This is the second of a 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

Taper design

This is a trilogy of three papers on the design of wire coil valve springs. For reasons of space, this second paper has been split across two issues of Race Engine Technology – you will find the second instalment of Paper Two, which takes the form of an Appendix, in issue 37 and then Paper Three in issue 38.

In the first paper, Paper One (published in issue 35), we examined in detail the design of five (non-tapered) springs; (a) the inner and outer springs for the intake valve of a NASCAR 'Cup' engine; (b) the single intake valve spring from a large capacity V8 inboard marine unit; and (c) the inner and outer valve springs from a motorcycle engine. In this second paper, Paper Two, we examine in detail the design of three tapered springs; (a) and (b) round wire springs from two (speedway racing) motorcycle engines and (c) an ovate wire spring from a large capacity vee-twin motorcycle power unit. In the third paper, Paper Three, we will 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 (supposedly) 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 modelled in commercial FEA software to acquire the same load and stiffness data as well as the natural frequency and shear stress characteristics. In all twelve cases, the measured and computed

Fig.1 Test springs; JW, GM, and SS

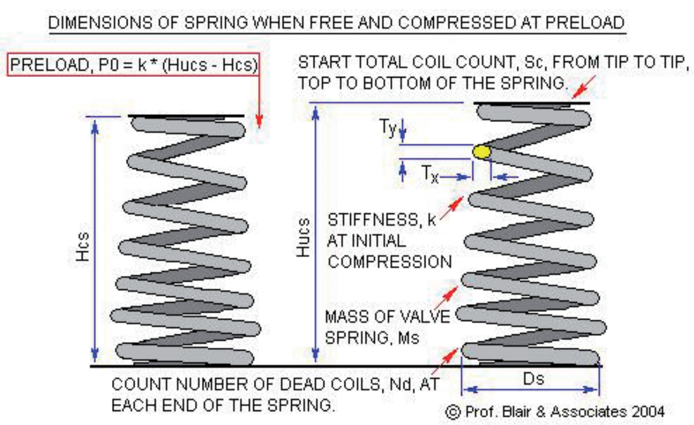

Fig.2 Information on basic tapered valve spring geometry

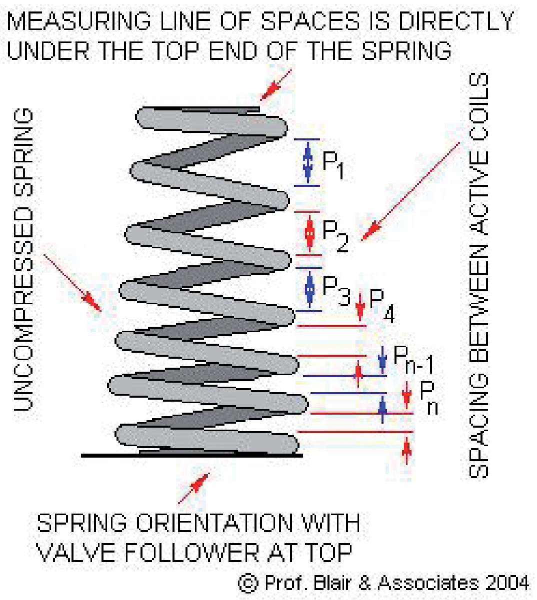

Fig.4 Information on tapered valve spring coil spacing

data are compared numerically and graphically and the physical geometry of every spring is numerically presented so that others, e.g., designers of valve springs, maybe including some makers of valve springs, can compare their theories with our measurements.

THE GRAPHICS NOMENCLATURE ACROSS THE TRILOGY OF PAPERS

In this Paper Two, the Figures are conventionally labelled as Fig.1 to Fig.23. The same applies to the References. However, to avoid pedantic repetition, any Figure from Paper One of the trilogy can be referred to very simply. For example, if we wish to refer to Fig.1 in Paper One here within the text of Paper Two, then it will referred to as Fig.1.1. Similarly, as you can see in the previous paragraph, if we wish to refer to References [1] or [4] from Paper One they will be referred to here in Paper Two as [1.1] and [1.4].

