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A straightforward and low-cost pre-inspection measurement method for small gears

L.L. Alhadeff*, T. Slatter

Department of Mechanical Engineering, The University of Sheffield, Mappin St., Sheffield S1 3JD, UK

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ABSTRACT

On-line or rapid inspection of parts is essential in streamlining manufacturing processes. A novel pre-inspection method for measuring small gears is proposed. This method requires little specialist equipment outside that normally found in a laboratory or on a shop floor. Gears are measured using a standard optical microscope. These are then processed using an image processing algorithm to give a percentage error in tooth profile. This allows only gears of sufficiently high quality to be "passed on" to more sophisticated inspection techniques. The technique is used to analyse sub-centimetre diameter gears produced using WEDM. It is found that the technique provides a simple but effective method of determining how close a gear is to the required geometry. While the result is basic, it is extremely quick and inexpensive to perform alongside the manufacturing process. This method provides a capability to small companies and production lines for pre-inspection of gears before detailed analysis without purchasing specialist equipment.

1. Introduction

In manufacturing, time losses are critical [1] in terms of production efficiency. Production errors lead to loss of time and resources. For quality control, off-line inspection is necessary [2]. However, on-line inspection mitigates errors in manufacturing processes and reduces overall waste [3].

Typically, measuring gears requires specialist equipment such as height-gauges [4], specialist test apparatus, CMMs (coordinate measuring machines) and trained personnel [5]. It can thus be very expensive and slow [6]. Where gear production is of prototypes, and during early production, there can often be high error rates and modification cycles are needed [7,8] and failure. Furthermore, small businesses or research labs producing small volumes of gears lack the capability or capital to carry out their own testing and rely on external services. Small gears may clearly fail to meet quality measures without this being immediately apparent. Sending these for measurement is a waste of time and resources.

A simple technique is described herein for pre-inspection of gears before formal characterisation takes place. Minimal specialist equipment is required and measurement can likely be carried out on-site in a machine shop. Results are almost instantaneous, requiring only processing time, and allow gears which are obviously outside tolerance to be rejected. The benefit of this technique is that gears that do not meet specification can be discarded before expensive inspection, and manufacturing techniques can be evaluated early on in the process.

1.1. Gear measurement

When assessing the quality of gears, both form errors and position errors are considered [9]. Form errors describe a deviation from the nominal shape, and these include profile errors (depicted in and lead errors (Fig. 1b). Position errors describe the accuracy of the location of teeth, and include pitch error (Fig. 1b) and runout (Fig. 2b). Profile error increases noise where gears are meshed, while lead error reduces the load-carrying capacity of the gears [5]. Form errors affect motion transfer. Thus, all of these errors must be correctly understood to assess the quality of a gear.

1.1.1. Tactile techniques

Traditionally, gear measurement has taken place using tactile or specialist optical measurement, with equipment such as CMMs, optical comparators, precision height gauge sets (all of which are expensive and specialist) or rotation through small angular increments and numerous measurements either optically or with calipers. Each of these require specialist equipment and are slow [10]. Tactile measurements include techniques such as double flank testing and probing using either a CMM or rolling test.

* Corresponding author.
E-mail address: lisa.alhadeff@sheffield.ac.uk (L.L. Alhadeff).

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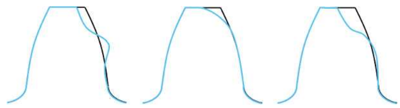
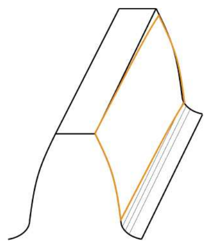
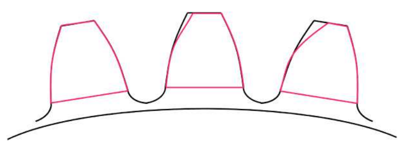


(a) Profile errors, characterised by a deviation from the nominal profile. These increase noise.

