Inspection of curvic couplings using a CMM

N.B. Orchard
Specialist Engineer – Inspection Technologies
Manufacturing Technology Department,
Rolls-Royce plc, United Kingdom
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Abstract

The inspection of curvic coupling geometry is usually done by using a mating master curvic to check the transfer of a very thin coating of engineering blue from the master to the curvic being inspected. The mating master curvic is also used to measure dimensions such as swash, radial runout and overall stacking height. Although the method is relatively quick, it needs a skilled eye to interpret the bluing patterns, and it does not produce any numerical data on the curvic form. The development of new methods for machining curvic couplings places a greater emphasis on having numerical data in order to provide inspection feedback. Rolls-Royce has investigated the use of a coordinate measuring machine (CMM) to inspect curvic couplings, and this paper discusses some of the problems and successes.

1 Introduction

Curvic couplings were first introduced by Gleason [1] in 1942 as a development of spiral bevel gears, intended to meet the need for couplings with high accuracy and high load carrying capacity. They also provide an extremely effective means of aligning two rotating components due to the self-centring effect of the design. The general arrangement of a typical curvic coupling is shown in Figure 1.
Curvic couplings are produced by plunging a cup shaped grinding wheel towards the blank material, i.e. the wheel is moved along its axis of rotation, parallel to the curvic axis. The grinding wheel has a chamfer angle on its edge equivalent to the flank angle required on the curvic tooth, the chamfer being on the outside for the concave coupling, and on the inside of the wheel for the convex half. This arrangement results in the tooth face having a conical form, with one half of the coupling having concave faces and the other half having convex faces. Figure 2 shows a concave curvic being cut, and Figure 3 shows the convex side.
Figure 3: Cutting a convex curvic coupling

It is important to note that the grinding wheel machines two teeth simultaneously, the left hand side of one tooth on the way in, and the right hand side of a different tooth on the way out, so the faces of these two teeth lie on the same cone. After each cut the curvic blank is rotated through the pitch angle of the teeth and another pair of faces is cut. In some couplings a slot is machined in the middle of the teeth in order to allow the joint coupling bolts to apply the clamping force through the centre of the teeth. This gives the appearance of having two concentric rows of teeth, but they still share the same geometry, and there is still only one pitch plane and one radius at which the tooth/gap distances are equal (the pitch circle) – see fig 4.

Figure 4: A split-face curvic coupling with space for clamp bolts
2 Conventional curvic inspection

For many years the only feasible means of inspecting a curvic coupling has been to test its goodness of fit with a mating master curvic. Inspection is done by applying engineering blue to the teeth on the master and yellow ochre to the curvic part being inspected. After mating the halves together with enough pressure to ensure good contact, the curvic teeth are visually examined to check that they have blue over most of the central part of every face. This is done at regular intervals during the machining of the teeth so that small adjustments can be made to the grinding machine, ensuring that by the time the wheel reaches full depth the correct geometry has been produced. Dimensions concerning the position of the curvic as a whole with respect to the datum faces of the component on to which it has been machined are also inspected using the master curvic. By clocking the side of the master as it is rotated in contact with the component, the radial runout is assessed. Clocking the top of the master gives the swash and overall stacking distance (or height).

The use of a single pair of masters to control all subsequent curvics made to that design guarantees interchangeability of components at any time in the future. What it does not guarantee however is that the master was made to the precise dimensions specified by the designer. This is of no real consequence in conventional cup-wheel grinding because it is relatively easy to adjust the grinding machine to get the blue pattern in the right place. However, if curvic couplings are to be produced on CNC machines, the lack of numerical error data could make it difficult and time consuming to achieve the correct geometry. It is for this reason that it was decided to investigate the possibility of measuring curvic couplings on a CMM.

3 CMM curvic inspection

Measurement of gear geometry is a well known art, and there are several suppliers of high accuracy gear inspection machines. These machines generally use scanning probes to trace the form of the gear tooth and compare the contour with a master form. Older systems rely on the operator to look for errors on the printouts, but newer systems can automatically calculate key dimensions and highlight out of tolerance conditions. Unfortunately these machines are at the top end of the market, and apart from the high cost of the machine itself, they require expensive controlled environments in order to operate to their specified accuracy. They also have a technical limitation in that the probe is required to take measurements in the correct (i.e. known) position on the tooth. The problem is that until the curvic has been measured and the best-fit alignment done, the true position of the centre and the pitch plane are unknown. Gear measurement software is not generally designed to do the sort of best fit alignment of the whole component that is needed for curvic coupling evaluation.

