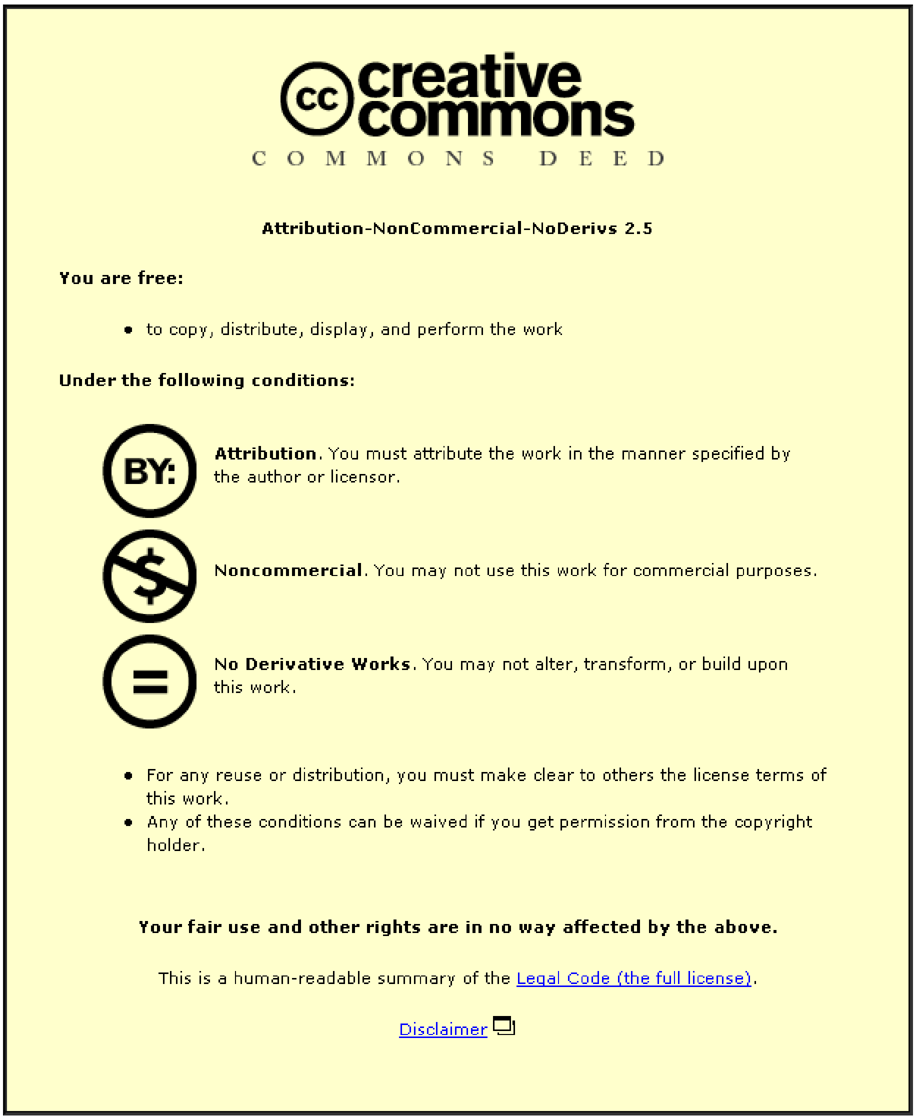

American Journal of Vehicle Design, 2013, Vol. 1, No. 2, 36-43
Available online at http://pubs.sciepub.com/ajvd/1/2/4
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DOI:10.12691/ajvd-1-2-4

The Use of a Two Stage Dimensional Variation Analysis Model to Simulate the Action of a Hydraulic Tappet Adjustor in a Car Engine Valve Train System

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Received June 13, 2013; Revised November 14, 2013; Accepted December 16, 2013

Abstract Dimensional variation analysis (DVA) models have been used in the manufacturing industry for over 20 years to predict how minor variations in the size, shape and location of the components parts is likely to propagate throughout and affect the overall dimensions, operation and performance of a complete mechanical system. This paper is one of in series of four papers that describe how different techniques can be utilised to aid the creation and application of DVA models. This paper explains the development and use of a two stage DVA model to simulate the action of a hydraulic tappet adjuster and dimensional interdependence that exists between the adjustment of a hydraulic tappet and the actuation (opening & closing) of the cylinder valve. The three other papers cover the use of kinematic constraint maps to prepare the structure of a DVA model; the use of virtual fixtures, jigs and gauges to achieve the necessary component location and the required variation measurements, and the use of 3D plots to display large numbers of DVA results as a single 3D shape. A hydraulic tappet adjustor performs two functions; it is part of the valve train system that actuates (opens & closes) the cylinder valve and it also self adjusts to take up any free play in the valve train system. These two functions, tappet adjustment and valve actuation, are separate operations that occur at different times during the valve train operating cycle and so need to be modelled as different configurations in a DVA model. In a conventional multiple configuration DVA model, each configuration has to be fully constrained and mathematically closed independently of any other model configuration. This requirement makes it difficult to include the interdependence between tappet adjustment and valve actuation. The two stage approach overcomes this limitation by allowing the output variation from the tappet setting configuration to be carried over into the valve actuation configuration and can thereby fully account for the interdependence between the two operations.

