This is the third and final part in our three-paper Special Investigation into valve spring design for race engines. The authors are:

Gordon P. Blair, CBE, FREng of Prof. Blair & Associates,
Charles D. McCartan, MEng, PhD of the Queen's University Belfast
and **W. Melvin Cahoon, BSc** of Volvo Penta of the Americas

Progressive design

I n the first paper, Paper 1, we examined in detail the design of five (non-tapered) springs; the inner and outer springs for the intake valve of a NASCAR 'Cup' engine, the single intake valve spring from a large capacity V8 inboard marine unit, and the inner and outer valve springs from a motorcycle engine.

In the second paper, Paper 2, we examined in detail the design of three tapered springs; round wire springs from two (speedway racing) motorcycle engines and an ovate wire spring from a large capacity v-twin motorcycle power unit.

In Paper 3, we examine in detail the design of four round wire progressive springs; (a) the inner and outer intake valve springs from an automobile engine and (b) the single intake and exhaust valve springs from a five-valve motocross racing engine.

There are twelve springs in total making up this three-paper investigation and they cover all examples of modern spring design from low to high speed engines, with parallel, progressive and tapered springs, and springs wound with either ovate or round wire. All springs are measured from free height to near coil bind for their load-deflection and stiffness-deflection characteristics. Also, all springs are measured physically and the geometry-based data are computed for their load-deflection and stiffness-deflection characteristics [1.4]. Three of the springs are selected to be modelled in FEA software [1.1] for the same data values and they are also experimentally measured for their natural frequency characteristics which are then compared with computations. In all twelve cases, the measured and computed data are compared numerically and graphically and the physical geometry of every spring is numerically presented so that others can compare their theories with our measurements.

THE GRAPHICS NOMENCLATURE ACROSS THE TRILOGY OF PAPERS

In this Paper 3, the Figures are conventionally labelled as Fig.1 to Fig.29. The same applies to the References. However, to avoid

Fig.1 Test springs; 'UK outer', 'UK inner', 'YZ exhaust' and 'YZ intake'.

TR = tapered round wire TO =tapered ovate wire			
PR=progressive round wire PO= progressive ovate wire			
BASIC INPUT DATA			
SPRING	UK inner	UK outer	YZ exh	YZ int
TYPE	PR	PR	PR	PR
Sc	10	7.375	7.5	7.5
Ms (measured, g)	19.8	50.1	13.1	13.4
Hucs (mm)	50	49.7	37.75	36.45
Hcs (mm)	?	?	?	?
Ds (mm)	38.5	27.5	19	19
Ts (mm)	2.46	3.83	2.4	2.37
k (measured N/mm)	9	26.3	12.5	12.6
Nd	1	1	1	1
COIL SPACING			
SPRING	UK inner	UK outer	YZ exh	YZ int
coil space P1 (mm)	3.9	4.7	4	3.9
coil space P2	3.9	4.8	4.3	4.1
coil space P3	3.9	4.9	4.3	4.1
coil space P4	3.9	4.8	4.2	4
coil space P5	3.9	1.8	2.5	2.2
coil space P6	3.3	1	1.2	1.1
coil space P7	1.6			
coil space P8	1.6			
COMPUTED OUTPUT COMPARED WITH MEASUREMENT			
SPRING	UK inner	UK outer	YZ exh	YZ int
Ms (measured, g)	19.6	50.6	13.1	13.4
Ms (calculated, g)	19.8	50.1	13.3	13.1
k (measured N/mm)	9	26.3	12.5	12.1
k (calculated N/mm)	8.4	24.3	12.7	12.1
DEF bind (measured)	26	22	20.3	19.5
DEF bind (calculated)	26.4	22.2	20.5	19.4

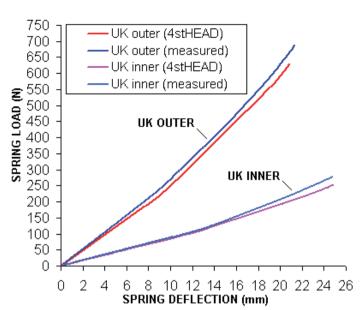Fig.2 Input and output data for the geometry of the valve springs.