THE VALVE SPRINGS (PAPER TWO)

In Fig.1 is a photograph of the three valve springs. From left to right

TR = tapered round wire TO =tapered ovate wire			
PR=progressive round wire PO=progressive ovate wire			
SPRING	JW	GM	SS
TYPE	TR	TR	TO
Sc	5	5	7
Ms (measured g)	37.4	34.8	98.5
Hucs (mm)	37.9	37.5	60.2
Hcs			
Ds (mm)	30.4	30.6	36.62
Ts (Ty if ovate) (mm)	3.97	3.96	4.5
Tx (if ovate) (mm)			5.6
k (measured N/mm)	52	45	46
Nd	1	1	1

Fig.3 Basic valve spring geometry for the three test springs

SPRING	JW	GM	SS
TYPE	TR	TR	TO
coil space P1 (mm)	6.3	6.4	4.44
coil space P2 (mm)	6.2	6.5	7.13
coil space P3 (mm)	6.1	6.5	7.51
coil space P4 (mm)			6
coil space P5 (mm)			3.95

Fig.5 Valve spring coil spacing for the three test springs

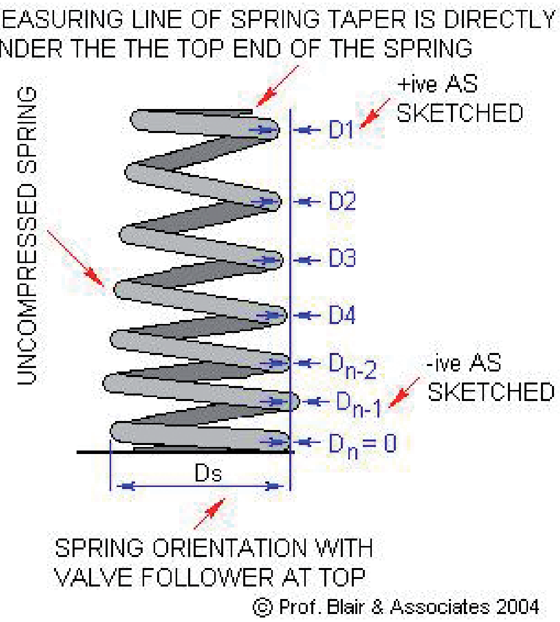

Fig.6 Information on the taper of the valve spring coils

are the two valve springs used in motorcycle speedway racing, JW and GM, followed by the SS valve spring from a touring motorcycle. All are used on intake valves.

In Fig.2 is the relevant information page from the 4stHEAD software [1.4] explaining the data symbols for the basic geometry of a tapered spring and in Fig.3 are the actual data values for the three springs in question. You can see that one spring (SS) is made with ovate wire whereas the other two are wound with round wire and, it should be noted, the ovality of the wire in the SS spring is, as noted previously in Paper One with respect to the 'HM inner' spring, not visually obvious.

In Fig.4 is another information page explaining the data symbols for the pitch spacing of tapered spring coils and in Fig.5 are the actual data values for the three springs in question. The final software information page explaining the data symbols to record the taper geometry of such a valve spring is shown in Fig.6 and the relevant numerical data for the test springs are given in Fig.7.

From Fig.1. the taper of the JW and GM springs is relatively minor, e.g., the diameter of the top coil of the JW spring is just 3.6 mm less than the bottom coil whereas the top coil diameter of the SS spring is some 8 mm less than the bottom coil. The main advantage of a tapered spring design is that it should be lighter and stiffer at zero deflection than a parallel coil spring. The main disadvantage is that, assuming the taper is reasonably significant as in the SS spring, it is normally not possible to fit an inner coil spring. Hence, the single ▶

SPRING	JW	GM	SS
TYPE	TR	TR	TO
side clearance D1 (mm)	1.8	1.1	3.99
side clearance D2 (mm)	1	0.9	1.7
side clearance D3 (mm)	0.5	0.5	0
side clearance D4 (mm)	0	0	0
side clearance D5 (mm)	0	0	0
side clearance D6 (mm)			0

Fig.7 Valve spring coil taper for the three test springs

tapered spring design must satisfy the overall design requirements for the load and stiffness control of the valve and the dynamic stability of the entire valvetrain while not becoming over-stressed in the process. We have decided to discuss in some considerable detail the basic design principles of tapered springs because the literature contains no guidance for a spring designer; this discussion will be conducted in an Appendix to Paper Two to be published in the next issue (RET 37).

MEASUREMENT OF THE VALVE SPRING LOAD AND DEFLECTION

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

In Fig.8 is plotted the measured load-deflection characteristics of the three test springs. The JW and GM speedway racing valve springs have very similar behaviour, which is not too surprising as the engines into which these springs fit are almost identical, they race against each other almost daily on tracks world-wide, and so some design cross-fertilisation can be expected. In Fig.9 is plotted the slopes of the load curves, i.e., the spring stiffness, and the higher stiffness of the JW and GM springs tallies with the lesser slope of the SS spring in Fig.8.

As noted previously in Paper One, the measured stiffness data increases with deflection in a series of steps rather than in some smoothly continuous sweep.