Keywords: *Dimensional variation analysis, Engine valve train, dimensional variation behaviour*

Cite This Article: L.C. Sleath, and P.G. Leaney, “The use of a two stage dimensional variation analysis model to simulate the action of a hydraulic tappet adjustor in a car engine valve train system.” *American Journal of Vehicle Design* 1, no. 2 (2013): 36-43. doi: 10.12691/ajvd-1-2-4.

1. Introduction

DVA (dimensional variation analysis) models have been widely used by automotive companies [1,2,3,4] and to a lesser extent by aerospace companies [5,6,7,8] and other manufacturing companies [9] for over 20 years. A DVA model can simulate how minor variations in component size, shape and location are likely to propagate in all six degrees of freedom throughout the assembly and operation of a mechanical system. DVA models have proved very successful in predicting whether or not these minor component variations, when taken collectively, are likely compromise the overall operation, performance or quality of the complete system. The use of a DVA model provides the engineering team with the means to identify potential dimensional variation problems in advance, during the design phase, while there is still time to ‘design out’ the variation or to devise effective measures to control the variation once in production. As the software used to build DVA models has advanced over the years, in parallel, the DVA users have developed numerous management procedures, application techniques and ‘tricks of the trade’ to model specific situations [10-17]. The advances in software combined with the development of new procedures and techniques have substantially increased the capability of the DVA model and the complexity of the systems that can be modelled.

Hydraulic tappet adjusters are part of the valve train system that actuates (opens & closes) the cylinder valve. Hydraulic tappet adjustors are fitted to automatically take up any free play in the valve train systems. The adjustment of the tappet length and the actuation of the valve occur at different times during the valve train operating cycle. The tappet length is adjusted on the cam heel when the valve is fixed in the closed position, whereas the valve opens and closes on the cam lobe when the tappet length is fixed. There are sufficient differences in terms of the timing and component locations to regard the tappet adjustment and the valve actuation to be separate operations and this requires each operation to be modelled as a separate configuration in a DVA model. However, dimensional variation in the tappet adjustment could influence the opening and closing of the valve making the operation of the valve dependant on the tappet adjustment and creating an interdependence between the two operations. Variation in the valve train components can affect the operation of the valve train by causing variation in the valve timing and maximum lift. The inclusion of a hydraulic tappet adjustor takes up the clearance in the valve train and can compensate for some, but not necessarily all of the component variation. Depending on the exact system configuration, a hydraulic tappet adjustor can compensate for variation in the length of the valve stem, but not for variation in the length of the rocker arm or the height of the cam lobe.

In a conventional multiple configuration DVA model, each configuration has to be fully constrained and mathematically closed independently of any model other configuration. This requirement makes it difficult to include the interdependence between tappet adjustment and valve actuation. To deliver reliable results a DVA model should account for as many known sources of dimensional variation as possible. To not include a known variation source (the influence of tappet adjustment on valve actuation) in a DVA model of the valve system limits the capability of the DVA model and challenges the integrity if the DVA results. The aim was to overcome this limitation by developing a two stage approach that would allow the output variation from the tappet setting configuration to be carried over into the valve actuation configuration. The carry over of variation creates the required interdependence between the two configurations that simulate the tappet adjustment and valve actuation operations in the DVA model.

1.1. The Advantages of Hydraulic Tappet Adjustors over Conventional Screw Type Adjustors

Several large manufacturers such as Land Rover, Ford, Honda and Mitsubishi use hydraulic tappet adjusters in preference to the older screw type adjuster. The hydraulic tappet adjuster has several advantages; the assembly of the valve train is simplified as no manual adjustment is required. Transient thermal effects during the engine warm up period can be accommodated thereby improving engine efficiency. The automatic adjustment of the hydraulic tappet adjusters compensates for certain types of long-term wear in the valve train, maintaining the engine in optimal condition for longer.

Considerable research has been undertaken on the effect of variations in the valve timing of engines [18,19]. This work has shown that variations in the valve timing can have a significant effect on both engine performance and emissions. Indeed several variable valve timing systems [20,21,22] have been developed that exploit the fact. In such systems, the valve timing and lift are varied deliberately to enhance the engine performance. However, the valve timing and lift may also be affected by the inherent variation in the processes used to manufacture and assemble the components. This variation, unless properly controlled, may accumulate to the point where it becomes detrimental to product performance. DVA is often used to resolve such issues when they arise [3]. To determine the effects of such variation on the valve train requires the ability to simulate the dimensional variation behaviour of the entire valve train, including the hydraulic tappet adjusters, throughout the operational cycle.