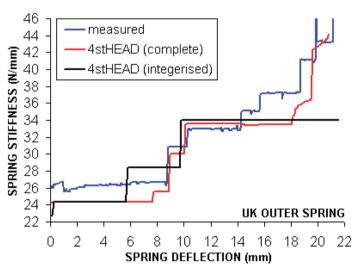Fig.3 Measured and computed load characteristics of both UK springs.

Fig.4 Measured and computed stiffness characteristics of the 'UK outer' spring.

Fig.5 Measured and computed stiffness characteristics of the 'UK inner' spring.

Fig.6 Computed shear stress characteristics of both UK springs.

pedantic repetition, any Figure from earlier Papers of the trilogy can be referred to very simply. For example, if we wish to refer to Fig.1 in Paper 2 here within the text of Paper 3, then it will referred to as Fig.2.1. Similarly, as you can see in the previous paragraph, if we wish to refer to References [1] or [4] from Paper 1 they will be referred to here in Paper 3 as [1.1] and [1.4].

THE VALVE SPRINGS FOR PAPER 3

In Fig.1 is a photograph of the four valve springs. From left to right are the two intake valve springs from an automobile engine, 'UK outer' and 'UK inner', and the exhaust and intake valve springs from a five-valve YZF motocross engine labelled as 'YZ exhaust' and 'YZ intake', respectively.

In Figs.1.2 and 1.4 are the relevant information pages from the 4stHEAD software [1.4] explaining the data symbols for the basic geometry of a valve spring and in Fig.2 are the actual input data values for the four springs in question. All of the springs are wound with round Cr-Si steel wire.
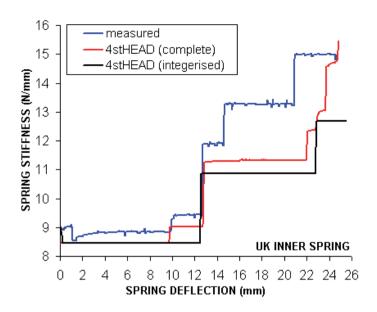
MEASUREMENT OF THE LOAD AND NATURAL FREQUENCY CHARACTERISTICS

As in Papers 1 and 2, each of the test springs is installed on a Lloyds tensile/compression test machine and its load-deflection characteristics measured in 1000 steps from its free height until coil bind. The measurement process is both accurate and detailed. The numerical differentiation of the measured load-deflection data yields the stiffness-deflection characteristics.

In Paper 3, we measure the natural frequency vibration characteristics of three of the twelve test springs, 'KW inner', 'SS', and the 'YZ intake' with respect to deflection. The measurements are recorded by a Polytec PDV-100 portable digital vibrometer connected to a Bruel & Kjaer portable PULSE 3560B data acquisition unit.

MODELLING BY 4stHEAD
OF THE VALVE SPRINGS

In Paper 3, as previously discussed in Papers 1 and 2, the theoretical modelling of the deflection of a valve spring under load is conducted ▶
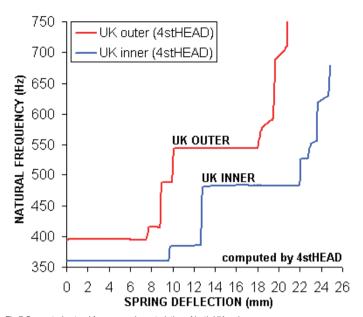
Fig.7 Computed natural frequency characteristics of both UK springs.

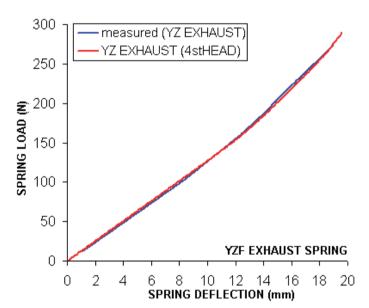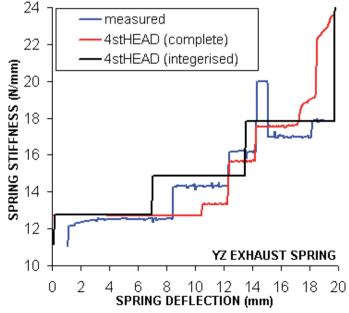Fig.10 Measured and computed load characteristics of the 'YZ intake' spring.