It can be seen in Fig.9 that the tapered SS spring is one which is more genuinely progressive than the other two in that its stiffness begins to increase at about half maximum deflection. The JW and GM springs only have increasing stiffness in the last 25% of their deflection. This is due to the spring taper only because, see Fig.5, the coil spaces for the JW and GM springs reveal almost no progression; those for the SS spring do so.

MODELLING BY 4stHEAD OF THE VALVE SPRING

In Paper Two, as previously discussed in Paper One, modelling of the deflection of the valve spring under load is conducted by two differing approaches. The first is called 4stHEAD [1.4], the basic theory is described in Paper One, and is applied in Paper Two to all three springs. The second is a FEA package called ANSYS [1.1] and is applied to the SS spring.

The modelling of the SS spring by 4stHEAD is illustrated in Fig.10. At zero deflection, this composite picture shows a photograph of the

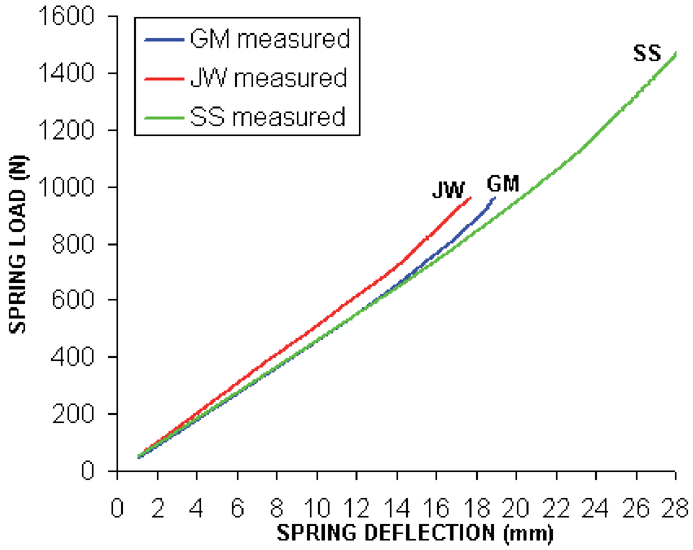

Fig.8 Measured load characteristics of the three test springs

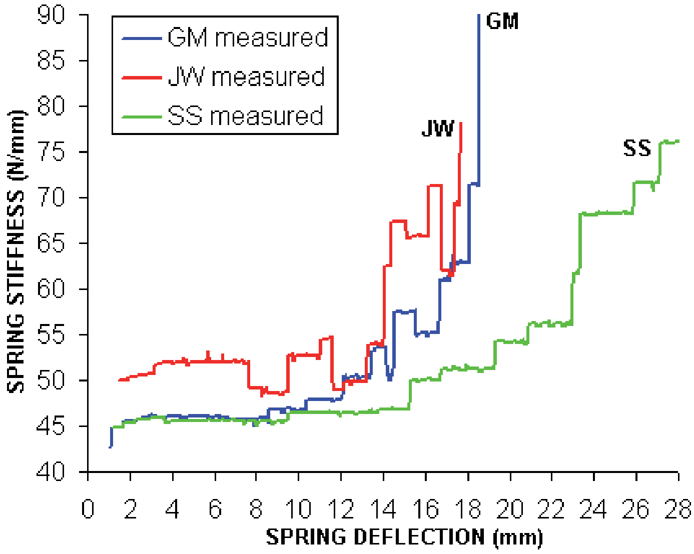

Fig.9 Measured stiffness characteristics of the three test springs

actual spring at the left and the ‘helix centre-line’ of the 4stHEAD model of the ovate wire spring coils is drawn to scale at the right. The model proceeds to be deflected in some 1000 steps until the coils are almost completely bound. The ovality of the wire in the SS spring is readily seen in the computer model at the right in Fig.10 but cannot be observed at the left in the actual photograph. We have raised this issue, the difficulty of observing that the wire in a valve spring may be ovate, because if one attempts to model, either by a FEA package or 4stHEAD, an ovate wire spring but treats it numerically as round wire by inserting the Ty wire dimension of Fig.2 as if a diameter and ignores the Tx value, the ensuing model prediction of spring mass and stiffness will typically be some 25% in error.

