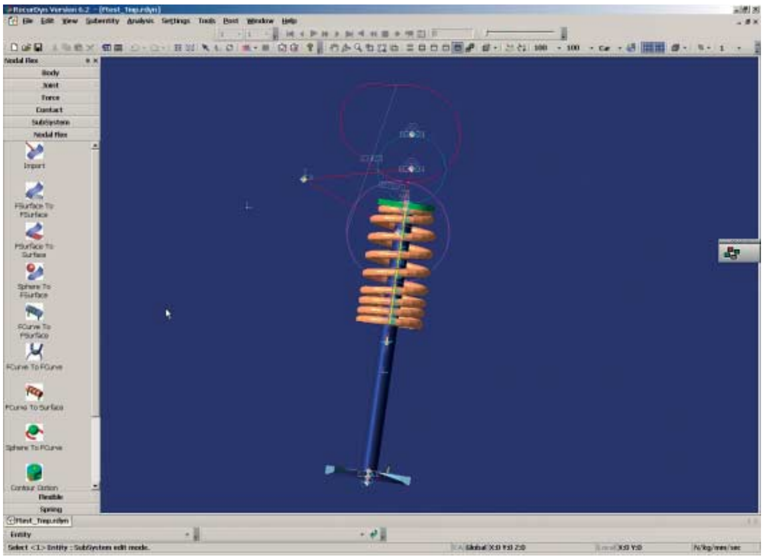

Figure 6: Finger follower with a wire spring in the RecurDyn simulation system.

with a spline is characterised, the contour can be modified exactly at those points at which the curvature radii of the cam profile, the Hertzian pressure or the entrainment velocity are influenced. Figure 5 illustrates the programme with which the spline of the follower can be modified. The characteristic points – positions of minimum concave radii at the cam profile and of maximum Hertzian pressure between the cam and follower – have been highlighted.

The follower contour at the valve: In order to reduce the transverse forces at the valve, a suitable follower contour at the valve end of the lever has to be developed. Here, the circular involute is a good solution. The circular involute can be derived directly from the valve train geometry. What is more, the circular involute has a roll motion characteristic in the movement with the valve. This allows a significant reduction in the transverse forces acting on the top retainer, and the stress on the pneumatic seals is relieved. Finally, the reduction in the friction loss means that the reliability of the valve train can be improved substantially.

The circular involute can be derived directly from the valve train geometry

The Interface to the Simulation System

The interface in the valve train calculation transfers the cam profile, valve train geometry and the valve spring to the simulation system. Stiffness values of the valve

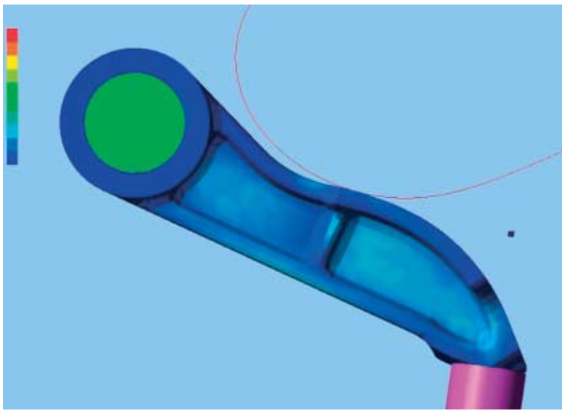

Figure 7: Finger and valve in a finite element structure.

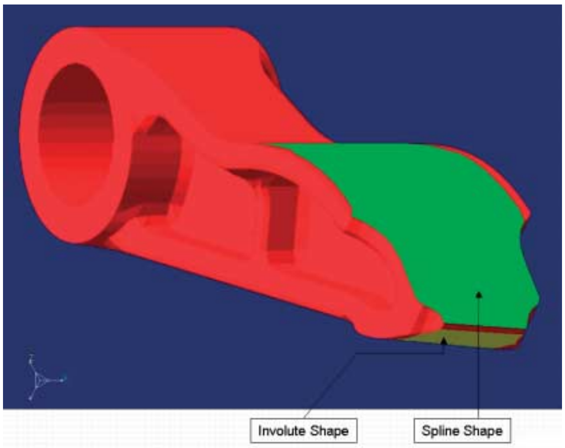

Figure 8: Finger in a finite element structure.

train, forces of inertia and the contact characteristics can be set in a wide-range tool. The simulation calculation runs as a background process and comprises the predefined speed range with the specified speed steps.