Fig.8 Measured and computed load characteristics of the 'YZ exhaust' spring.

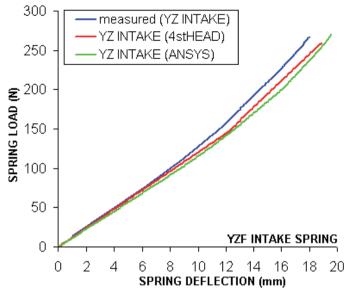Fig.9 Measured and computed stiffness characteristics of the 'YZ exhaust' spring.

by two differing approaches. The first is called 4stHEAD [1.4], the basic theory is described in Paper 1, and is applied in Paper 3 to the four valve springs. The results are correlated against the experimental measurements of the spring characteristics of load and stiffness.

In Fig.3 are plotted the measured and computed spring loads for the 'UK outer' and 'UK inner' springs. In Figs.4 and 5 are the spring stiffness characteristics for the 'UK outer' and 'UK inner' springs, respectively. In Figs.6 and 7 are the computed shear stress and natural frequency characteristics for the 'UK outer' and 'UK inner' springs.

It can be observed in Fig.3 that the theory computes the spring load profiles quite well. In Figs.4 and 5, it can be seen that much of the error in computing the spring loads arises because the starting point stiffness calculated for either spring is about 8% low; this is at variance with the other ten test springs where the starting point stiffness is accurately computed. This error has a compound (integration by definition) effect on the computed load levels, hence the 8% error. These valve springs are not particularly strong because the stiffness numbers involved are rather low; the 'UK outer' starting point stiffness is some 26 N/mm and it is computed at some 24 N/mm and for the 'UK inner' the equivalent data are 9 and 8.4 N/mm, respectively. In that context, computed stiffness errors of 2 and 0.6 N/mm,

"It can be observed in Figure 3 that the theory computes the spring load profiles quite well"
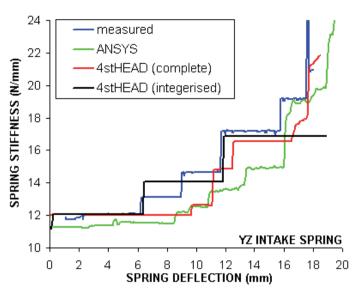
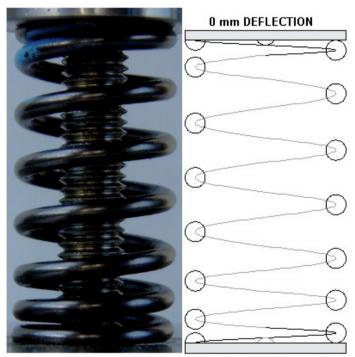Fig.11 Measured and computed stiffness characteristics of the 'YZ intake' spring.

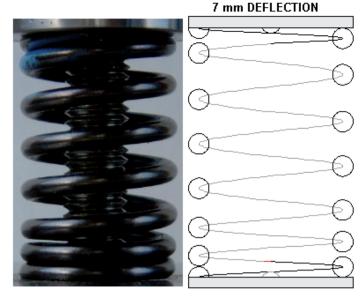Fig.12 The 'YZ intake' spring and its 4stHEAD model at 0 mm deflection.

Fig.13 The 'YZ intake' spring and its 4stHEAD model at 7 mm deflection.
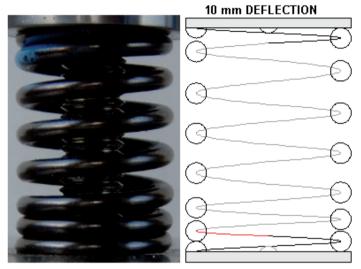

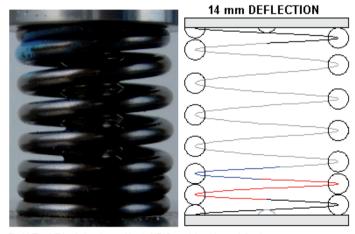Fig.14 The 'YZ intake' spring and its 4stHEAD model at 10 mm deflection.

