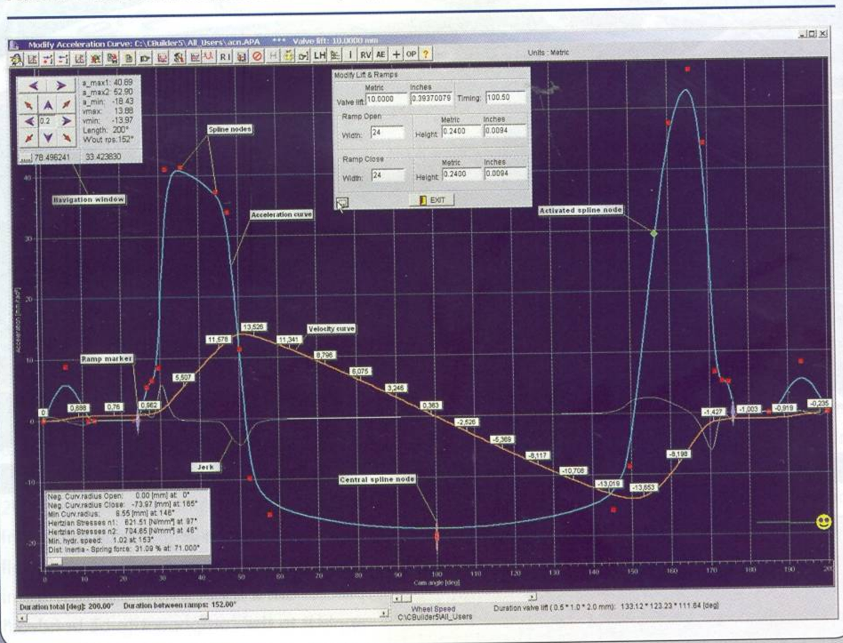
CATCHING THE FAST TRAIN

As conventional design reaches its limits, special design tools have been developed for valve trains in high-speed racing engines. Dieter Zuck analyses Camshaft Design System (CDS), a simulation tool finding applications in Formula One

FIGURE 1 GRAPHICAL USER INTERFACE (GUI) FOR MODIFICATION OF THE ACCELERATION CURVE



LEFT Velocity and numerical values are displayed in this GUI

OPPOSITE The CDS simulation system has been harnessed for valve trains in all areas, from series production to Formula One

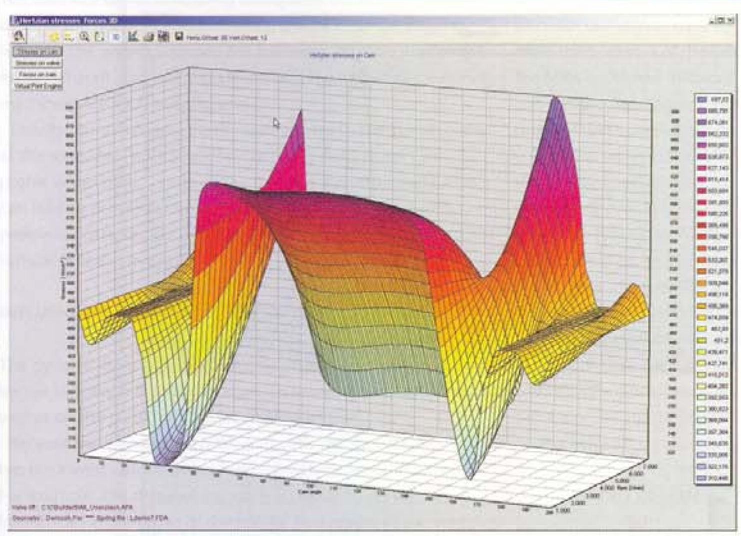
CAMSHAFT Design System (CDS) is a computing tool for the design of different types of valve trains. It is used in almost all areas of engine development: series-production passenger car development, large diesel engines and all areas of motor racing, as well as by system suppliers, in research and in teaching.

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 purpose of the system is the development of high-quality valve acceleration curves that comply with the hydrodynamic boundary conditions of the charge cycle while at the same time 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. For example, using the multi-body simulation programme RecurDyn from FunctionBay, as the application of the spline approach means that they do not display numerical noise in the calculated acceleration curves.

