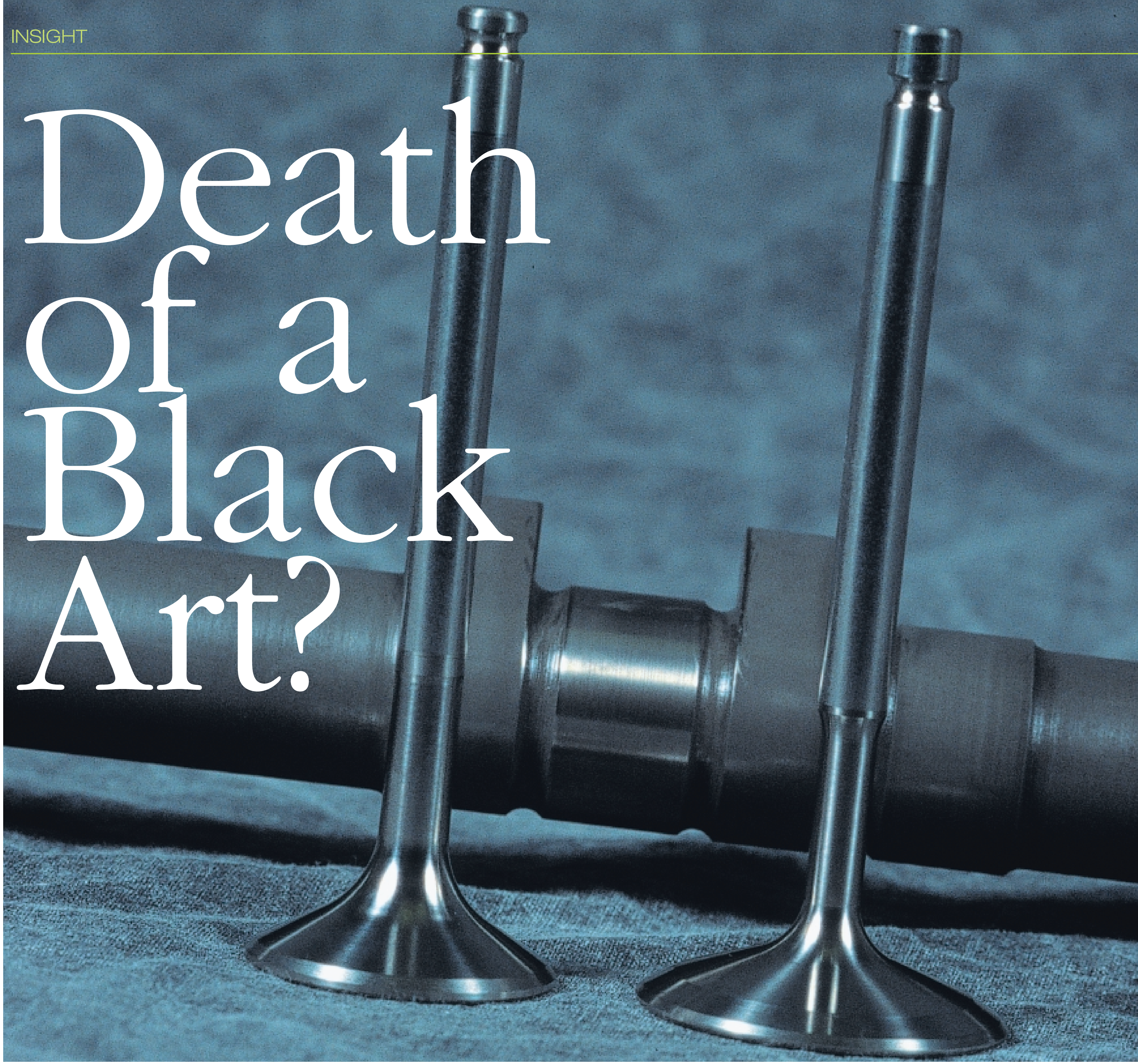
Death of a Black Art?