A simpler approach to gear measurement is to measure a number of single points on each tooth from which the tooth geometry can be calculated. This is not a common approach but some work in this field has shown useful results [2],
and single point probing is easier to apply on most CMMs. The use of a standard CMM would also have significant cost benefits over the purchase of a high accuracy gear measuring machine. There are, however, several causes for concern when considering the use of a CMM to inspect curvic couplings. The major concern is whether or not a CMM is accurate enough. If it is accurate enough, is the software adequate to do the calculations and best fit? If the software is up to the job, will the inspection cycle time be too long? What is the best way to display the results in order to be most effective? Rolls-Royce has undertaken some work to find answers to these questions, and this paper looks at the results of the accuracy assessment.

4 CMM accuracy

The usual starting point for assessing the accuracy requirement of a CMM is to look at the tightest tolerance on the drawing that has to be measured. In this case assessing the accuracy requirement is difficult because the component drawing does not specify a dimensional tolerance, but simply demands adequate contact between mating faces [3]. This means that an assessment has to be made of how big the gap can be between mating faces before they fail to blue, i.e. how thick is blue? In practice the thickness is likely to vary from operator to operator, but simple tests measuring two slip gauges with a blued face between them indicate that blue is in the region of 0.003mm to 0.006mm thick. The volumetric accuracy of a typical CMM is about 0.005mm over the size of say a 200mm diameter curvic, with a repeatability of about 0.003mm. This indicates that it is questionable that a standard CMM would be accurate enough, and it may be necessary to consider using a special high accuracy CMM. However, as no attempt has been made to use a CMM on curvics before, it was felt that it would be worth trying.

4.1 CMM accuracy tests

The CMM used was a Mitutoyo Euro Apex 121210 (See Figure 5), located in a standard shop-floor environment that has a typical temperature range of about 10°C, although measurement at the extremes is avoided if possible. The machine has a U3 accuracy specification of \((4.9 + 5L/1000)\ \mu m\), and is fitted with a temperature compensation system. A parametric curvic measurement program was written that enables key variables to be changed easily to suit requirements. These variables include the basic curvic geometry parameters such as radius of curvature, number of teeth, number of rows of teeth etc., and also the measurement parameters such as the number of points to measure on each tooth and the spacing between points. The program then automatically calculates both the nominal curvic geometry and all the 3D coordinates of the required measurement points. Before measurement of the teeth, a rough alignment program establishes the approximate position and orientation of the curvic. This alignment is intended to be accurate enough to avoid significant ball tangency errors when probing the tooth face. An error of 1 degree will result in a tangency
error of $0.3\mu m$ when using a 2mm diameter stylus, but will also result in the probe missing the tooth face, so the tangency errors due to misalignment are therefore ignored.

Figure 5: Mitutoyo Euro Apex 121210 CMM

The curvic used for these trials was an inspection master, with 44 split-face teeth (i.e. in two rows), an outside diameter of 160mm, face width of 8mm, and a grinding wheel radius of 168mm. (Approximate dimensions). The program measured 16 points on each face, 8 on each half of the split face. After measurement a best fit routine was used to establish a revised co-ordinate system for the curvic, and then the metal condition error of each of the 1,400 points was calculated. In order to make the results more manageable, the mean value of the 16 points on each face was calculated and presented as the mean pitch error for the whole face. The results were then plotted separately for the left hand and right hand faces. The pitch error is used as the primary parameter for assessment of accuracy because it has the greatest effect on the bluing capability. Errors in the tooth flank angle or radius of curvature are easily corrected by altering the dressing of the grinding wheel, but errors in pitch are usually due to machine inaccuracy, which is more difficult to eliminate.

4.1.1 Repeatability tests
The first test was to check the repeatability of the measurements obtained without moving the part. Two consecutive runs of the program were made and the results are shown in Figure 6 for the left hand faces. It is important to note that the error value is the deviation of the face from its nominal position and includes the actual errors in the curvic manufacture as well as the errors in measurement. The purpose of this test is only to look at the repeatability of the measurements, not to make any judgement on the curvic itself. The results show
very good repeatability, with a maximum difference of 0.8μm, and standard deviation in the difference between the two sets of measurements of only 0.4μm.