> "The cam profiles obtained are especially suitable for subsequent dynamic simulation calculations"

FIGURE 2 HERTZIAN STRESSES WITH INCREASING ENGINE SPEED



SYSTEM ARCHITECTURE

The flexibility and adaptability of CDS are due to the modular structure of the programme, which is made possible by programming with Borland C++BUILDER for Windows operating systems. New requirements can be integrated without difficulty and customisation can be carried out quickly. A special module, such as a new type of valve train, can be integrated without the need to re-install the system.

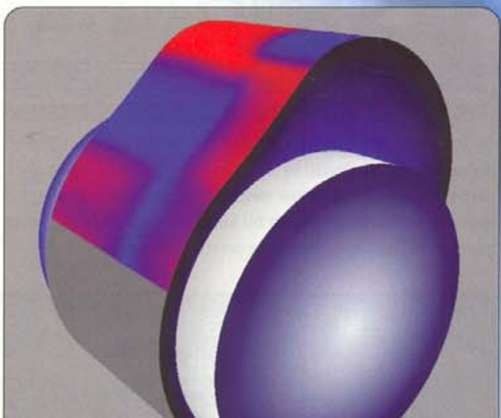
THE ACCELERATION CURVE

The stresses on a valve train mainly depend 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 1).

The generation of the acceleration function with any number of spline nodes allows any required characteristic to be obtained. This acceleration curve can be simply optimised and adapted by moving the nodes with the mouse pointer or the navigator. In this way, the curve can be quickly changed without any loss of accuracy.

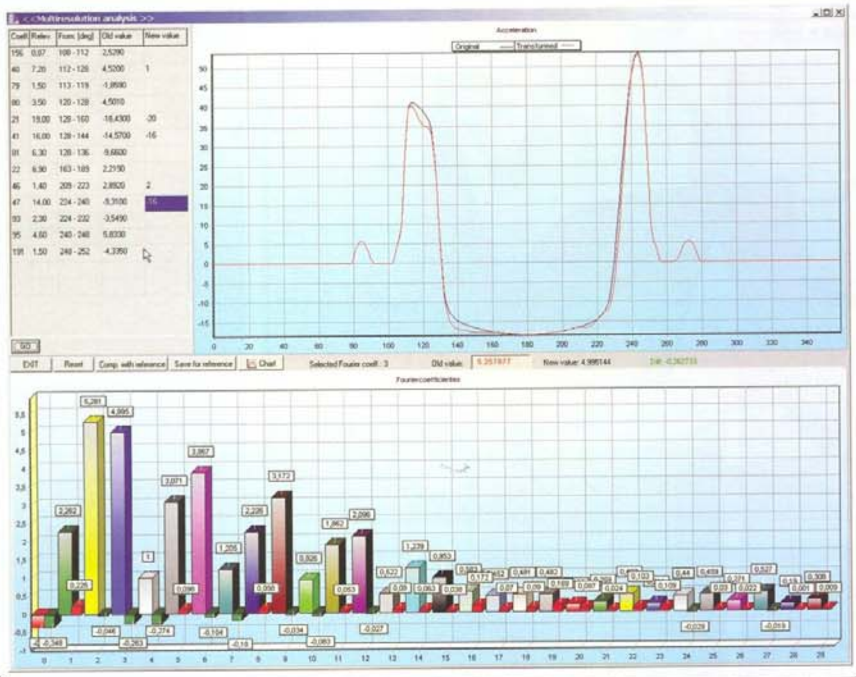
The dynamic opening and closing behaviour of a valve train is decisively influenced by the ramp in the acceleration curve. For this reason, it is possible to define the length and height of the ramp. The shape of the ramp depends on the type of valve train and the operating conditions, so the ramp shape can be freely defined by the user.

During the computation process, the spline nodes characterising the ramps are automatically scaled to the required height to obtain the ramp lift. If the valve lift width has to be changed, a central spline node (green) is defined. If this spline node is enabled, the valve lift width can be set using the slider that is visible in the lower left part of the screen. The curve extends or shrinks accordingly. The acceleration curve and the ramp shape remain unchanged.



A pointer tool is visible in the lower right-hand side of the screen. It directly shows the area conditions in the first integral of the curve. The solver performs the correct area balancing for the calculation. This ensures that only valve lift curves with smooth ▶

FIGURE 3 MULTI-RESOLUTION ANALYSIS



derivations are obtained.

