The measurement of involute worm wheels

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Abstract

This paper describes the traditional methods used for checking worm gears, using contact marking techniques and discusses a new method for the analytical measurement of worm gears which uses a CNC gear inspection machine at the UK National Gear Metrology laboratory. Some of the development and validation problems are discussed and example measurement results are given.

1.0 Introduction and Background

Equipment, standards and procedures for the measuring of involute spur and helical gears have been available for many years. During this time, manufacturers of involute worm gears, although an important part of the transmission business, have not had this luxury because the geometry of involute worm gears is far more complex than involute spur and helical gears. A typical worm gear pair is shown in Fig. 1. The development of analytical inspection techniques could not be implemented until CMMs or CNC machines, with sufficiently powerful computers became available.

1.1 Conventional Contact Marking Inspection Procedure

The involute worm is an accurate screw thread with an involute profile and it is relatively simple to measure. Standard gear inspection machines or CNC gear checking machines may be used with acceptable accuracy. The worm wheel is far more complex. It is not feasible to build a mechanical inspection machine for checking worm wheels. Worm wheel manufacturers have traditionally used a contact marking test procedure, as outlined below:
Manufacture a master or 'standard' worm, which is inspected using gear inspection machines to verify it is of acceptable accuracy.

Use a gear hobbing machine to cut the worm wheel using the nominal calculated setting data.

Set the worm gear in mesh with the 'standard worm'. Lightly cover the worm with soft marking blue and obtain a contact marking pattern.

Check the contact pattern and backlash. If the test results are not satisfactory, the hobbing machine settings are adjusted and the worm wheel is re-cut. The direction and amount of adjustment are at the discretion of the hobbing machine operator, based on experience rather than theoretical knowledge to improve the contact marking.

The process is repeated until a satisfactory contact mark is obtained and the batch of worm wheels is subsequently manufactured.

This procedure is easy and does not require a detailed knowledge of the geometry. The procedure is not good at identifying individual profile, pitch and lead errors hence it is difficult to determine the error sources.

1.2 Conventional CNC inspection procedure

With the introduction of CNC inspection machines and CMMs, complex surfaces can be measured with acceptable accuracy. The difficulties associated with defining the geometry of worm wheels has meant that most machines which claim to inspect worm wheels do so as a comparative measurement. They define tooth surface errors as differences between a master worm wheel and the individual worm wheel being inspected. The results from these comparative measurements are of limited value because the real geometry is still unknown.

1.3 New CNC inspection procedure

An absolute worm wheel measurement process has been developed by Design Unit at the University of Newcastle upon Tyne. This absolute measurement technique inspects the worm wheel profile and lead errors with respect to the theoretical tooth form. The new measurement process uses a CNC gear measuring machine and has the following advantages:

- It is easier to determine the source of individual errors and hence quantify process capability.
- The geometry of the worm wheel surfaces outside the 'no-load' contact region can be quantified.
- Errors due to the master worm and master worm wheel are excluded.
- Geometry of worm gears can be optimised since confusion caused by previously unquantifiable manufacturing errors has been eliminated.
- The results obtained are of direct significance for worm gear performance.
- The accuracy is verifiable.
2.0 Measurement Principle

Before any measurements can be made, the theoretical tooth surface must be defined. The tooth surface is generated by a mathematical kinematic model [1] of, what is effectively the worm wheel manufacturing process, with the exception that the cutting tool geometry and machine setting is replaced by the mating worm geometry. The measurement of the total topography of the tooth, with respect to the mathematical model is feasible, but this would be time consuming. It was decided that sufficient information could be obtained by measuring 'profile' errors, in user-defined transverse sections, and a single 'lead' error (see Figs. 2a and 2b). Normally more than one transverse section needs to be measured since worm wheel profiles may vary significantly from one section to another, which is different from the method adopted when inspecting a parallel axis spur and helical gears.

The measurement method was simplified further by measuring the lead error at the worm wheel pitch cylinder. The calculation of the theoretical tooth lead shape at this unique diameter is determined by two factors 1) the shape of the 2D curve produced by the intersection of the worm helicoid with the pitch plane, and 2) the corresponding rotation of the worm wheel, which effectively rolls this curve (see Fig. 3) around the pitch cylinder.

Once the curve has been calculated, measurement of the tooth lead error is implemented by moving the probe along a spatial trajectory and simultaneously rotating the worm wheel to measure the resulting curve.