As shown previously in Fig.1.11, should any spring element bind on a dead coil element the helix line is coloured red and, should any spring elements bind on other active coil elements the helix line through those elements is locally coloured blue. These effects may be seen in Figs.15 to 17. If an element binds it cannot deflect and so the stiffness rises; if many elements bind at the same juncture then the

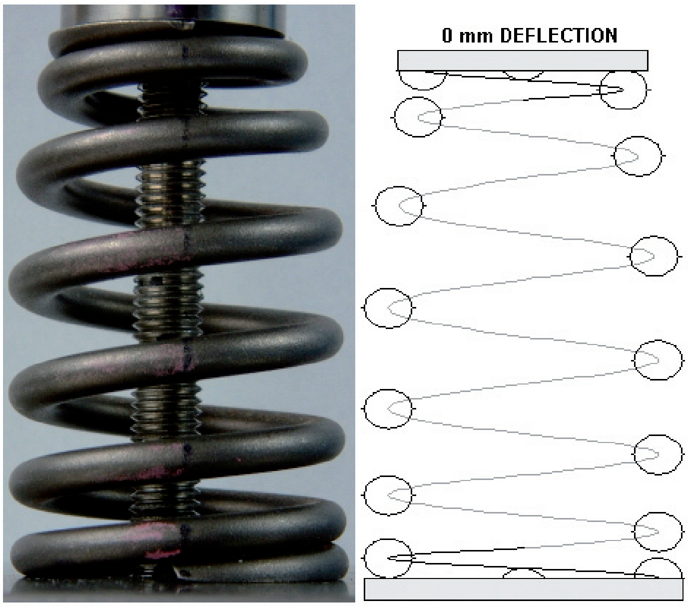

Fig.10 The SS spring and its 4stHEAD model at zero deflection

COMPUTATION BY 4stHEAD			
SPRING	JW	GM	SS
TYPE	TR	TR	TO
Ms (measured g)	37.4	34.8	94.2
Ms (calculated g)	35	35.3	98.5
k (measured N/mm)	52	45	46
k (calculated N/mm)	51.2	48.3	45.7
DEF to bind (measured mm)	18.3	19.5	30.05
DEF to bind (calculated mm)	18.6	19.4	29.03

Fig.11 Measured and computed data for the three test springs

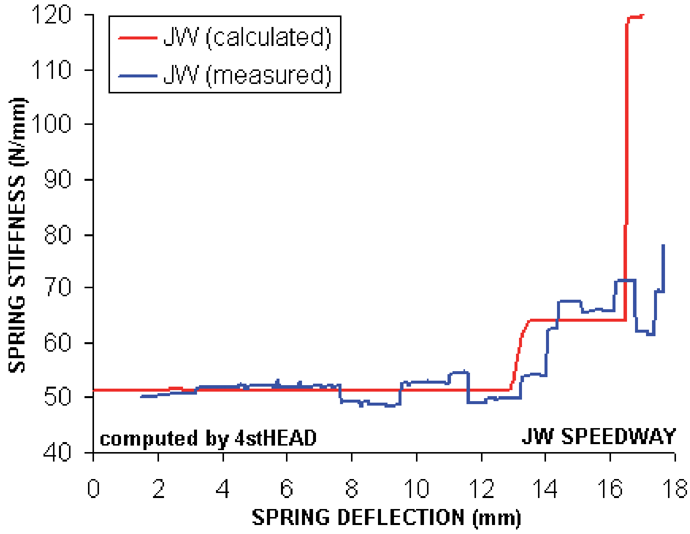

Fig.12 Measured and computed stiffness for the JW valve spring

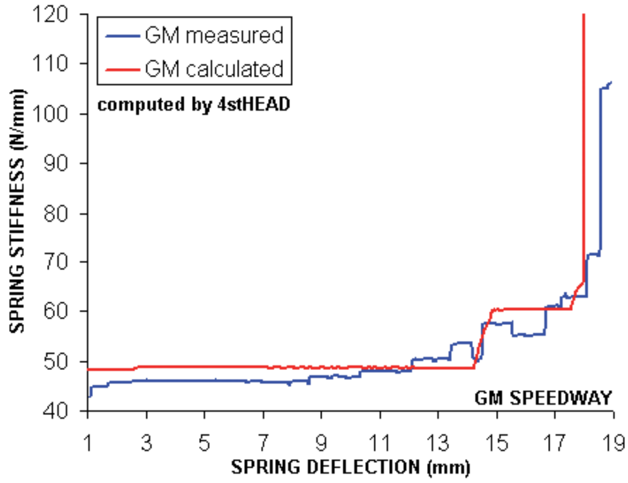

Fig.13 Measured and computed stiffness for the GM valve spring

stiffness rises in steps and not continuously. The theoretical models and the measurements confirm this behaviour.

Hence, the 4stHEAD model can predict load, stiffness, natural frequency and shear stress as a function of spring deflection to full coil bind as well as basic parameters such as the mass of the spring and its deflection until the coils are all bound. Accuracy of modelling is clearly important for design purposes, so in Fig.11 for the JW, GM and SS springs is a table of measured and computed data for the mass of each spring (Ms), the free length stiffness (k) and the deflection of the spring to coil bind (DEF). The correlation error between calculation and experiment for this basic data is very low considering the complexity of the model and the actual geometry of the wire coils.