Mark Oldham of Barnham Racing Engines looks at the scope for the use of 4stHEAD software in the design and development of competition engines

Camshaft design, or more correctly valve lift profile design, has long been a black art performed by a quiet individual in the corner of a large automotive design office. These individuals were held in awe by their contempories because of their knowledge of the high level mathematics required to calculate spline curves and design valve springs. However, those days are coming to an end with the advent of software such as that created by Prof. Blair & Associates, namely "Four-Stroke Head - Design and Analysis Software" (4stHEAD for short).

This package is aimed at the engine designer who may not necessarily have any previous in-depth knowledge of valve lift design or cam manufacture or valve train dynamics. The software's design intent allows highly sophisticated valve train design decisions to be made in the CAD office alongside the normal day-to-day 3D modelling. Over the years, 4stHEAD has matured from a basic valve lift design program into a fully-functional suite capable of designing-in virtually all of the parameters that make up a competitive racing four-stroke cylinder head.

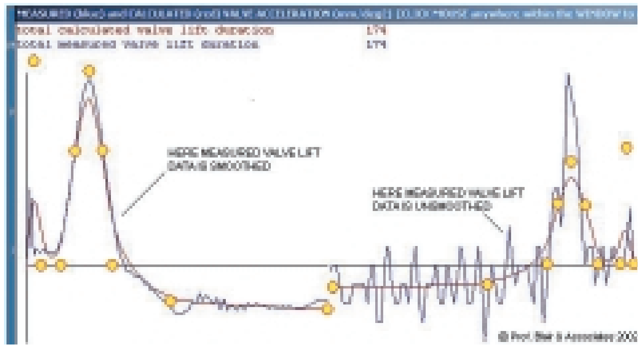
The software package can be used in the motorsport, automotive or industrial design industries although Professor Blair's background and supporting text "The Design and Simulation of Four-Stroke Engines" [1] leans towards competition engine design. 4stHEAD is also fully compatible with Optimum Power Technology's "Virtual 4 Stroke" engine simulation software product [2]. In short, all of the design outputs from 4stHEAD can be exported directly into 'Virtual 4 Stroke' for engine design simulation.

The software comprises nineteen modules which can be split into six sections; valve lift profile design, cam profile manufacture, dynamic valve train analysis, valve train geometry in the cylinder head, air cooling and, finally, empirical assistance for performance-related valve sizing and ducting design.

The first section, valve lift profile design, provides the user with three methods to design a valve lift profile. The methods are HMB, GPB and GPBv2. Each method allows the user to create the opening and closing ramps independently of each other (although they must join smoothly at maximum lift) by specifying, in the case of the HMB method, cam angles, acceleration factors and lift, and in the case of both GPB methods the cam angles and acceleration (mm/deg/deg).

With each method it is possible to import any valve lift file (in .txt format) that is measured in mm (or inch) lift for each cam or crank angle, which you can then copy and analyse using the 4stHEAD software. One of the problems that occurs when attempting to analyse the valve lift profile emanating via an existing camshaft is that the measured data tends to have small errors in it, leading to "jagged" and ➤

Figure 1. The acceleration curve of measured valve lift data being smoothed by 4stHEAD.



(albeit minutely) inaccurate lift curves. With 4stHEAD this data can also be analysed because the software uses very advanced smoothing techniques as shown in Figure 1.

Figure 1 shows the acceleration diagram of some measured data (blue line) and the copy of that data (red line) using the GPB method. The closing ramp (RH side) is shown unsmoothed and you can see how scattered the data points are after they have been differentiated twice from the measured lift values. The opening ramp (LH side) has been through one smoothing iteration and you can easily see the effect that has had in smoothing the raw data.

After smoothing the measured data it is possible to estimate the line of best fit by clicking and dragging the turn points shown as the yellow markers in the figure. With these techniques it is possible to copy imported lift files with incredible accuracy and thence to analyse that data and of course by doing this to someone else's valve lift curve you now know exactly how it was designed!