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

> "MRA establishes a correlation between the Fourier orders with their global action and the local effects of the coefficients"

The cam profile generated in this way is of high numerical quality, which is very important if it is to be used in a dynamic simulation. On the other hand, a profile of this kind can only be obtained from a law of valve motion that complies with the same numerical requirements. The spline method used for calculating the valve lift curve offers all possibilities for achieving the required numerical quality by way of the second derivative of the law of valve motion (acceleration).

Calculation of the first derivative (velocity) is also available as an option. For the design of sensitive areas of valve lift (eg the ramps), the user can display the first integral (velocity with related values) to facilitate the design of the contact speed of the valve.

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 for assessing producibility of the cam. For example, the spring force inertia distance, the curvature radii, compression forces and the lubricating film thickness at the cam contact surface are calculated as characteristic values of the dynamic behaviour and displayed in a window.

All steps of the optimisation process can be viewed in summary with the typical characteristics in the development history and restored if necessary. This allows systematic optimisation to be carried out with automatic documentation.

A description of the complete functionality of the system is beyond the scope of this article. However, it should be noted that other interfaces to CAD systems and to manufacturing, quality control and testing that ensure the homogeneous nature of the subsequent processes are optionally available.

MANUFACTURING & QUALITY CONTROL

The interface to manufacturing and quality control generates data for the grinding and measuring machines in the required formats. The system supports the following grinding machines: Kopp, Schaudt, Fortuna and Landis, and the following measuring machines: ADCOLE and Hommel.

Usually, for roller pickups, the data relates to the centre path of the follower. This makes the contour points of the cam profile wider in the range of the negative curvature radii. This can lead to problems during manufacturing. To avoid such problems, data can be calculated in constant angle steps on the surface of the cam profile

INFLUENCING DYNAMIC BEHAVIOUR

The dynamic behaviour of a valve train depends to a great extent on the stiffness and attenuation of the valve train components as well as on the points of contact and the joints.

Because the valve spring is the part with the least stiffness and has the lowest natural frequency, its influence is particularly 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 multi-resolution analysis (MRA).

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 in Figure 3 shows the Fourier coefficients that can be assigned to a frequency with reference to the speed of the camshaft. After the Fourier coefficients that are to be modified have been selected, the MRA coefficients that affect the selected Fourier order are displayed in a tabular form. The relevance shown in the table is a measure of the influence that the MRA coefficients have 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 influence of the modified MRA coefficients on the acceleration curve. The coefficients are selected in such a way that there is no effect on the ramps. 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 can be displayed in the development system. The acceleration curve is adapted to the reference curve by moving 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 is obtained after the dynamic simulation. At this time, the calculations are made exclusively on the valve lift curve.

VALVE SPRING DESIGN

The dynamic behaviour of the valve spring as the element with the least stiffness in the valve train dominates the overall dynamic behaviour of the system. It is therefore necessary to have a powerful, dynamic model for the design of the valve spring.

All boundary conditions for the characterisation of the valve spring, such as the wire profile (with any shape), pitch characteristics and outer shape, are considered. Like the pitch design, the outer shape of the spring is characterised by a spline.

Figure 4 shows the manipulation of the pitch curve. The curve is manipulated at the spline nodes. Placing a reference curve under this curve makes it possible to copy or re-design ▶