Perhaps the more important question is, can the 4stHEAD model predict the varying stiffness-deflection characteristics of these tapered and progressive springs?

In Figs.12 and 13 are shown the comparisons for the JW and GM springs of the measured and computed stiffness characteristics. Not unlike the HM springs in Paper One and as already mentioned above, there is almost no (coil space) progression on either of these two springs, apart from that due to the taper of the coils, but the 4stHEAD model quite convincingly captures the measured behaviour.

"There is almost no progression on these springs yet the model convincingly captures the measured behaviour"

MODELLING BY FEA OF THE VALVE SPRING

The SS spring is modelled in ANSYS [1.1] and in Fig.14 at spring deflections of 0, 12, 16 and 22 mm are shown snapshots from the ANSYS modelling procedure. In Figs.10, 15, 16, and 17 are shown photographs of the SS spring, and snapshots from the 4stHEAD analysis, at each of the same noted deflections. There is a close correspondence between the photographs of reality at each deflection ▶

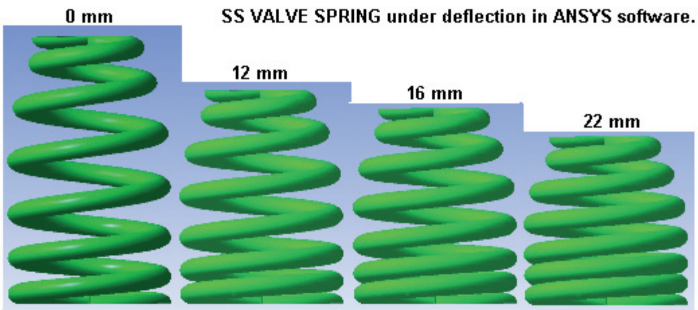

Fig.14 The ANSYS model of the SS spring at several deflections

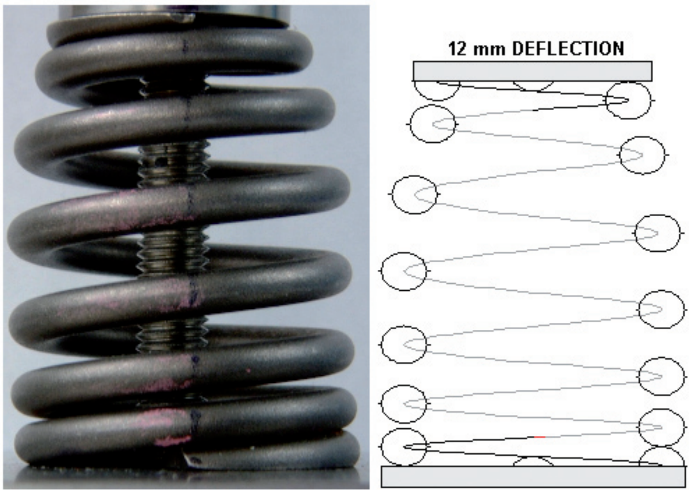

Fig.15 The SS spring and its 4stHEAD model at 12 mm deflection

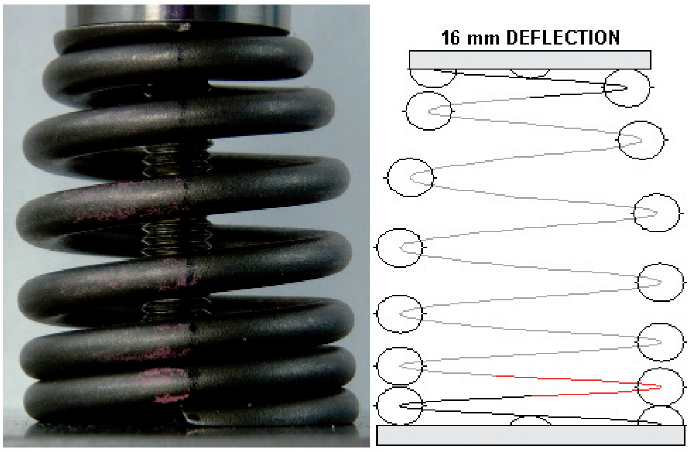

Fig.16 The SS spring and its 4stHEAD model at 16 mm deflection

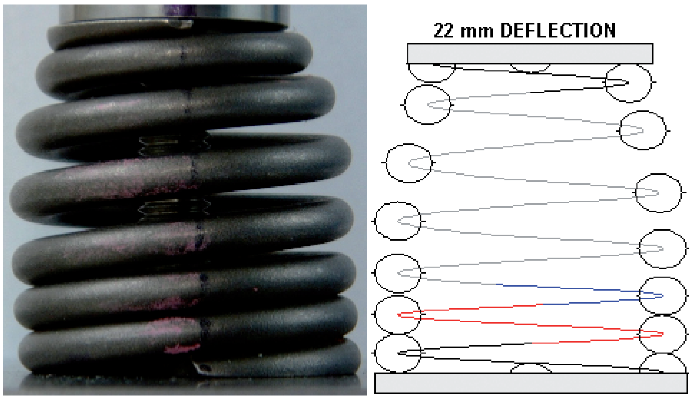

Fig.17 The SS spring and its 4stHEAD model at 22 mm deflection

and the virtual pictures from ANSYS and 4stHEAD of coil spacing, binding, and disposition. With these real and virtual similarities, it is not too surprising to find that the numerical data computed by ANSYS and 4stHEAD satisfactorily matches the measured data; this can be found in Figs.18 and 19 for load and stiffness, respectively. In Fig.19, it is arguable whether ANSYS or 4stHEAD more closely matches the measured data for spring stiffness. What is more satisfactory is that the