It cannot be emphasised enough that the smoothing routines inherent in these valve lift profile design methods are the most sophisticated available anywhere. These smoothing routines lead to 'reduced jerk' which is actually 'lesser impulse' on the valvetrain and that means reduced stresses and lower valvetrain noise without diminishing the performance-related characteristics of that valve lift profile.

All three methods graphically show the lift, velocity, acceleration and jerk curves with maximum and minimum values displayed numerically so that the designer can iterate towards the required lift curve with ease. The software saves the results in a text format file which can be imported directly into an Excel spreadsheet for comparison, presentations and reports. Each method of valve lift design (HMB, GPB and GPBv2) has its own merits so I will deal with each separately in the following paragraphs.

THE HMB METHOD

This is a very quick and easy way to create a valve lift profile based on the lift curve. The user can input maximum lift, ramp type, acceleration, transition and deceleration zones. Also included are two acceleration factors to control the shape of the negative and positive acceleration curves.

The "Z" factor controls the shape of the negative period of the acceleration curve around peak lift. The higher the number (it must be less than 1) then the flatter the period of negative acceleration. The positive acceleration factor "N" can have values of 2, 4, 6 or 8. The lower values give a sharper positive acceleration peak and the higher values give a broader peak as shown in Figure 2.

A very useful exercise for the user is to be able to see the effects these acceleration factors have on the "jerk" (the rate of change of acceleration) and on the shape of the cam profile and both these parameters are catered for in the software.

A high value of jerk will impose greater loads on the valve train and sharp corners in the negative acceleration zone (high values of Z) will lead to a sharp cam profile and high Hertz stresses. The jerk graph is shown immediately on calculation of the lift curve with maximum and minimum values tabulated and the cam profile can be seen to scale in the cam manufacture section discussed later.

Figure 2. Manipulating the acceleration curve using the HMB method.

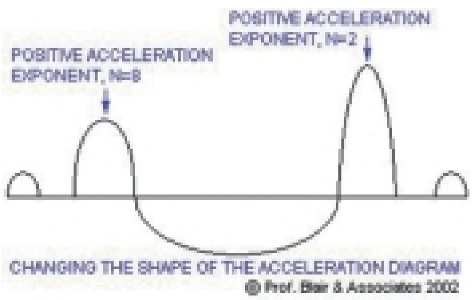


Figure 3. Manipulating the acceleration curve using the GPB method.

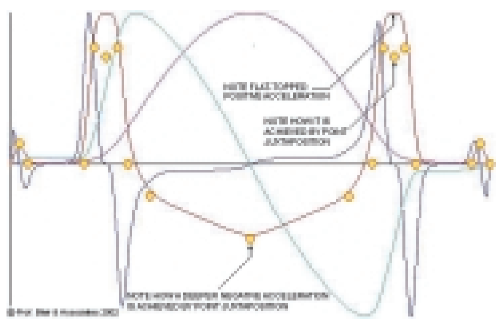


Figure 4. Asymmetrical acceleration curve created using the GPBv2 method.

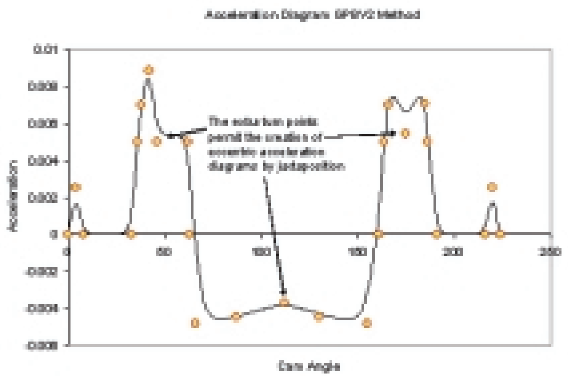
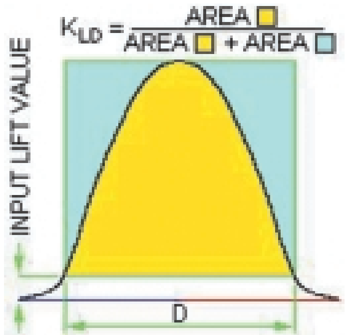


Figure 5. The lift duration envelope is calculated at every iteration of the design.