Fig.15 The 'YZ intake' spring and its 4stHEAD model at 14 mm deflection.

respectively, have to be considered very acceptable.

Nevertheless, the profiles of the load and stiffness characteristics for both springs are well captured by the 'complete' model and, of equal importance for the accuracy of dynamic valvetrain modelling, the 'integerised' spring model satisfactorily mimics the major stiffness profile changes.

In Fig.6 are the computed maximum shear stress characteristics for the 'UK outer' and 'UK inner' springs. As might be expected for an automobile engine, the maximum stress levels exhibited at some 1000 MPa place their design in the longer-term durability category. In Fig.7 are the computed natural frequency characteristics for the same springs. As these are typical progressive springs, the range of frequencies covered varies by some 50%.

In Fig.8 is plotted the measured and computed spring loads for the 'YZ exhaust' spring, and in Fig.9 are its spring stiffness characteristics.

In Figs.10 and 11, the same comparisons are made for the load and stiffness behaviour of the 'YZ intake' spring. The accuracy of the 4stHEAD modelling of the load and stiffness of both YZ springs is quite good; indeed even the 4stHEAD 'integerised' model captures most of the measured stiffness profiles of these two progressive springs. Of the two springs, the accuracy of the 4stHEAD modelling of the 'YZ intake' spring is less effective, particularly in the spring deflection range from 6 to 12 mm.

Fig.2 shows the modelling comparisons for the more basic valve spring data such as spring mass Ms, initial spring stiffness k, and the deflection of ▶
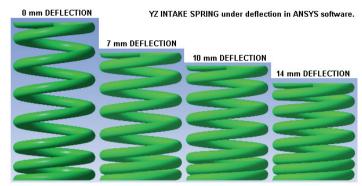
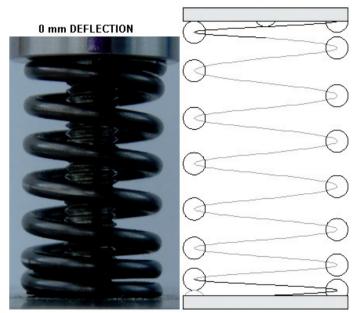Fig.16 The ANSYS model of the 'YZ intake' spring at 0, 7, 10 and 14 mm deflection.

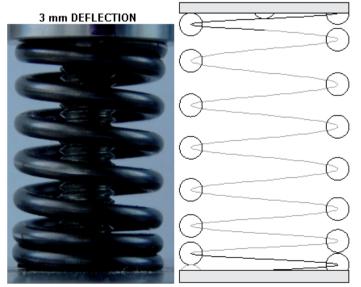Fig.17 The 'KW inner' spring and its 4stHEAD model at 0 mm deflection.

Fig.18 The 'KW inner' spring and its 4stHEAD model at 3 mm deflection.

Fig.19 The 'KW inner' spring and its 4stHEAD model at 5 mm deflection.

Fig.20 The 'KW inner' spring and its 4stHEAD model at 7 mm deflection.

the spring to coil bind DEFbind. The accuracy level for the prediction of these important design data values ranges from good to excellent.

MODELLING BY FEA OF THE 'YZ intake' VALVE SPRING

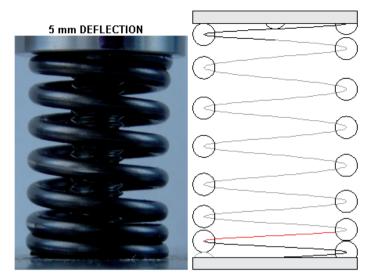The second modelling approach is by a FEA package called ANSYS [1.1]. The springs are described using only the same geometrical input data as employed within the 4stHEAD software. It is applied to the 'KW inner' spring in Paper 1, to the SS spring in Paper 2, and here it is applied to the 'YZ intake' spring.