quality of fit of the theory to experiment for the SS spring is much superior to that reported for the 'KW inner' spring in Fig.1.12. The ANSYS software predicts that the mass of the SS spring is 89.5 g and the free spring stiffness is 45.1 N/mm; this does not match the measured data so well as that determined by 4stHEAD, as already noted in Fig.11.

FURTHER DESIGN DATA AVAILABLE FROM THE COMPUTERS

One of the important design criteria for valve springs is their natural frequency which, to prevent resonance, should not match either an excitation frequency from the camshaft or any of its followers or components. Both 4stHEAD and ANSYS will predict the natural frequency of a valve spring at any given deflection and the results are plotted in Fig.20 for the JW, GM and SS valve springs. It can be seen that the theoretical data from ANSYS and 4stHEAD for the SS spring are in close agreement. There are perhaps some 600 points or more on each of the graphed lines for the 4stHEAD computation but only three points by ANSYS for the SS spring as calculations for natural frequency by FEA are extremely time consuming.

While the reader will be pleased to see that the 4stHEAD and FEA (ANSYS) software closely agree with each other as to the natural frequency of the SS valve spring, the reader's next question will obviously refer to the quality of correlation of either theory with measured natural frequency data. Here there is good news and bad news; the quality of correlation of theory and experiment for this

> "The next question will refer to the quality of correlation of either theory with the measured natural frequency data"

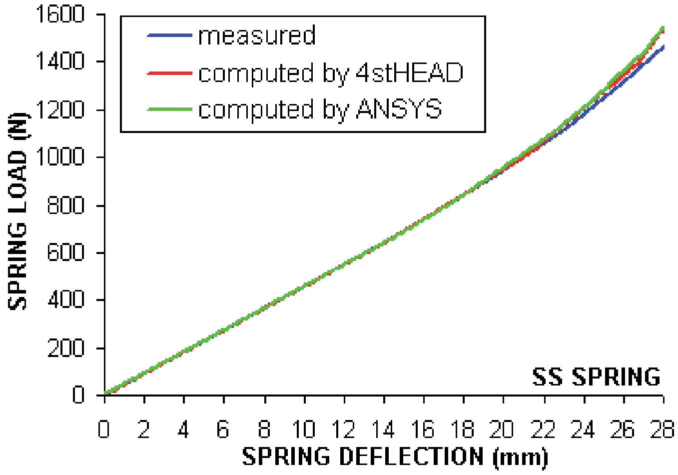

Fig.18 Measured and computed load characteristics of the SS spring

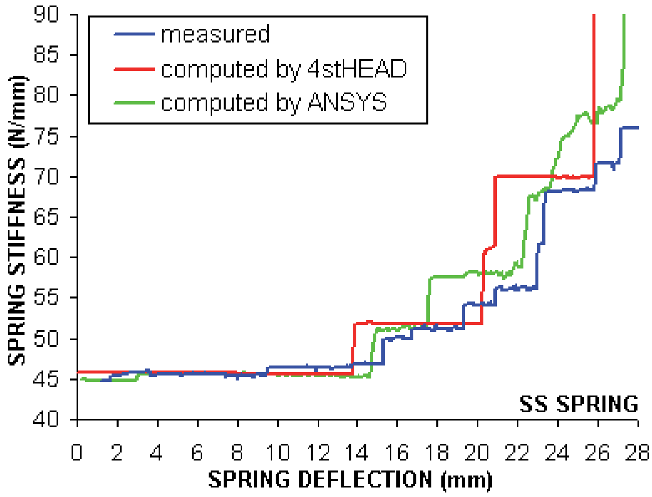

Fig.19 Measured and computed stiffness characteristics of the SS spring

parameter is good but the bad news is that the reader will have to patiently await Paper Three of these papers to read the evidence about it.