THE GPB METHOD

This method uses an integration approach to manipulate the acceleration curve. The user is presented with an acceleration curve specified by shape in both angle and acceleration (mm/deg/deg). The valve lift is calculated automatically by integrating the acceleration curve firstly to velocity and then to valve lift. The opening and closing sides of the curve are smoothly wedded around maximum lift and can be symmetrical or asymmetrical as the user requires.

To put it crudely, to increase the valve lift the user decreases the value of negative acceleration. In comparison to the HMB method, the GPB method needs more iteration to find the required solution but offers much more flexibility to the designer.

A total of 18 turn points can be moved "independently" of each other (by clicking and dragging on screen) and this gives the user that increased flexibility over the HMB method. Figure 3 shows how to achieve a flat topped positive acceleration zone (high value of "N" in the HMB method) and a deeper negative acceleration (low value of "Z" in the HMB method) by point juxtaposition.

THE GPBV2 METHOD

This uses the same technique as the GPB method but it utilises 24 turn points to compute the acceleration curve. To use this many points is "geometrical overkill" for a normal valve lift profile but this method permits a huge amount of flexibility so that a truly eccentric valve lift geometry can be created (Figure 4). This can be particularly useful for pushrod systems where the dynamics of the system mean that the valve does not necessarily follow the intended path or also for chasing the piston down the bore with an asymmetrical profile so as to avoid piston to valve contact problems.

With all the three valve lift design methods the user needs to know how well the valve lift curve may operate within an engine. The more area under the valve lift curve then, all things being equal, the better it will fulfil its function. The software predicts a valve lift-duration envelope ratio, as seen defined in Figure 5, at any user-specified lift value giving the designer this vital piece of information every time he changes any of his input parameters.

"The dynamic forces and stresses throughout the springs are predicted"

VALVE TRAIN ANALYSIS (COIL SPRINGS)

The next module of the software concerns the dynamic analysis of valve motion. The complexity of valve spring motion is dealt with by 4stHEAD with a mathematical model of the spring mass system, as shown in Figure 6.

Figure 6 shows the model for a pushrod system and there are separate models for flat tappet, finger follower and rocker arm systems. As you can see from Figure 6 the mathematical model is made of many spring damper systems which allows the user to be very specific in detailing the components that make up his valve train design.

Each coil of each spring is dealt with as a separate but continuous component, which allows progressive coiling and even ovate wire types to be analysed. The model also deals with component separation between them at each juncture where this is possible. In Figure 6 these junctures are at the camshaft/follower, follower/pushrod, pushrod/rocker and rocker/retainer interfaces.

Valve bounce and float can be predicted (hopefully there won't be any unless the user actually wants to move into the valve-lofting mode!) and the software shows all the output graphically. The dynamic forces and stresses throughout the springs are predicted and each coil is calculated separately and graphically represented. ➤

Figure 6. The mathematical model for the dynamic analysis of a pushrod system.

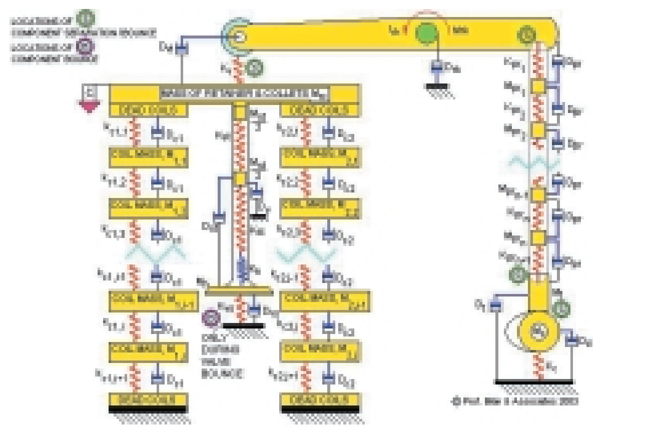


Figure 7. The predicted dynamic exhaust valve lift of a NASCAR type pushrod engine under firing and motoring conditions.