FIGURE 4 GUI FOR MANIPULATION OF THE PITCH CURVE

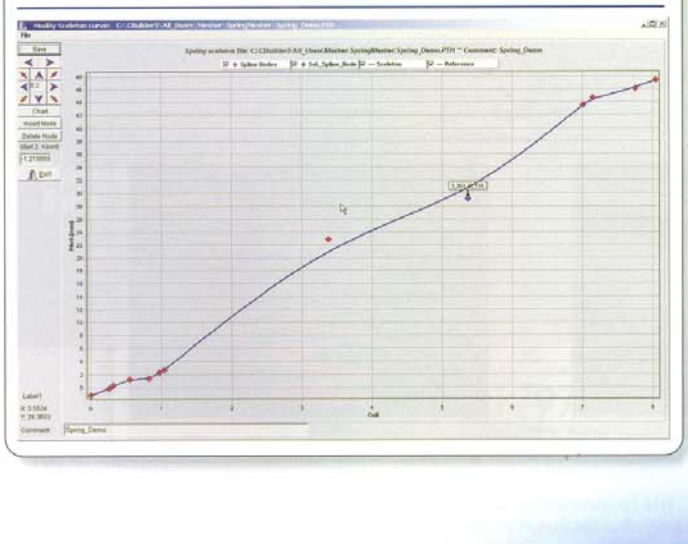
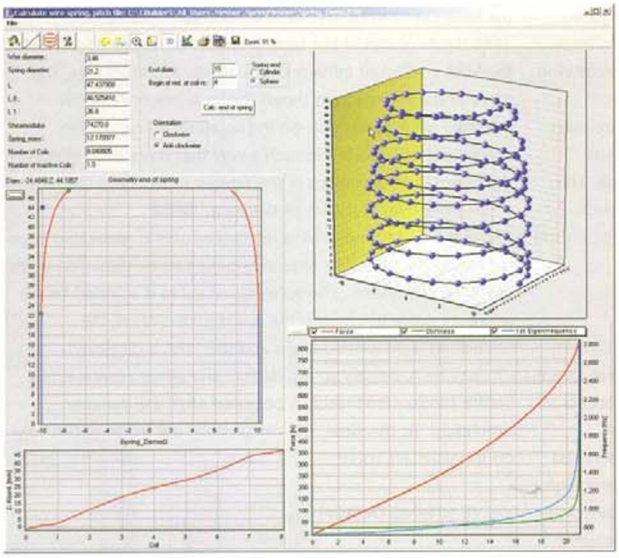


FIGURE 5 CALCULATION OF THE VALVE SPRING



available winding curves.

The calculation yields the skeleton curve of the spring, the spring force curve of the compressed spring, the spring stiffness curve and the natural frequency curve. It also provides two types of spring, one multi-inertia and one FEM. The files representing the calculated springs are transferred to the simulation system, and the simulation calculation with the modified springs can then begin.

> "The variable follower contour at the valve end allows valve angles of more than 90° to the horizontal"

PNEUMATIC VALVE SPRINGS

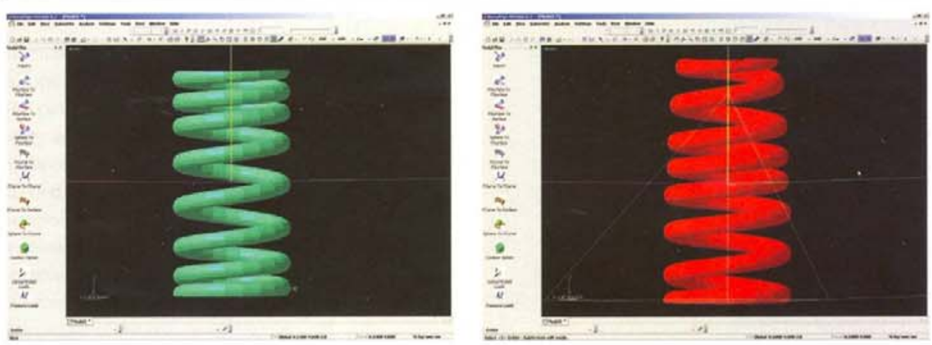
The extremely high speeds of Formula One engines cannot be achieved with wire springs due to their dynamic characteristics. Pneumatic springs, on the other hand, are able to develop the forces necessary to counteract the forces of inertia that act at such extreme speeds.

Equally high are the compressive forces at the cam profile and the cam follower as well as the deformation forces acting on the valve. As a result, it was necessary to develop a valve train concept that minimised both the compressive forces at the cam and the transverse forces at the valve.

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.