In Figs.10 and 11 are plotted the predictions by ANSYS for the load and stiffness characteristics of the 'YZ intake' spring, by comparison with those computed by 4stHEAD. In Fig.10, the 4stHEAD model more closely matches the experimental load than the ANSYS model. In Fig.11, the rise in stiffness between 6 and 11 mm deflection is not well captured by either model. From 11 to 18 mm deflection, the ANSYS model of the measurements is not as good as that of the 4stHEAD model. Significant disparities occur between theory and experiment at certain deflections and in Fig.11, the values of 7, 10 and 14 mm could well be selected to represent 'computation black spots'.

In Figs.12 to 15 are photographs of the 'YZ intake' spring at 0, 7, 10, and 14 mm deflection, side-by-side with the 4stHEAD model of the spring at the same heights. In Fig.16 are the ANSYS images of the spring at the same deflections.

In Fig.11, the experimental stiffness at 7 mm has increased so a coil, or portion of a coil, is bound. In Fig.13, the photograph shows that clearly; the 4stHEAD model does not, i.e., no red colouring of the helix centre-
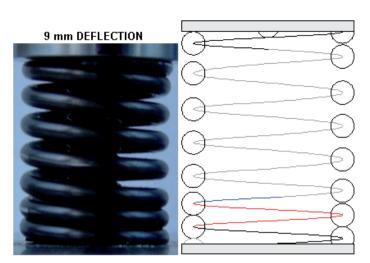
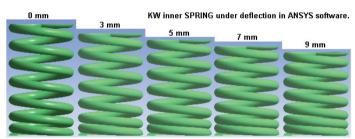Fig.21 The 'KW inner' spring and its 4stHEAD model at 9 mm deflection.

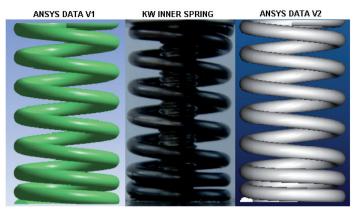Fig.22 The ANSYS model of the 'KW inner' spring at 0, 3, 5, 7 and 9 mm deflection.

Fig.23 The ANSYS geometry data v1 and v2 of the 'KW inner' spring.

Fig.24 The stiffness characteristics of the 'KW inner' spring using ANSYS data v1 and v2.

line, and neither does the ANSYS model in Fig.16. By 10 mm deflection, the photograph in Fig.14 shows at least an entire coil is bound, but the 4stHEAD model only shows 25% of the bottom coil bound; the ANSYS model in Fig.16 would appear to have bound about the same amount as the 4stHEAD model. By 14 mm deflection in Fig.15, the photo and model images of the spring coils are very similar as are the computed stiffness values in Fig.11; the ANSYS model in Fig.16 would appear to have trapped slightly fewer coil elements at this deflection.

The ANSYS model predicts that the spring mass Ms is 12.6 g with the starting point stiffness k at 11.4 N/mm; it can be seen from Fig.2 that the 4stHEAD model tends to calculate this basic design data more accurately, as already determined for the 'KW inner' and 'SS' springs in Paper 1 and Paper 2, respectively.

"…and could well be selected to represent 'computation black spots'"

MODELLING BY FEA OF THE 'KW inner' VALVE SPRING

For the FEA modeller of the 'YZ intake' spring these are somewhat disappointing results, particularly as the behaviour recorded for this spring is very similar to that already presented for the 'KW inner' spring in Paper 1 in Figs.1.12 and 1.13. There, the FEA model also failed to capture the initial binding of the bottom active coils on the dead coil. To illustrate that this claimed phenomenon is similar, the Figs.17 to 22 are created for the 'KW inner' spring. The Figs.17 to 21 show photographs of the spring side-by-side with its 4stHEAD model at 0, 3, 5, 7 and 9 mm deflection and in Fig.22 are the ANSYS images at the same deflections. By 9 mm deflection in Fig.21, the 4stHEAD model and the actual spring photo of the spring's coils look very similar; not so the ANSYS model. On the other hand, at 5 mm deflection where ANSYS fails to mimic the actual spring stiffness, the 4stHEAD model has trapped 50% of the bottom coil, the photo shows more of the actual coil trapped. As confirmation, the ANSYS model in Fig.22 shows almost no part of the bottom coil being trapped.