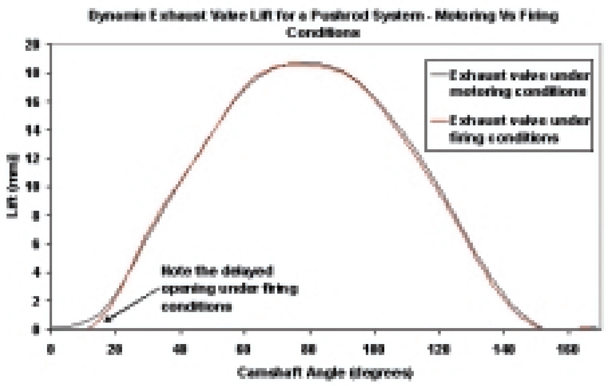
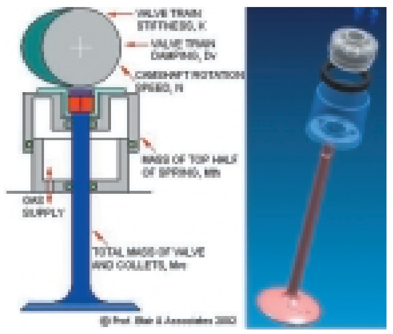


Figure 8. On the left the input geometry of the gas spring is shown as a piston and gas filled cylinder and on the right a 3D model of a typical gas spring system.



The valve train can be analysed under motoring or under firing conditions with gas pressure taken into account. This gives very interesting results when analysing the exhaust valve motion for pushrod systems when opening the valve against cylinder pressure (see Figure 7).

The prospective user is advised in the information pages of the software to measure the actual valve train motion using a "Spintron" machine or some other similar measuring system. In this way the measured data can be matched to the model by adjusting the damping coefficients in the software. Even if the user does not have access to valve train motion measuring equipment the software will allow the prediction of resonant problems and valve spring stresses and the ability to input that data into an engine simulation for the prediction of its performance characteristics.

VALVE TRAIN ANALYSIS (GAS SPRINGS)

A separate module allows the analysis of pneumatic springs and although I have not used this module in anger I can testify that the mathematical model is based on a successful Formula One design.

Figure 8 shows the structure of the geometrical model upon which the spring dynamic analysis is based. The program allows the use of air, nitrogen or carbon dioxide as the spring medium. The mathematical model incorporates unsteady gas dynamic and thermodynamic theory to predict the valve behaviour and, considering the creator of this model, one can be assured that it is somewhat more sophisticated than anything else out there in the marketplace.

Figure 9. The geometrical input required to build the mathematical model of a finger follower system.

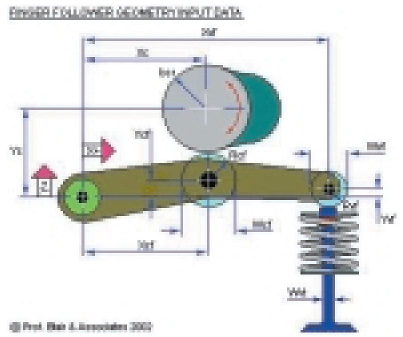
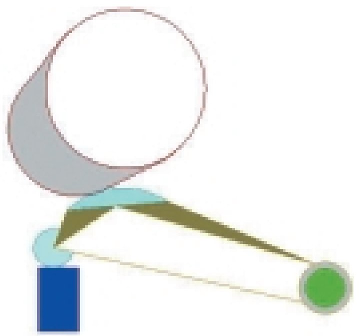


Figure 10. A snapshot from the on-screen dynamic graphics of the moving cam follower mechanism and the rotating cam design which is drawn to scale.



CAM MANUFACTURE

The cam manufacture module takes the designed valve lift and marries it to the follower geometry to produce a cam manufacturing file. The software copes with flat and bucket tappets, roller tappets, finger followers, rocker arm followers and pushrods with valve rocker arm followers. The user has to input a large amount of data but this is entirely reasonable when the geometry and dynamics required to compute an output are considered.