Representing the cam follower contour by means of a spline allows the contour to be modified at precisely those points at which the curvature radii of the cam profile, the compressive forces or the entrainment velocity are influenced. ▶

FIGURES 6 & 7 VALVE SPRINGS DESIGNED USING THE SOFTWARE



BELOW The figure shows the follower profile and the distribution of Hertzian stresses related to the follower profile

FIGURE 8 GUI FOR MANIPULATING THE FOLLOWER SPLINE

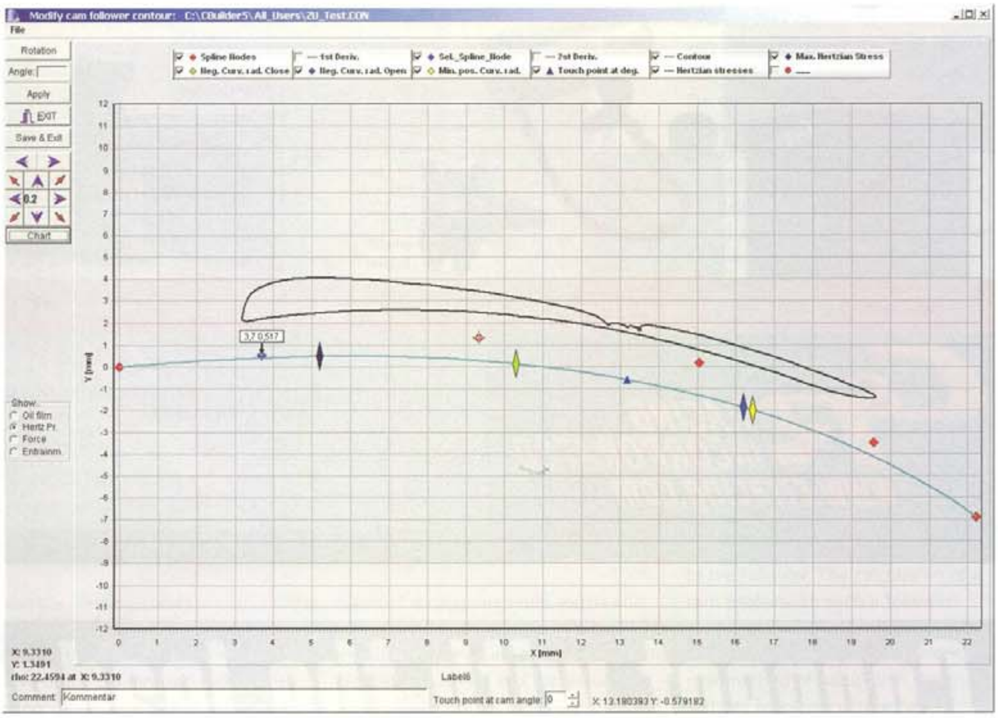


Figure 8 shows the graphical user interface that is used to modify the spline of the cam follower. The characteristic points – the positions of the minimum concave radii at the cam profile and the position of the minimum positive radius of curvature of the maximum compressive force between the cam and the follower – have been marked. This allows the cam profile to be modified by changing the contour of the follower.

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. It can be directly derived from the valve train geometry. What is more, the circular involute has a roll motion characteristic in its movement with the valve. This allows a significant reduction in the transverse forces acting on the top retainer to be achieved, and the stress on the pneumatic seals is relieved.

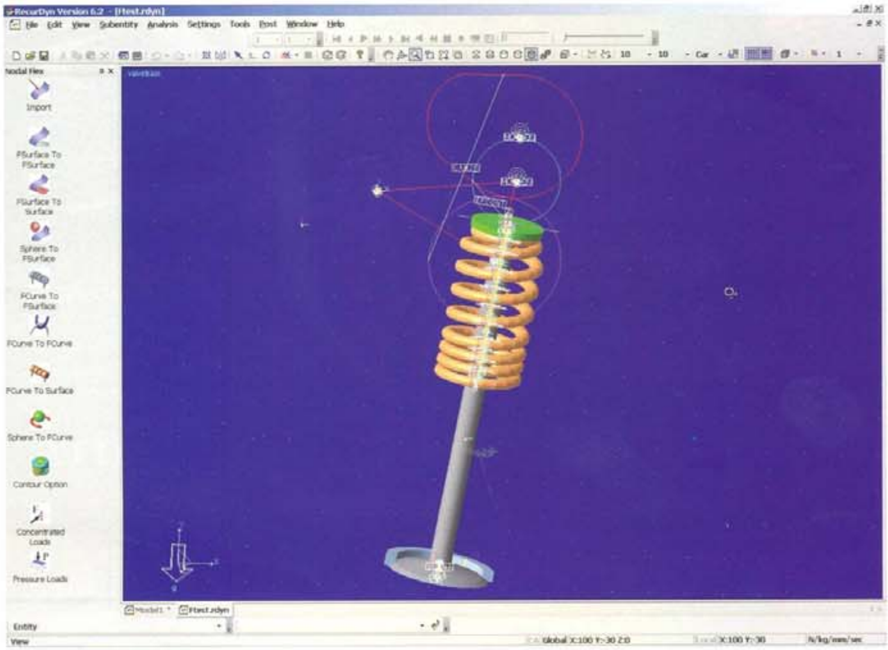
An important advantage is that the variable follower contour at the valve end allows valve angles of more than 90° to the horizontal (Figure 8). This allows the knuckle of the lever to be placed at locations other than in the centre of the cylinder head. As a result, a shorter lever with a higher stiffness and lower moment of inertia is obtained which in turn reduces friction and improves the reliability of the valve train.