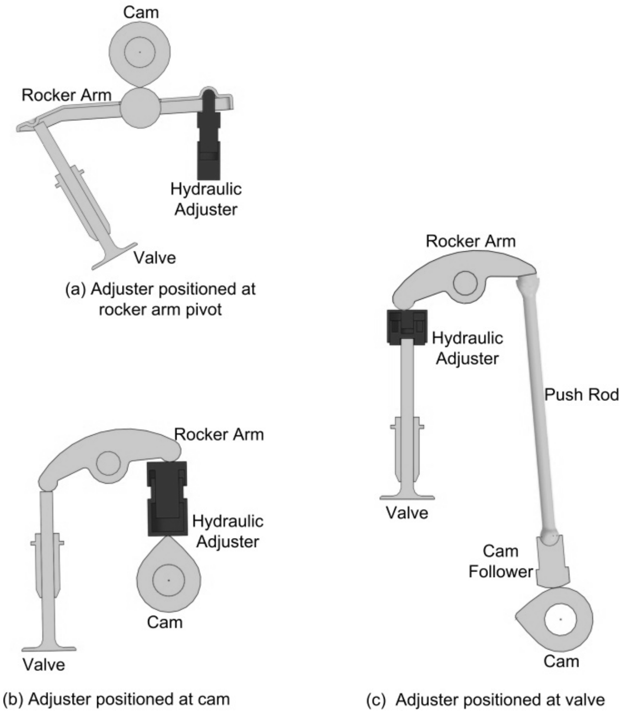

Figure 1. Common hydraulic tappet adjuster locations

In valve trains employing screw type tappet adjusters the size shape and location of the component parts are fixed and fully defined. Thus simulating the dimensional variation behaviour of the valve train is comparatively straightforward. In valve trains, containing hydraulic tappet adjusters the length of the hydraulic adjuster is variable, it is defined by the position of the adjacent components with which it is in contact. These adjacent components are subject to the effects of variation and they may also move in space as the valve train progresses through its operational cycle making it difficult to define the axial length of the hydraulic tappet adjuster. The position of the hydraulic tappet adjusters in the valve train will depend on the specific engine design, but hydraulic tappet adjusters are commonly found in one of three positions, at the rocker arm pivot, between the cam and the rocker arm or between the rocker arm and the valve stem (Figure 1).

This paper proposes a method for simulating the dimensional variation behaviour of valve train systems containing hydraulic tappet adjusters. The method is applicable to any of the three common locations for hydraulic tappet adjusters shown above and is capable of defining the axial length of the hydraulic tappet adjuster. The method has been developed for use with vector loop based DVA software and could be used in other DVA software.

2. Operation of Hydraulic Tappet Adjusters

In order to appreciate the significance of the assumptions made to simulate the behaviour of a hydraulic tappet adjuster it is necessary to consider the general principles behind how the adjuster operates. In its simplest form, the hydraulic tappet adjuster consists of a cylindrical barrel closed at one end with a spring situated between the closed end of the barrel and a very close fitting hollow plunger that slides in the barrel to form a telescopic strut (Figure 2). A series of oil galleries in the barrel and plunger allow pressurised oil, from the engine lubrication system, to enter the centre cavity of the hollow plunger and, by means of a spring loaded non-return valve in the plunger, into a compression chamber formed between the closed end of the barrel and the plunger (Figure 2). The cycle of operation for the hydraulic tappet adjuster commences when the engine valve closes and the load applied to the valve train by the compressed valve spring is removed. This allows the spring-loaded plunger of the adjuster to extend and take up any clearance in the valve train. As the plunger extends the volume of the compression chamber increases, reducing the pressure of the oil trapped within. This in turn opens the non-return valve of the plunger allowing oil to flow into the compression chamber until the pressures equalises at which point the non-return valve closes. When the cam follower makes contact with the cam flank, a load is applied to the hydraulic tappet adjuster by the valve train. This load compresses the oil trapped in the compression chamber and prevents the non-return valve from opening. The oil in the compression chamber is a high bulk modulus fluid that acts as if it were a rigid strut maintaining the relative positions of the hydraulic adjuster barrel and plunger and thus, the overall length of the hydraulic adjuster. The hydraulic adjuster remains in this state until the engine valve closes and the operational cycle begins anew.

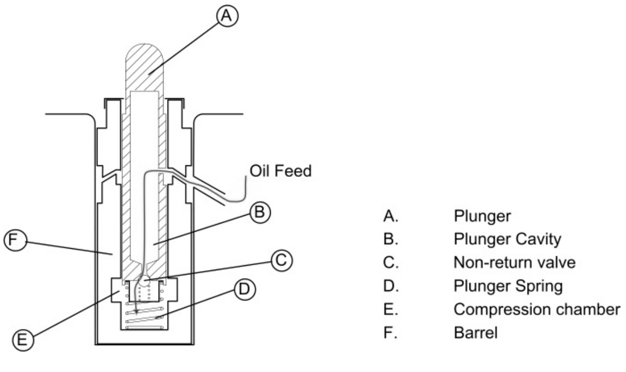

Figure 2. Hydraulic tappet adjuster

The above can be considered the idealised operational cycle of the hydraulic tappet adjuster. In the real world, hydraulic tappet adjusters are manufactured in such a way that they exhibit tappet leak down. This is the controlled escape of oil from the compression chamber between the plunger and the adjuster barrel. This attribute is to ensure that the engine valve always returns fully to its seat.