The target of the simulation with RecurDyn is the subsequent dynamic evaluation of the valve train kinematics developed in CDS, especially under the action of the calculated cam profile. One focus of study is the excited natural frequencies of the valve spring in the range of the lift and base circle phases, because the resonant ranges of the spring, as the lowest frequencies in the system, are critical to the dynamic behaviour of the valve train, especially at high speed. A so-called multi-mass spring and a diagram as a genuine finite element structure are available for the detailed imaging of the valve spring. This finite element structure is also available for the valve and lever, Figure 6.

In order to enable the assessment of CDS-designed ramps for the opening and closing of the valve under dynamic aspects, RecurDyn has a series of hydraulic clearance compensation elements. Whereas the hydraulic behaviour of this backup element is almost rigid in the phase of highest acceleration, it is critical to the characteristics of the valve set-down behaviour, in particular, for example, in connection with the closing ramp of the cam. Depending on the frequency range or detail of a problem under study, certain parts, in most cases the levers (finger follower, rocker arm, etc.) or the valve, can also be substituted by flexible components and can be studied in RecurDyn. In this way, the dynamic action caused by the flexural elasticity of levers and valves can also be considered, Figure 7 and Figure 8.

To avoid having to generate a new valve train every time in the standard range, a library of valve trains with preset parameters has been developed and included in the RecurDyn/Valve module. Their data can either be input manually or – preferably – can be imported automatically in CDS via the interface. Thus, when used in combination, CDS and RecurDyn provide a simulation environment that constitutes a closed development loop from the design of the fundamental valve train kinematics to the detailed simulation of dynamic behaviour.

The post-processing provides views of the result of the simulation in 3D or 2D images, Figure 9.

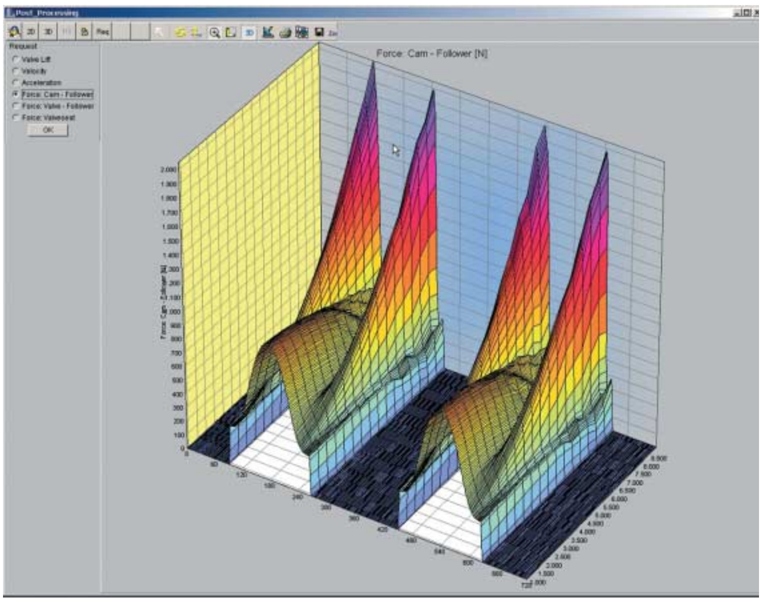

Figure 9: Simulation post-processing: force at cam with increasing speed.

Concluding Remarks

The use of CDS for development tasks in motor racing and especially Formula 1 proves the high capability of this development tool. The close cooperation with the users and partners and their valuable input have made CDS a universal tool for valve train development.

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