3.0 Measuring Equipment

A Gleason GMS 430 CNC gear measuring machine situated in the UK’s National Gear Metrology Laboratory was used to implement and test the measurement procedure. This is a standard 4-axis gear measuring machine (3-linear axes and 1 rotary axis) with a Tesa GT-31 (bi-directional), single axis probe.

4.0 Practical Considerations

There were a number of practical problems which were given careful consideration when developing the measurement procedure.

- When the worm wheel is manufactured, the hob which is used to cut the worm wheel has a slightly different geometry to the worm with which the worm wheel will run. The worm geometry was chosen for the kinematic mathematical model because, it was easier to implement and allowed a direct comparison of measured results with the traditional contact marking tests.
- When measuring lead errors, a given error in axial datum will result in approximately a 40% error in lead measurement. This proved troublesome
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on a CNC machine with a single axis probe which could only measure in the transverse plane. This problem was overcome by bonding a ball of calibrated diameter onto the axial datum. The ball could be probed in the transverse plane and the height of the axial datum determined with adequate accuracy.

- Axial datum errors in the worm wheels proved to be a common problem in the samples of worm wheel which have been measured. Rather than rejecting a worm wheel because of an axial datum error, this error was quantified. The new datum was used to re-measure the worm wheel, and the new datum recorded to assist assembly. This avoids time consuming removal and re-shimming of the gears in the gear case.

- When measuring large diameter worm wheels a high frequency error of 2μm was noted on the lead error trace (see Fig. 4a). After investigating this phenomenon it was concluded that this was caused by torsional wind-up of the spindle due to static friction while ‘nulling’ the probe reading. A null-band range of ±2μm was applied to the probe, the residual probe reading being accounted for as part of the measurement process. Fig. 4b shows that after filtering the signal, this effect is reduced. This filter will not affect the validity of the measured result.

5.0 Validation of the measurement results

This is a unique measurement method, therefore the direct comparison of results from a second source is not possible. The following section shows how the results have been validated:

- The measuring machine, a Gleason GMS 430, CNC parallel axis gear inspection machine has had its accuracy verified in accordance with British Gear Association Codes of Practice [2]. These relate to the accuracy requirements and test procedures used to traceably verify the accuracy of the machine for checking parallel axis gears. The calibrated uncertainty (Ugs) of the machine is ±1.5μm for profile and ±1.8μm for lead measurement.

- Changing the size and geometry of the stylus changes the correction used to ensure the probe contacts at the correct point on the wheel flank. If the calculated geometry is wrong, there will be significant differences in measurement results with different probes. The lead error result obtained by using a 1mm and 2mm diameter probe differed by less than 1μm / 50mm face width.

- Comparison of measurement results with contact marking tests (see Fig. 5) show good correlation.

- The measurement of the profile error in a specific axial section called, the involute section, allowed us to compare the results between the new worm wheel measurement software and standard parallel axis software. The measurement results are identical, although the results are presented at
6.0 Typical Measurement Results

Fig. 7 and Fig. 8 show a typical application of the measurement procedure: the results are from a passenger lift drive which exhibited excessive noise and vibration. Fig. 7a shows the lead measurement results and Fig. 7b shows the profile results. It is clear that there are large profile errors which would cause excessive noise and vibration during operation. This was diagnosed as a tooling error, not a fundamental design error.

The hob, which cut the worm wheel was re-ground and a new worm wheel manufactured. The results from this wheel are given in Fig. 8. This shows significant improvements in profile and lead errors. When tested, noise and vibration levels were accepted. This type of diagnostic work would not be possible without the development of this software and measurement technique.

7.0 Conclusions

A new analytical measurement procedure for involute worm wheels has been developed and validated at the UK’s National Gear Metrology Laboratory. The technique has been used successfully over the last 4 years to measure worm wheels of different sizes. For the first time it has allowed manufacturers to analytically quantify the accuracy of worm wheels.

8.0 Acknowledgements

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References

Figure 1: Worm and wheel pair

Figure 2a: Profiles to be Measured

Figure 2b: Lead to be Measured
Figure 3: Lead trace on the wheel pitch cylinder

Figure 4: Filtering the ripples caused by the measuring system
Figure 5: Comparison between measurement traces and the contact pattern

Figure 6: Profile deviation in the involute section
a) Measured with the worm wheel measurement software
b) Measured with the involute gear measurement software
Figure 7a: Profile errors of the old wheel

Figure 7b: Lead errors of the old wheel
Figure 8a: Profile errors of the re-cut wheel

Figure 8b: Lead errors of the re-cut wheel