INTERFACE TO THE SIMULATION SYSTEM

The interface in the valve train calculation transfers the cam profile, the valve train geometry and the valve spring to the simulation system. Stiffness values for the valve train, the forces of inertia and the contact characteristics can be set in a tool with a wide range. The simulation calculation runs in the background and includes the pre-defined speed range with the specified speed steps.

The aim of the simulation using RecurDyn is the subsequent dynamic evaluation of the valve train kinematics developed in CDS, especially under the influence of the calculated cam profile. Particular attention is paid to the excited natural frequencies of the valve spring in the range of the lift and base circle phases, since 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 speeds. ▶

FIGURE 9 FINGER FOLLOWER WITH WIRE SPRING IN THE RECURDYN SIMULATION SYSTEM



A so-called multi-inertia 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 9).

In order to enable the CDS-designed ramps for the opening and closing of the valve to be assessed under dynamic perspectives, 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 particularly critical to the characteristics of the valve set-down behaviour, for example in connection with the closing ramp of the cam.

Depending on the frequency range or the detail being examined, RecurDyn also allows certain components – usually the levers (finger follower, rocker arm, etc) or the valve – to be substituted by elastic components. This makes it possible to examine additionally the dynamic effects caused by the bending elasticity of the levers and valves.

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

The post-processing (Figures 10 and 11) provides views of the result of the simulation in 3D images.

The use of CDS for development tasks in motor racing and especially in Formula One proves the high capability of this development tool. Close co-operation with the users and partners and their valuable input have made CDS a universal tool for valve train development. ■

> "A closed development loop from the design of the valve train kinematics to the simulation of dynamic behaviour"

FIGURE 10 FORCE AT THE CAM WITH INCREASING SPEED

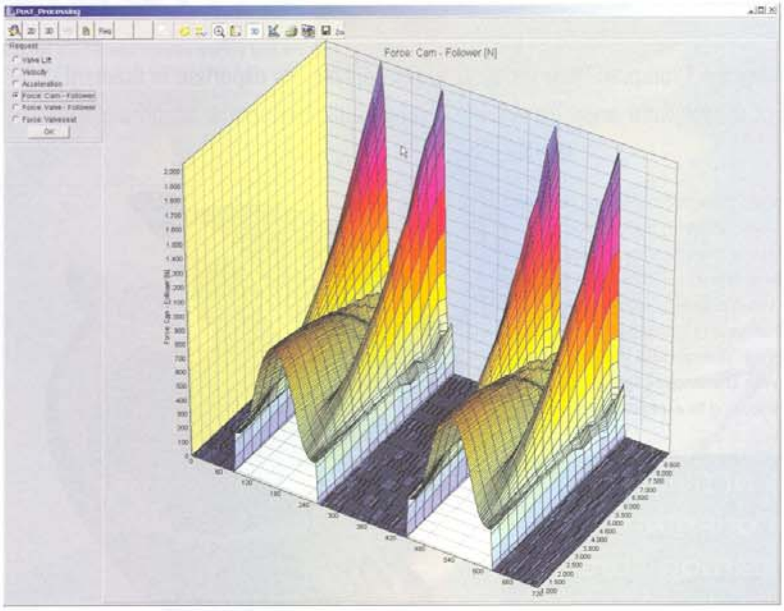


FIGURE 11 FORCE AT THE VALVE SEAT WITH INCREASING SPEED