![Euro CMM Repeatability (Left Hand Faces)](image)

Figure 6: Measurement repeatability of Euro CMM with no movement

While this is encouraging, the actual dimensions are not necessarily very accurate. The results will contain one component that is the true dimension, one component that is the random variation (repeatability) of the CMM, and one component that is the CMM accuracy error. We can see that the random element is very small, but it is not possible to tell from these results how much of the accuracy error is due to the component, and how much is due to the CMM. In theory the curvic master should be perfect, and any errors in the results are entirely due to the CMM. As the 2-3μm variation is within its accuracy specification this is entirely feasible. In reality the curvic is unlikely to be perfect, but the true errors are not yet known. One approach to improving the accuracy of the CMM would be to error map the relatively small volume of the CMM in which the curvic is measured, but this could be time-consuming and of limited value in the long term if temperature effects are significant.

4.1.2 Error separation
Previous work [4] has shown the value of mathematical error separation techniques in improving measurement accuracy. The principle of error separation is that the object being measured does not change its size or shape during repeated measurement in different positions or orientations. Provided that the results in any one position are repeatable, differences in results between different positions must be caused by CMM accuracy errors, therefore it should be possible to separate out the three different components of the measurements.
We have shown that the repeatability component is very small, so the accuracy component should be large enough to calculate. However, before getting involved in some heavy-duty maths it was decided to test the much simpler and quicker method of using the mean values of measurements taken in several different positions. Obviously the greater the number of measurement positions, the nearer the mean will be to the true value. For practical purposes the number of repeats needs to be kept to a minimum, as it takes about an hour to measure the curvic, and another hour to calculate the results, so the trial was done with three positions. After the initial measurement the curvic was measured twice more, but with rotational adjustments made to its position on the CMM, so that for the second run tooth 12 was in the 6 o’clock position, and for the third run tooth 20 was in the 6 o’clock position. The starting point for the measurements remained at 6 o’clock but the results were shifted by the correct number of teeth so that the results plotted in Figure 7 show a like-for-like comparison.

![Euro CMM Repeatability with Repositioning](image)

**Figure 7: Euro CMM repeatability with repositioning**

It can be seen that the repeatability has deteriorated significantly, with a maximum difference of 4.3μm, and a standard deviation of 0.9μm, but this is to be expected as the machine accuracy is now affecting the results, not just the repeatability, and the performance is generally in line with the accuracy specification for this CMM. The mean of the three sets of results (shown in white) should now be a closer approximation to the true geometry of the curvic master, but as the total variation in the mean (3.5μm) is not significantly different from the repeatability variation (4.3μm), it is not valid to make this assumption without further proof.
4.2 High accuracy measurement

The simplest method of testing this hypothesis is to measure the curvic on a more accurate machine. As well as the standard Euro range of CMM, Mitutoyo manufacture a very high accuracy CMM, the Legex. This has a volumetric accuracy specification of $(0.48 + L/1000) \mu m$, and runs the same software as the shop-floor machines. An opportunity was taken to run the same program on the master curvic on the only Legex in the UK. Time constraints meant that only two runs were possible, so they were done in two different positions. The results are shown in Figure 8.

![Legex CMM Repeatability with repositioning](image)

The repeatability of the Legex shows a maximum difference of $0.7 \mu m$, and a standard deviation of $0.4 \mu m$. The total variation in the mean of the pitch results is $3 \mu m$, and visually the random variation appears much smaller than the systematic variation, so it is now reasonable to assume that the mean of the two sets of measurements shows the true geometry of the master curvic.

We can now compare the mean of the results obtained on the Euro CMM with the mean of those measured on the Legex, and the result is shown in Figure 9. Although not a perfect match, it can be seen that the Euro results show the same pattern of error in the master curvic as the Legex, with a correlation range of $+/1.1 \mu m$, and a standard deviation of correlation of $0.6 \mu m$. This shows that the repositioning technique has enabled the curvic to be measured on the Euro CMM to a higher degree of accuracy than the machine specification implies is possible.
5 Conclusions

The Euro CMM results are significantly more accurate than the specification suggests is reasonable or possible. While a single measurement cannot be relied on, the repositioning and averaging technique gives a means of using a low-cost CMM to provide high accuracy results, and provide useful feedback to the machining process. We can also see that although the bluing checks on the master produce near perfect results (otherwise it would not be acceptable as a master) it still appears to have pitch errors of up to 1.5μm in it. This provides a starting point for determining the dimensional accuracy tolerance for curvic couplings. The initial estimate that the thickness of blue is between 3μm-6μm is still valid, but more measurements need to be taken on production standard curvic couplings to establish the upper limit of acceptability. The CMM program needs to be developed further to calculate a mating fit alignment that will enable the correlation between the CMM measurements and the bluing patterns to be assessed.

References