3. Simulation Assumptions

To simulate the dimensional variation behaviour of a hydraulic tappet adjuster certain assumptions are made concerning the operation of the hydraulic tappet adjuster these are

- When the cam follower makes contact with the cam flank the hydraulic adjuster becomes rigid, instantaneously.
- When in the rigid condition the length of the adjuster remains fixed.

The first assumption is considered reasonable as the non-return valve built in to the plunger only remains open while there is a sufficient pressure differential across the valve to overcome the valve closing spring. This pressure differential will decline once the adjuster plunger reaches its maximum extension and the non-return valve may well close before the cam follower makes contact with the cam flank. The second assumption is necessary to determine the length of the hydraulic tappet adjuster in the simulation model. Once created the simulation model can then be modified to take into account tappet leak down. However, the inclusion of the tappet leak down is beyond the scope of the present paper. For the purposes of describing the method the system characteristics of interest are the valve lift for a given rotation of the camshaft and the cam angle when the valve first opens and first closes.

4. Modelling Method

The basic method for analysing dimensional variation of an assembly to determine the dimensional variation behaviour is to construct a DVA model, which is then analysed. The DVA model consists of the CAD geometry that defines the nominal size, shape and location of the component parts. The CAD geometry is then overlaid with assembly features that define the extent of the component variation in the assembly. The degrees of freedom between mating assembly features on adjacent component parts are appropriately constrained to form the connections that join the component parts together in the desired arrangement or configuration.

A two part DVA model is created to simulate the behaviour of a system containing hydraulic tappet adjusters. This change in method is necessary as the axial length of the hydraulic tappet adjuster is defined by the relative location of the adjacent component parts to account for the interdependence between setting the adjuster length and the operation of the valve.

4.1. DVA Model Part 1, Setting the Adjuster Length

The first part of the DVA model has three objectives;

- To set the overall axial length of the hydraulic tappet adjuster.
- To identify those variation source elements that contribute to the variation distribution of the hydraulic tappet adjuster overall length.
- To identify those variation source elements that contribute to the hydraulic tappet adjuster variation distribution but also have secondary effects that do not affect the hydraulic tappet adjuster itself but do affect a key characteristic of the system and to quantify that effect.

4.1.1. Defining the Length of the Hydraulic Tappet Adjuster

The method of defining the hydraulic tappet adjuster axial length is demonstrated using the component configuration shown in Figure 3; this simulates the behaviour of system in which the hydraulic tappet adjuster is located between the cam and the rocker arm. This system was chosen to illustrate the method, as it is the only arrangement in which it is necessary to both, determine the length of the hydraulic tappet adjuster and accommodate gross motion of the hydraulic tappet adjuster. In the other two arrangements (Figure 1), the hydraulic tappet adjuster either, acts as a pivot for the rocker arm and is thus static or the hydraulic tappet adjuster is in direct contact with the valve. In the latter case, a simpler solution is available. From the description of the operational cycle of the hydraulic tappet adjuster, when the valve is on its seat and the cam follower (hydraulic adjuster) is in contact with the base circle of the cam, the hydraulic adjuster will extend to fill the gap between the cam and rocker arm (Figure 3). The distance between the cam base circle and the contact point on the rocker arm is thus the length of the hydraulic adjuster. When the configuration changes and the adjuster is no longer in contact with the cam base circle it has been assumed that the hydraulic adjuster becomes rigid and of fixed length instantaneously. Thus, the length of the hydraulic adjuster defined in the arrangement shown in Figure 3 is applicable across the whole operational cycle of the valve train. The length of the hydraulic tappet adjuster is determined by the simple expedient of using an assembly level measurement to find the distance between the two ends of the adjuster when measured along the centre line of the adjuster. It should be noted at this point that the two halves of the hydraulic tappet adjuster are modelled as individual component parts and not as a sub assembly. This is essential to ensure that the two halves of the hydraulic tappet adjuster are capable of independent movement in the simulation model. If they were added as a sub assembly the positions of the two halves relative to each other would be fixed. The complete sub assembly would be capable of independent movement but not the component parts.

The first part of the DVA model should be viewed as a virtual jig [23] used to align the two halves of the hydraulic tappet adjuster. The output from this part is the measured length and variation distribution of an aligned, hydraulic tappet adjuster. While the output defines the length of the hydraulic tappet adjuster it is not in a form that can be directly imported into the second part of the DVA model. The variation distribution represents the net effect of all the variation sources that influence the length of the hydraulic tappet adjuster. For example if variation increases the length of the valve then the length of the hydraulic tappet adjuster will reduce so that it still exactly fills the gap between the rocker arm and the cam. The variation distribution of the hydraulic tappet adjuster relies on a long valve being matched with a short adjuster and vice versa. When the data is exported, this link is broken and the possibility exists of a long valve being matched with a long adjuster in the measurement process. This would add an extra variation source to the DVA model rendering it inaccurate.