The 4stHEAD and ANSYS software predicts the shear stress for all spring elements along the wire at any given deflection. The maximum value at any given deflection is noted and stored for analysis by the designer. In Fig.21 is plotted the shear stress computed by 4stHEAD for all three springs and by ANSYS for the SS spring. It can be seen that 4stHEAD and ANSYS are in close agreement for the stress-deflection characteristics of the SS spring. At maximum deflection the GM and JW springs exceed the nominal safe stress limit of 1250 MPa. The actual maximum deflection under engine conditions, i.e., preload plus maximum valve lift, may not nominally approach the coil bind or maximum spring deflection values of some 16 to 17 mm and therefore the JW and GM springs could be presumed not to experience these unsafe stress levels. However, these GM and JW engines are motorcycle racing engines and, should the rider inadvertently allow the engine to exceed its maximum safe engine speed, the ensuing coil spring surge could easily produce enough extra coil compression yielding maximum deflection of the bottom spring coils and so cause valve spring failure.

In a tapered spring the bottom coils are the softest springs because they have the larger diameters. For those familiar with speedway

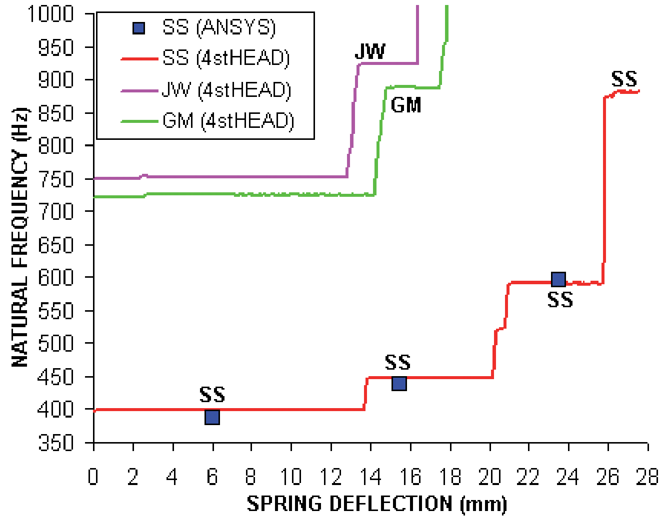

Fig.20 The computed natural frequency characteristics of the test springs

motorcycle racing, the phrase above 'should the rider inadvertently allow the engine to exceed its maximum safe engine speed' will raise a wry smile. At the start line of a speedway race the four riders line up behind the gate and, with clutch engaged, wind the throttle wide open and await the gate to lift! The word 'inadvertently' above could more legitimately be replaced by 'deliberately'! The valve spring designer of a speedway engine could do worse than remember this 'mot juste'.

The lower stress levels exhibited by the SS spring emphasise the point that this is a valve spring designed for a 'production' motorcycle and so must provide durability.

DYNAMIC MODELLING OF THE VALVE SPRINGS

In Paper One it is pointed out that the 'complete' modelling of the valve spring in 4stHEAD, like ANSYS using many hundreds of elements to describe the spring, cannot be employed within a dynamics model of the entire valvetrain of the engine [1.4, 1.6, 1.7]. We must use an 'integerised' model of the same spring created at the same juncture as the 'complete' model analysis, which conveniently leaves the designer but a single mouse click away from running the entire dynamics model with the 'integerised' spring(s). Consequently, for accuracy of dynamic ▶

"The four riders line up behind the gate and, with clutch engaged, wind the throttle wide open and await the gate to lift!"