Figure 9 shows an example of the user input required to define a finger follower system. You can see that there are some 12 values to define this system's geometry, and the cam or valve contacts can be designed as either pads or rollers, such is the thoroughness with which 4stHEAD deals with this complex problem.

When designing a valve lift file the user has to consider parameters such as Hertz stresses at the cam/follower interface, oil film thickness, the minimum tappet diameter and the minimum cutter radius for a re-entry type cam profile. All these points are dealt with directly by the software and calculated for the user to read straight from the output page.

Using a finger follower as an example of this cam design process, when the computation is finished the user can see the actual cam under design and its follower mechanism rotate in a movie mode on the screen; a snapshot of this process is shown in Figure 10. As the follower and cam movements are computed and displayed independently, if the on-screen dynamic graphics show no geometrical defects then the user can proceed to output

Figure 11. The Hertz stress output for a finger follower system.

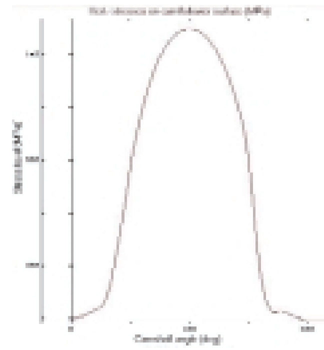
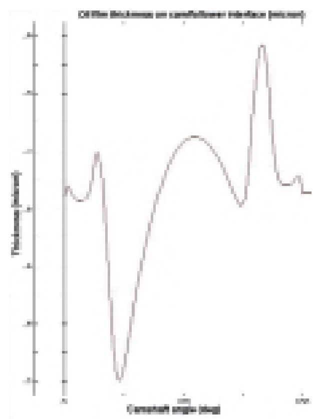


Figure 12. The oil film thickness output for a finger follower system.



the cam design for cam manufacture with confidence in the machined outcome.

Figures 11 and 12 show the output graphs for Hertz stress and oil film thickness respectively, both for the finger follower system illustrated in Figure 9. In Figure 11 the Hertz stress can be seen to be around 1050 MPa over the nose of the camshaft profile at about 100 deg camshaft angle. Recommended maximum values for Hertzian stresses are given in the information pages of the software so that the user can use these as a target when designing his valve lift curve.

The oil film thickness is dictated by the geometry, load and relative velocity, and the lubricant viscosity at its working temperature at the cam/follower interface; Figure 12 shows the solution for a finger follower system. The solution is complex and this is indicated by the shape of the curve which shows the oil film thickness varying from 0.3 to almost 0.9 microns. It would not be intuitive to predict this varying oil film thickness so the

> "The user can see how the valves interact with the piston, bore and indeed how close the valves are to tangling"

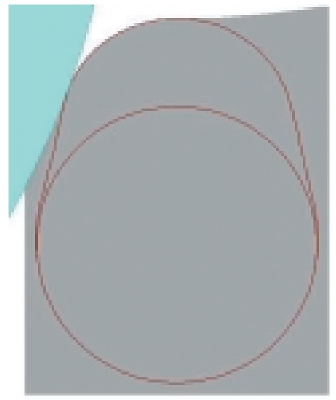


Figure 13. A snapshot from the on-screen dynamic graphics showing a finger follower cam lobe design being profiled by a cutter.

benefits of having this feature in the software are clear.

Figure 13 shows the output of a finger follower cam lobe design being profiled by a cutter. This feature is displayed as an animated movie and this allows the user to view his design to scale. If there are any geometrical manufacturing problems with the design such as an "axe head" profile or an extremely small radius then these will be highlighted with this feature.

All these factors add up to a very design-friendly piece of software that allows the designer to iterate towards the optimum solution as quickly as possible. The output files of cam grinding text are formatted for direct use in many standard grinding machines such as Toyoda, Landis, Berco, or even precisely for Newman Cams to implement. The manufacturing output data can also be exported for in-house cam grinding for those with CNC grinding machine facilities.