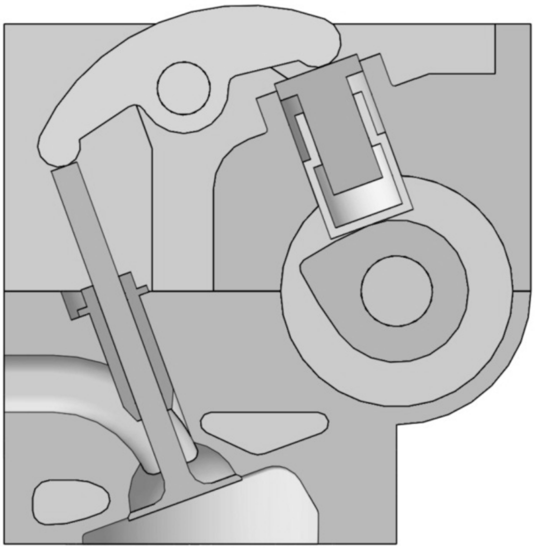

Figure 3. Component configuration used to define the length of the hydraulic tappet adjuster

Previously it has been assumed that when the hydraulic tappet adjuster breaks contact with the cam base circle, it instantaneously becomes rigid and of fixed length, thus the standard deviation of the hydraulic tappet adjuster variation distribution is equal to zero. The mean length of the hydraulic tappet adjuster without its variation distribution can be imported into the second part of the DVA model. If the variation distribution of the hydraulic tappet adjuster is to be set to zero then the variation source elements that contribute to the variation distribution of the hydraulic tappet adjuster must be identified and also set to zero to avoid double counting any of the variation source elements.

4.1.2. Identifying Which Variation Sources Affect the Hydraulic Tappet Adjuster Axial Length

The complete valve train contains numerous sources of variation. Some of these will affect the length of the hydraulic tappet adjuster others will not. Those variation sources or at least the elements of those variation sources that affect the length of the hydraulic tappet adjuster are negated by the action of the adjuster as it takes up any clearance in the system. By including a contributor analysis, a function common to most DVA software, in the analysis of the hydraulic tappet adjuster axial length those variation source elements that affect the length of the hydraulic tappet adjuster can be identified. This identification is aided by the introduction into the CAD model of a local co ordinate system. The local co ordinate system is aligned such that one axis is coaxial with the longitudinal axis of the hydraulic tappet adjuster (Figure 4).

The assembly joints in the first part of the DVA model are aligned, where appropriate, to the local co ordinate system rather than the global co ordinate system. When using only the global co ordinate system any variation source that causes translation along either the X or Z axes (Tx, Tz) may affect the length of the hydraulic tappet adjuster to some extent. Variation in Tx and Tz may also influence parameters that, for example affect the valve lift or valve timing. However, using the local co ordinate system only those variation sources that have a Twelement are likely to affect the hydraulic tappet adjuster length thus reducing the number of potential contributors.