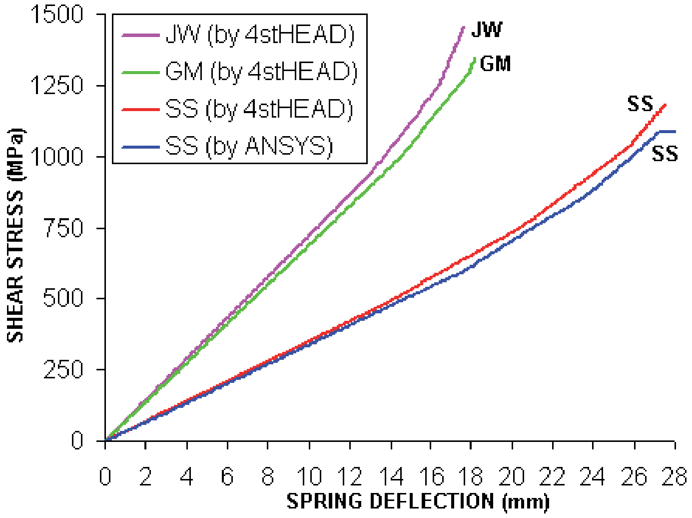

Fig.21 The computed shear stress characteristics of the test springs

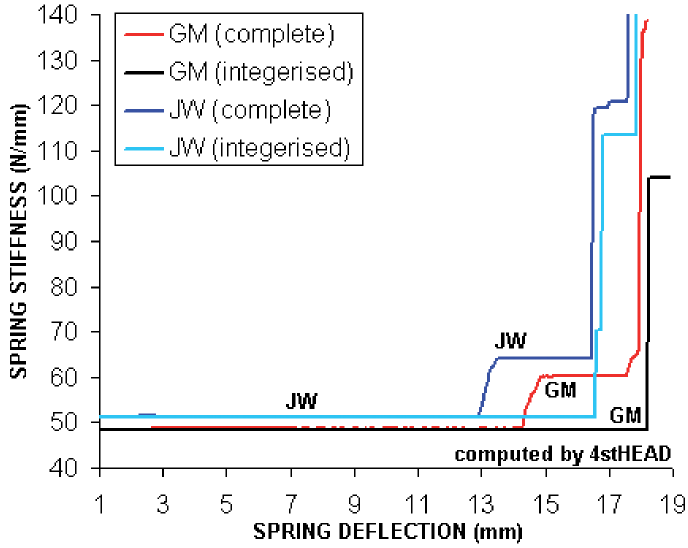

Fig.22 Stiffness characteristics of the integerised models of the JW and GM springs.

"Which leaves the designer a single mouse click away from running the entire model with the 'integerised' spring(s)"

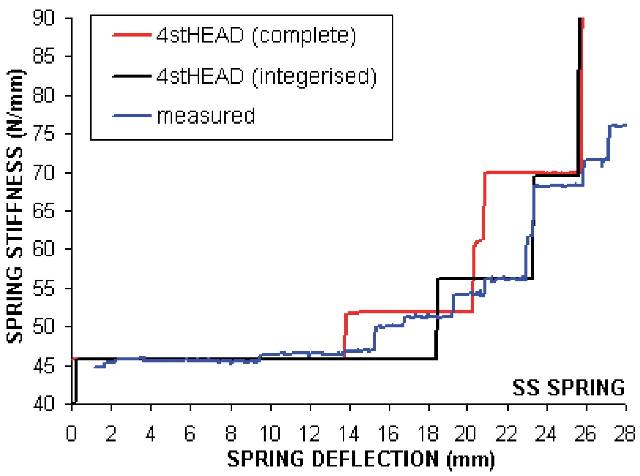

Fig.23 Stiffness characteristics of the integerised model of the SS spring

simulation, it is important that the 'integerised' model which has fewer coil elements represents as closely as possible the stiffness-deflection characteristics of the 'complete' model or, even better, closely mimics the measured stiffness-deflection characteristics.

In Fig.22 is plotted the stiffness-deflection characteristics of the 'complete' and 'integerised' models of the JW and GM springs. While the early progression points around 13 and 14 mm are not captured by the 'integerised' model, the major changes of stiffness near coil bind at 16.5 and 18 mm are accurately recorded. In short, the 'integerised' model of these springs will be effective during dynamic modelling of their entire valvetrain [1.4].

The modelling situation of the 'integerised' SS spring proved to be more than acceptable, as can be seen in Fig.23 where it is arguable that the 'integerised' spring is a better mimic of the stiffness-deflection characteristics of the measured data than either the 4stHEAD 'complete' model or the ANSYS model seen in Fig.19.

CONCLUSION

The Paper Two adds to the evidence given in Paper One that it is possible today to theoretically model the load, stiffness and stress characteristics of even the most complex helical springs that are typically used in engine valvetrains, not only with some reasonable degree of accuracy but also reasonably quickly on a desktop PC, using software [1.4].

This permits the designer not only to analyse both statically and dynamically existing valve springs for suitability within his engine design but also to create new, more optimised, spring designs to improve the stability of his engine's valvetrain.

PAPER TWO APPENDIX: THE BASIC DESIGN PRINCIPLES OF TAPERED VALVE SPRINGS

This will be published as the Paper Two Appendix "BASIC DESIGN PRINCIPLES OF TAPERED VALVE SPRINGS" in the next issue (37) of Race Engine Technology in 2009. As the Appendix is approximately the same size in text and graphics as Paper Two itself, it is much too large to be published with it; hence, its sequential publication in the next issue. ■

ACKNOWLEDGEMENTS

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