If one examines the photographs of the 'YZ intake' and the 'KW inner' springs at zero deflection, in Figs.12 and 17, respectively, and compare the helix profiles of the bottom coils with their 4stHEAD models and also the ANSYS models in Fig.16 and 22, respectively, it could be argued that the actual bottom spring's coils lie flatter than the models. In short, the single measurement of coil spacing decreed in Fig.1.4, used in the modelling process of the spring helix, is inadequate ▶
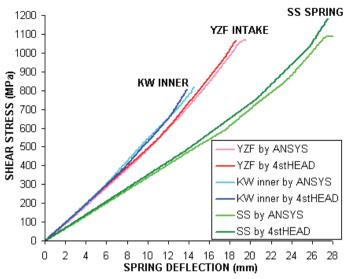
Fig.25 The shear stress characteristics of three springs computed by 4stHEAD and ANSYS.

Fig.26 The natural frequency of the 'KW inner' spring computed by 4stHEAD and ANSYS.

to describe the finer detail of the helix of the bottom coils of a progressive spring. To examine this contention, the 'KW inner' spring helix profile was measured in great detail and a second ANSYS model of the spring was created and labelled as 'ANSYS data v2'. The ANSYS model it created is shown in Fig.23, together with a photo of the spring and the original ANSYS model of Fig.22, now labelled here as 'ANSYS data v1'. The new ANSYS data model appears to better mimic the flatter bottom coils of the actual spring. However, when the ANSYS model is run and the output stiffness data plotted in Fig.24, it can be seen that 'ANSYS data v2' produces some small gains in accuracy for the prediction of the measured spring stiffness characteristics; it should be borne in mind that a designer using an FEA package to design this type of spring would not have available the 'measured helix profile v2' as input data. For the 4stHEAD modeller, the relatively accurate 'integerised' model of 'KW inner' is a most significant result when dynamic modelling of the entire valvetrain is conducted.

In Fig.25, is a composite graph of the computed shear stress characteristics of the three valve springs modelled by ANSYS and 4stHEAD, i.e., 'KW inner', 'SS', and 'YZ intake'. Both theoretical models are in close agreement regarding the stress levels of all three springs.

THE NATURAL FREQUENCY CHARACTERISTICS OF THREE TEST SPRINGS

We have measured here the natural frequency vibration characteristics of three of the test springs, 'KW inner', 'SS', and the 'YZ intake' with respect to deflection. The experimental results are shown in Figs.26-28, respectively. On each graph is shown the measured natural frequency data (Hz) with respect to deflection (mm) and are compared with the computations by 4stHEAD (complete and integerised) models and by ANSYS. As has been explained in previous Papers, natural frequency computations by an FEA model are quite slow even on a fast PC, and so only three ANSYS points are calculated and plotted on each figure.

It is interesting to note that the FEA model accurately predicts the natural frequency of each of the springs at or near the free spring height but once progression of the spring stiffness occurs only that for the 'SS' spring continues that trend. Both 4stHEAD models show satisfactory
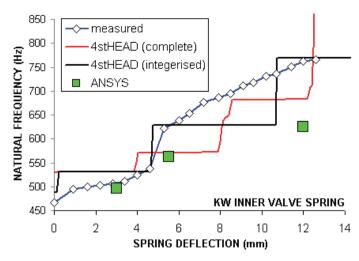
correlation of the measured and computed vibration characteristics over the complete deflection range of the three test springs.

It is also interesting to note in Figs.26-28 that the measured natural frequency (Hz) characteristics do not illustrate the same dramatic increases at significant deflection points as do the computed characteristics for the same springs. The computed data by 4stHEAD employs the equation, put forward in Paper 1 for natural frequency, which states that it is a function of the 'instantaneous' values at any deflection of the square root of the stiffness divided by the mass of the active coils. When either the measured or the computed stiffness 'jumps' up with deflection it follows that it is the result of the binding of active coil elements which clearly also lowers the mass of the active coils. In short, the equation numerator is increased and the denominator is reduced so the natural frequency characteristic profile should mimic the dramatic steps in the (measured or computed) stiffness profile; while there are 'steps' in the measured profiles in Figs.26-28, they could no longer be described as 'dramatic'.