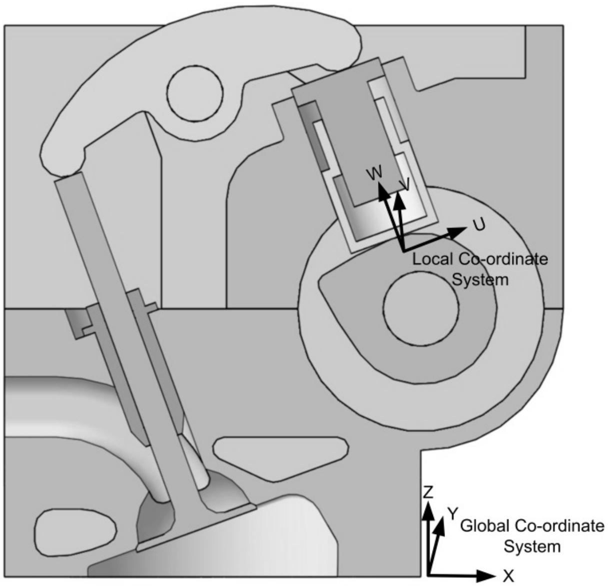

Figure 4. Local and global co ordinate systems

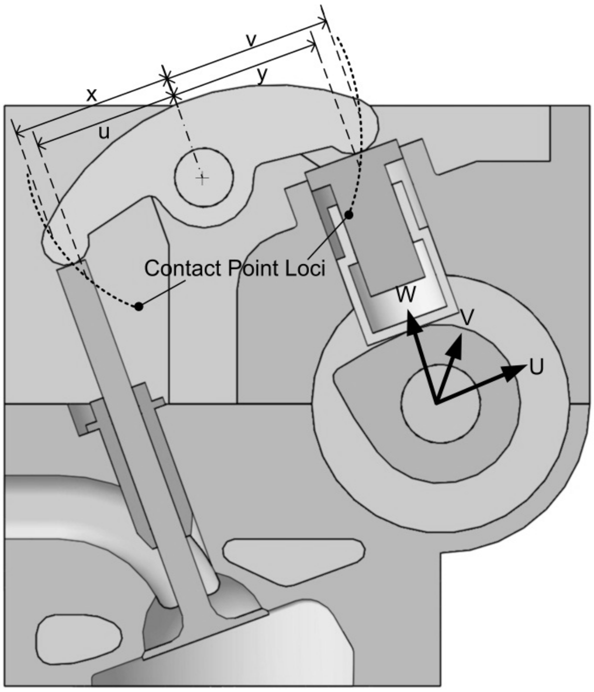

Figure 5. Effect of valve length on the rocker lever arm ratio

4.1.3. Identifying and Quantifying Variation Source Secondary Effects

Some variation sources may produce both an obvious primary effect and a more subtle secondary effect on the system. Consider the length of the valve stem when setting the length of the hydraulic tappet adjuster (Figure 3), as the length of the valve stem increases or decreases it will cause the rocker arm to rotate slightly. This will in turn increase or decrease the distance between the other end of the rocker arm and the base circle of the cam effectively changing the length of the hydraulic tappet adjuster as it negates the variation. However, as the rocker arm rotates it will cause the contact point between the rocker arm and the valve stem to move across the face of the valve stem. This will change the effective length of the rocker lever arm (Figure 5). The lever arm is defined, in this instance, as the distance between the rotation axis of the rocker arm and the contact point between the rocker arm and the valve stem measured in the U direction (Figure 4). A similar affect will occur at the other end of the rocker arm at the contact point between the rocker arm and the hydraulic tappet adjuster. The extent of the variation can be determined by measuring the distances x and y (Figure 5) in the first part analysis. This will give a variation distribution for each measurement as well as a mean value. The two affects may well be dissimilar in extent. Thus, a unit movement of the hydraulic tappet adjuster may move the valve by a distance x/y or u/v depending on whether the valve stem is above or below mean length. The question thus arises as to how the effects of variation are to be simulated especially so when a single variation source element gives rise to two different effects one of which influences the length of the hydraulic tappet adjuster and one which does not, but does influence a key characteristic of the system.

4.2. DVA Model Part 2, Simulating the System Behaviour

The first part of the DVA model identified and quantified the axial length of the hydraulic tappet adjuster, the variation sources that affect the axial length of hydraulic tappet adjuster and any secondary effects they may have on the other key characteristics of the system. The second part of the DVA model is dependent on this information to achieve a different set of objectives these are;

- To simulate the manner in which the hydraulic tappet adjuster negates the effect of certain variation source elements.
- To ensure that any secondary effects of variation sources negated by the action of the hydraulic tappet adjuster are retained in the DVA model.
- To simulate and analyse the effects of variation on the valve lift and valve timing.

4.2.1. Simulating the Behaviour of the Hydraulic Tappet adjuster

A significant feature of the second part of DVA model is that the valve is no longer in contact with its seat. In consequence, the length of the hydraulic tappet adjuster must now be defined externally. As noted earlier the variation distribution of the hydraulic tappet adjuster should not be imported into the second part of the simulation models as it creates an additional source of variation. It should, however, be remembered that the hydraulic tappet adjuster is designed to negate the effects of variation that would otherwise create clearance or slack within the valve train system. The solution is to set the hydraulic tappet adjuster to the mean length as defined by the first part of the DVA model. Those variation source elements identified as contributors to the variation distribution of the hydraulic tappet adjuster are also set to zero. The variation sources contribute no variation to a length that does not vary, thus ensuring consistency between the two. A benefit of using a local co ordinate system and aligning the assembly joints to that system now becomes apparent in that most of the variation source elements that require modification will be Tw elements (Figure 4). The overall effect is consistent with the assumed real world behaviour of the system in that the hydraulic tappet adjuster is of fixed length and any variation sources that might cause clearance are negated by the action of hydraulic tappet adjuster.

4.2.2. Retention of Secondary Variation Source effects

Despite the DVA model having two parts, the behaviour of a single valve train is being simulated. It is therefore important that the effect of each variation source element appears once and once only in the simulation model. Any source of variation that may affect the length of the hydraulic tappet adjuster must appear in the first part of the DVA model used to define the length of the hydraulic tappet adjuster. Equally, there may be sources of variation present that do not influence the length of the hydraulic tappet adjuster but do influence the valve lift or timing. These effects must be included in the second part of the DVA model. For example, it has been shown that a secondary effect of variation in the length of the valve can influence the valve lift (Figure 5). Yet in the second part of the DVA model the valve length of has been set to its mean value. The secondary effect therefore needs to be incorporated into the second part of the DVA model by some other means. To do so requires an assembly level measurement of x and y (see Figure 5) to be included, in part one of the DVA model. On analysis, it will give a variation distribution for x and y. This variation distribution can be incorporated into the simulation models by using a root sum of the squares (RSS) method to add it to the Tu element of the positional tolerance of the curved end of the rocker arm. Thus, the effect of a variable valve length on the valve lift and timing is present in the simulation model even when the valve length is fixed. This is possible because the centre of curvature of the end of the rocker arm drives the location of the contact point between the valve and rocker arm. The contact point is defined as the point of intersection between the curved end of the rocker arm and a line parallel to the valve axis that passes through the centre of curvature of the end of the rocker arm.