DESIGNING A 2, 3 OR 4 VALVE HEAD

The next seven modules are concerned with designing a basic two, three or four valve cylinder head with respect to the geometry of the valves and clearances between the valves, the cylinder bore walls and the piston. The modules are designed to cover the basic geometrical layout of cylinder head layouts used by current engine technology: four-valve head with vertical or pentroof valves, two-valve head with vertical or side valves, two-valve wedge and hemi head and finally a three-valve head with side-valves.

The user specifies the basic geometry, valve head sizes, valve angle, etc., and imports the valve lift output files which, if the user is iterating through a cylinder head design, will have recently been created using 4stHEAD. The program calculates the physical geometry of the combustion chamber and valve layout so that the user can see how the valves interact with the piston, bore and ➤

> "An even more advanced program will be added which will predict the valve pocket geometry within the piston"

indeed how close the valves are to tangling. This output is displayed as data and perhaps more usefully as a scale-animated movie so it is possible to verify any "collisions" that might take place. The piston cut-outs, combustion chamber surface area and valve masking factors are all calculated.

Figure 14 shows the output data for the piston cut-outs, so it is easy to see how valve lift file and cam timing are going to affect the combustion chamber shape. The cam timing can be changed just by typing in a new value and the resulting effect on piston cut-outs or valve tangle can be viewed immediately.

Figure 14. The piston cut-out dimensions are calculated for a pent roof head design.

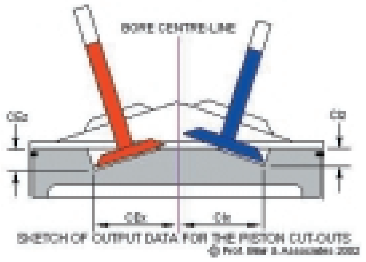
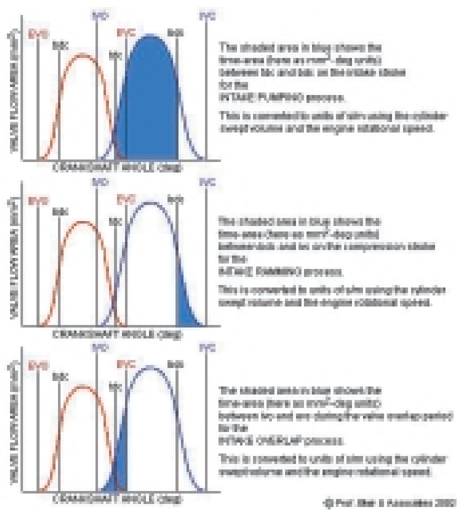


Figure 15. The time areas of the intake module are calculated from the users input and shown here shaded in blue.



It is my understanding that an even more advanced program will be added shortly as a user-upgrade to the 4stHEAD suite. This will predict the valve pocket geometry within the piston, and the machining cutter size and locations to manufacture it, for any three-dimensional orientation of a lifting valve above a moving piston.

AIR COOLING

(A text extract taken from the website [3]):
"Examples of the air-cooling of the cylinders of an engine can be found in industrial engines and in motorcycles, to cite but two examples. The design of finning for air-cooled engines has been aided by the publication of research work by Thornhill et al in a SAE paper 2003-32-0034 which links back to, and is compatible with, previously published data on aircraft engines by NACA some 60 years ago.

"This program, which is within the 4stHEAD suite of programs, takes the approach given by these authors for the heat transfer coefficients of air-cooled fins. It expands that into a design program for the heat dissipated from the finned cylinder head and the cylinder barrel of an air-cooled four-stroke engine as a function of that supplied by the combustion of the fuel or as related to the work output of the engine."

COMBINING VALVE DESIGN WITH ENGINE GEOMETRY

The previous sections of this suite of software have been concerned with designing the mechanical motion and geometrical layout of a four-stroke cylinder head. The final section contains two modules which are concerned with designing the gas dynamic empirical criteria (specific time-areas) so that the performance of the engine can be matched to the mechanical side. The theory is based on Professor Blair's SAE R186 textbook [1] which takes empirical data for a number of different types of well-developed engine designs with optimized valving and ducting and aims to offer a good starting point to achieve the required breathing characteristics.