It is interesting to speculate the reason for this 'smoother' measured behaviour. The computation of natural frequency data is conducted along with load/stiffness where the spring deflection moves continuously in small steps from free spring height to near coil bind. As this procedure applies also to the measured load-stiffness data, it is therefore not surprising that both show the 'dramatic jumps' in both natural frequency

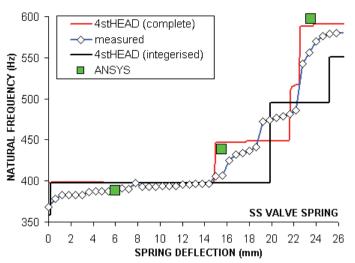"…only if that beauty is ratified by experiment are they other than a chimera."

Fig.27 The natural frequency characteristics of the 'SS' spring computed by 4stHEAD and ANSYS.

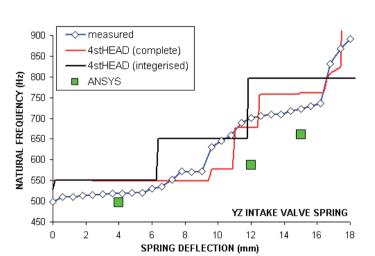Fig.29 Spring helix profiles are computed by 4stHEAD to export for manufacture.

Fig.28 The natural frequency of the 'YZ intake' spring computed by 4stHEAD and ANSYS.

and stiffness. However, while the measured natural frequency is also recorded with the spring held at a known deflection but in a separate experiment, the measuring instrument records the vibration of the spring coils after it has been 'energised' to vibrate by tapping it 'gently' with a 'hammer'. Here, the coils vibrate to and fro in a dynamic manner quite different to the static load measurement procedure. While they may only oscillate by a few microns, coil elements which are bound may temporarily become unbound before rebinding again giving the 'smoother' signal of the measured natural frequency. It is possible to further speculate that, during a real valve spring deflection in an actual valvetrain, the spring deflection is much more unidirectional for significant time periods during both valve opening and closing and so the computed natural frequency characteristics are probably more relevant in modelling the real world dynamic situation.

EXPORT OF SPRING MANUFACTURING DATA

All of the CAD or FEA systems available in the market place permit the export of the helices of the active coils of the valve spring, including those of the closed and/or ground dead coils. This is clear from the ANSYS pictures seen in all three of our Papers. The designer may then pass all of the basic spring geometry data, see Fig.2, and the helix
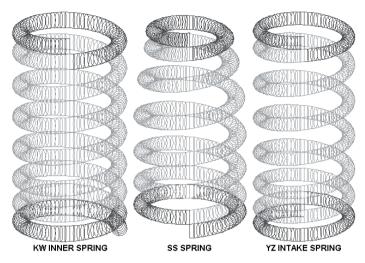
data typically seen in Fig.16, to the spring manufacturer to make the winding die. The 4stHEAD software executes the same functions of manufacturing data export including that of the spring helix data in both Cartesian X,Y coordinates and also in polar R, theta data at every 5 degrees along the entire spring. The 4stHEAD output for the helices of the 'KW inner', 'SS' and 'YZ intake' is shown in Fig.29 each drawn to scale but not to a common scale. Active coils are drawn in 'grey' and dead coils in 'black'. The faces of all spring computation elements at every 5 degrees are clearly visible. The dead coils are shown 'closed' but not 'ground'. The 4stHEAD helix picture is definitely not as 'pretty' as that produced by CAD/FEA software packages such as ANSYS, however accurately it fulfils its numerical purpose.

CONCLUSIONS

It is possible today to theoretically model the load, stiffness, natural frequency, and shear stress characteristics of all types of helical springs that are typically used in engine valvetrains, not only with reasonable accuracy but also reasonably quickly on a desktop PC, using appropriate software [1.4]. This permits the designer to analyse, both statically and dynamically, either existing or optimised valve spring designs to improve the behaviour of the engine's valvetrain.

It is only logical to undertake such valve spring design activity if the software being employed has been extensively ratified by experiment as being accurate. There is a presumption that, almost by definition, the beautifully-presented graphics-orientated software packages used nowadays for engineering design must be accurate; only if that beauty is ratified by experiment are they other than a chimera.

ACKNOWLEDGEMENTS

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