It has been stated that the effect of each variation source element must appear once and once only in the two parts of the DVA model. However, the sources of variation in the assembly may not be independent of each other. Consider the profile of the cam (Figure 3). In this particular instance, the cam profile consists of four facets, the base circle, the cam toe and the leading and trailing flanks. The four facets of the cam profile may be ground in a single operation to give a smooth profile with no discontinuities. Thus if the base circle of the cam varies in size the adjacent cam flank must also vary to the same extent if profile discontinuities are to be avoided. If discontinuities do occur then the realism of the simulation model is called into question.

Part one of the DVA model must include any variation in the cam base circle as this directly affects the axial length of the hydraulic adjuster. Equally, any variation in the cam flanks or cam toe must be included in part two, as these will directly affect the valve lift. Variation of the cam flanks is influenced by variation of the cam base circle. Thus, any variation in the cam base circle must be included in the second part of the DVA model as it indirectly affects the valve lift. As a result, variation of the cam base circle is present in both parts of the DVA model. However, in part one, variation of the cam base circle directly affects the length of the hydraulic adjuster, which negates any effect on the valve lift. In the second part of the DVA model, variation of the cam base circle indirectly affects the valve lift through the cam flank. However, as the cam base circle does not make contact with any of the other component parts of the assembly once the valve is open only the cam flank is affected by variation in the cam base circle. Thus while the cam base circle acts as a source of variation in both parts of the DVA model the two different effects of this variation source appear once and once only.

4.2.3. Simulating the Effects of Variation on the Valve Lift and Timing

To simulate the effects of variation on the valve lift and valve timing in the second part of the DVA model, two groups of simulation model configurations are required. The first group simulates the effects of variation on the valve lift, by fixing the angular position of the cam with, in this instance, a 5° increment in the cam angle between each configuration. The total rotational range covered being top dead centre (TDC) to 110° after TDC. The extent of the valve lift is then determined by an assembly level measurement incorporated in each model configuration. The second group, which has two configurations, simulates the effect of variation in the cam angle just as the valve is opening and closing. The position of the valve is fixed, in this instance, to 0.01mm off the valve seat with the hydraulic tappet adjuster in contact with the leading and trailing flanks of the cam respectively. This particular valve position was chosen as it describes two and only two positions in the operational cycle of the valve train whereas the valve is in contact with the valve seat for a significant portion of the operational cycle. The cam angle is then measured.

5. Analysis Results

The modelling method described above has been applied to valve train systems containing hydraulic tappet adjusters in the three common locations and was found to produce a viable simulation model. Figure 6 shows the results obtained when simulating the behaviour of system in which the hydraulic tappet adjuster is located between the cam and the rocker arm (Figure 3). The analysis results for the valve lift and valve timing of the hydraulic tappet adjuster are compared against those from an identical system but fitted with a screw type adjuster (Figure 6). The solid curves in Figure 6 represent the mean valve lift while the error bars represent the limit of variation in the valve lift at three standard deviations. Similarly, the columns represent the variation in the cam angle at the point where the valve is just opening or closing. The solid line represents the mean value while the shaded areas represent the variation at three standard deviations.

The system fitted with the hydraulic tappet adjusters shows significantly less variation than that fitted with the screw adjusters. This is to be expected as the hydraulic tappet adjusters are specifically designed to negate some of the variation. A second feature to note is that the system fitted with the screw adjuster shows a slightly reduced valve lift compared to the hydraulic tappet adjuster system. This is a reflection of real world practice where, even when hot, a slight clearance gap is usually left in valve trains fitted with screw adjusters to ensure that the valve always closes on the compression stroke. This same clearance gap is responsible for the apparently negative valve lift as the valve closes in a system equipped with a screw adjuster. The analysis is performed using vector loop based software where vector loop and simulation model closure are a necessary condition for analysis. While it is possible to simulate a variable gap, it is difficult to model. In this instance it was considered simpler to maintain model closure by allowing all the component parts to remain in contact and to interpret the negative valve lift as the opening of a clearance gap.

A comparison of the contributors to variation in the valve lift shows some significant differences and similarities between the two systems (Figure 7). The three major contributors in the screw adjuster system are absent from the hydraulic system contributors as they are negated by the action of the hydraulic tappet adjuster. Perhaps more significantly the remaining contributors appear in both systems in the same sequence. This suggests that both systems behave in a similar manner and only the action of the hydraulic tappet adjuster in negating certain variation sources distinguishes the two systems. The overall analysis shows that the simulation of the valve train system containing hydraulic tappet adjusters is consistent with real world expectations.