One module concerns the intake, and the other the exhaust, but both contain the same respective inputs and outputs. The user inputs swept volume, target rpm, target bmep, valve and port and manifold geometry, cam timing and imports his valve lift file be it a static design from HMB, etc., or a measured valve lift file, or a dynamic valve lift file from either of the 'valvetrain dynamics' programs.

The software then calculates the specific time-areas for blowdown, pumping and overlap, or intake ramming be it an intake valve, and compares them to the empirical data so that the user can see directly if the design should give the required performance results. The theory behind all this is that a 'time area per unit swept volume' for any engine, for any aperture, over any angular period and at a particular engine speed is related to the dimensionless gas mass flow. Therefore, for two dissimilar engines at dissimilar engine speeds but at similar bmep there should be some correlation between the time-areas for the same crank angle.

The empirical data is supplied for naturally aspirated engines at maximum power rpm so these factors are taken into consideration when comparing target and designed time-areas.

Figure 15 shows the graphical notation for the time areas of the intake module. The time areas are calculated in mm^2/deg units and converted into units of s/m (time-area per unit swept volume). The valve opening and closing points are marked EVO, EVC, IVO etc. The shaded areas in blue are the time areas that will be calculated from the users design input. The user can iterate through and change the various inputs to immediately determine if the design brief can been met.

> "I am sure that if you said to Professor Blair "I bet you couldn't do this with that software package of yours" it would be done!"

USER-FRIENDLY?

The opening page of the software includes a "getting started" tutorial which takes the user methodically through the software's topography and also a general information page which explains the intent of each module. Each of the nineteen design modules are activated by a single press of a mouse button and all of the modules are accompanied by an information page which helps the user through the design process with a "tutorial" and recommends design targets.

Demonstration files are included for each module so that the user can get up and running with little difficulty and indeed with the opening of each module the user is presented with a set of demonstration data so that the graphics and basic output can be viewed almost immediately. Each "button" is clearly labelled in a logical fashion so that navigating through the software is intuitive. With these features it is relatively easy for the user to pick up the operation of the program.

It must be remembered that this is a technical piece of software written by engineering minds so that you have to be able to understand what data you are inputting and what the program is telling you.

CONCLUSIONS

Clearly, Prof. Blair & Associates has done a tremendous amount of work to supply the user with a software package that allows the design of a valve train at the highest level of technology. The aim of the software is to open the world of valve train design to the everyday engine designer and this it has achieved.

The 'help' files that are indexed from within the software contain hundreds of images, some of which you see used above, and all of which describe to the user with considerable clarity the geometrical, or mechanical, or manufacturing, or mathematical, or gas dynamic implications of the design decisions being made. They and the text which accompanies them could almost make Prof. Blair & Associates another textbook!

Now it is possible for anyone in a design office to learn the once-secret black art of so-called 'camshaft design' and become every bit as expert in this field as their 'consultants'. Maybe more so as this 4stHEAD software is technically, and especially visually, far in advance of the 'spreadsheets' so commonly used in the 'trade'.

The software [3] is sold as a one-off purchase, which buys a perpetual license, training, technical support, and thus far, free upgrades as the software suite is continually expanded. The support given by Prof. Blair & Associates is second to none and customers have at times requested that the software be written in a certain way to suit their particular usage and such changes have then been added to the program for the benefit of every user. I am sure that if you said to Professor Blair "I bet you couldn't do this with that software package of yours" it would be done! That is something that could not happen with some of the more expensive software on the market.

References
[1] G. P. Blair, "Design and Simulation of Four-Stroke Engines", Society of Automotive Engineers, 1998, SAE reference R-186, www.sae.org.
[2] VIRTUAL ENGINES Engine Simulation Software, 'VIRTUAL 4-Stroke', Optimum Power Technology, Bridgeville, PA, www.optimum-power.com
[3] 4stHEAD Design Software, Prof. Blair & Associates, Belfast, Northern Ireland, www.profblairandassociates.com. ■