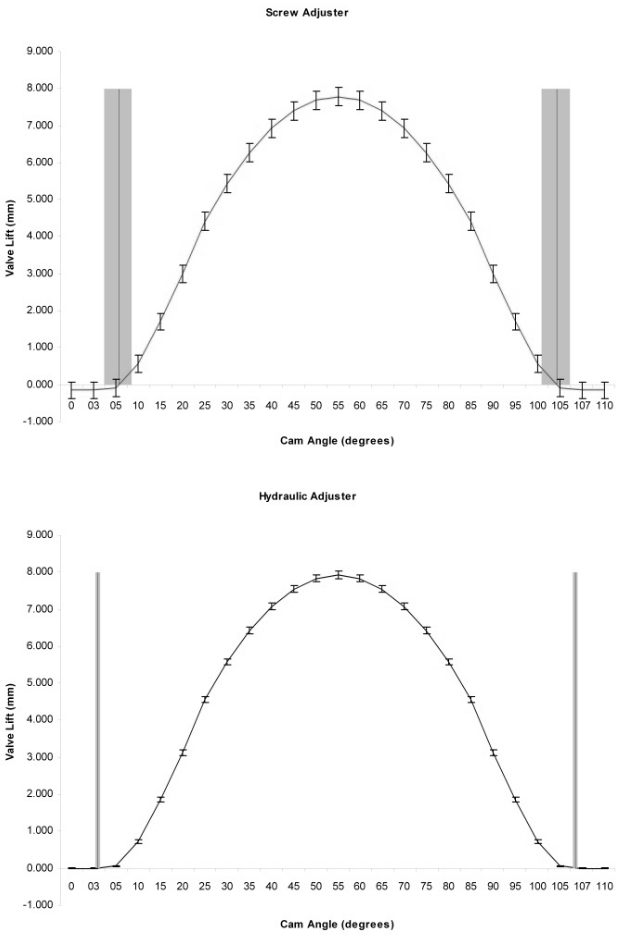

Figure 6. Valve train analysis output

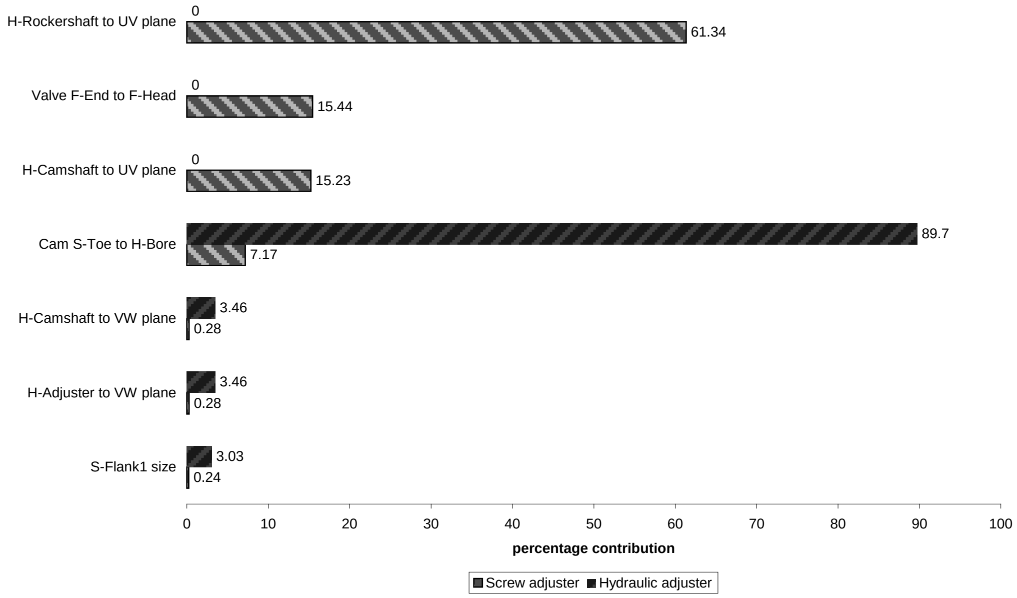

Figure 7. Comparison of contributors to valve lift variation

6. Conclusions

The method described in this paper provides the capability to model and simulate the dimensional variation behaviour of three common valve train configurations containing hydraulic tappet adjusters. This in turn enables the effects of variation on performance related characteristics such as valve lift and valve timing to be analysed. The described method while requiring a more complex two part simulation model can include and account for the all important interdependence between the adjuster setting and valve operation configurations and allows the analysis of assembly systems where one or more significant parameters are not defined from the outset.

Although the effect on the valve actuation from variation due to the tappet adjustment was small, never the less, this example of a hydraulic tappet adjuster still clearly shows that a two stage DVA model can be used to transfer the resultant variation from one model configuration into another model configuration. This increases the capability of the DVA model by allowing interdependence between one model configuration and another to be included and accounted for. The two stage approach relies upon:

- There being a suitable intermediate variable that can be used to carry over the variation. In this example of a hydraulic tappet adjustor, the ‘carry over’ variable was the effective length of the rocker arm. The output from the tappet adjustment stage was to calculate the resultant variation in the effective length of the rocker arm. This output variation from the tappet adjustment stage was then carried over as an input to the valve actuation stage to create the required interdependence.
- The careful segregation of the component variations between each of the two stages to avoid any of the component variations from being double counted.

7. Further Work

The method described in this paper has been applied to valve trains systems where the nominal valve lift and timing are fixed. However, the use of variable valve event (VVE) valve train systems is becoming more widespread. It will therefore be necessary to develop methods of simulating the dimensional variation behaviour of VVE valve trains and the hydraulic tappet adjusters they contain.

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