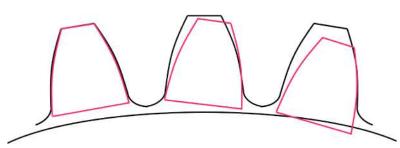


(b) Lead errors, a linear deviation along the face of the tooth. This affects load-carrying capacity.

Fig. 1. Form errors.



(a) Pitch error, the difference between nominal angular location and actual measured location. This affects motion transfer.



(b) Runout, radial displacement of gear teeth which is cumulative across teeth. This affects motion transfer.

Fig. 2. Position errors.

Double flank gear roll testing, consisting of a master gear meshed with the test piece, which measures centre-distance variation, which describes form errors. However, there has been difficulty in repeatability with this method due to part change, i.e. wear [11]. A further issue with this method is that slight sliding can occur, leading to unstable readings. Pueo et al. [12] also found fault in that there was no clarity or fixed guidelines for measuring or reporting in such inspection; necessary to allow comparison and repeatability of results between setups. An alternative to this method is a Double-Flank-Rack Probe (a rolling test using a probe rather than gear). This was found by Tang and Jia [13] to be faster and more repeatable than a gear-specific CMM although measurement time was not stated.

Latterly, faster and more accurate methods have been developed using more sophisticated optical techniques such as triangulation and interferometry, and acoustic techniques, which allow on-line measurement.

1.1.2. Optical techniques

There are various methods of optically measuring gears precisely – laser-line triangulation can deliver uncertainties of only a few micrometers, and can be used on-line [14]. However, triangulation can be inaccurate, and deviates form tactile measurements due to reflection from the gear flanks and other systematic errors [15]. Laser interferometry presents a better method, allowing faster scanning speeds than can be achieved tactically [16]. As the beam has a small diameter, it is able to penetrate into small topologies. A major advantage of this method is that it can offer on-line inspection – however, initial calibration is required. Previously, calibration was difficult and non-standardised although Seewig et al. [17] went some way improve this by developing a mathematical model. To further its applicability, this approach can also be carried out using a Light-emitting diode.

In addition to laser interferometry, white-light interferometry-based sensors for the surface topography measurement of tooth flanks have also been developed [18], allowing enhanced speed of measurement over laser interferometry (although resolution is reduced). The method lacks the ability to measure steep geometries, requiring vertical observation and line-of-sight between measurement instrument and surface (thus eliminating hears with very small width of space[16]. As with tactile measurements, a difficulty with interferometry is that optimisation of parameters such as brightness and exposure is often carried out using trial-and-error, and would benefit standardisation [19].

1.1.3. Acoustic techniques

When in operation, gear surface quality can be assessed by noise monitoring or acoustic emissions (AE). AE is less sensitive to background noise and resonance, although higher sampling rates are required. As a result of this lower susceptibility to environment, AE is considered much more reliable than vibration, which is not considered to consistently describe gear tooth damage [20]. Sophisticated modelling has been produced which allows AE to describe gear tooth topologies, profiles and asperity contacts. However, it requires gears to be meshed, i.e. at least tested in an operational environment, which is more time-consuming than measuring in the manufacturing environment [21]. All of the methods previously described represent the state-of the art in methods for high-quality gear measurements with improved timings as compared with traditional methods.

The proposed technique uses image-processing (described in Section 2) to give an indication of whether a gear has apparent geometrical errors. This can be used to determine whether the dimension or form of the gears lies outside the acceptable range. Surface topography and finish of teeth can be determined by methods such as stylus and optical profilometers, which is not possible optically. However, the information provided on geometry offers an initial-stage elimination of gears which do not meet specification, reducing the number of more time-consuming measurements taken.

2. Method

Three different sizes of gear were measured: 6 mm, 8 mm and 10 mm pitch diameter. Each of these sizes had varying numbers of teeth: 12, 18 and 24 respectively, with geometry derived from CAD (computer aided design). The gears were manufactured using a WEDM (wire electrical discharge machine). The gears had numbers of teeth and pitch diameter as indicated in Table 1, and a thickness of 1 mm. The gear is placed on a matt, red backdrop since a white background contained too much information in each plane for simple threshold calculations. An image processing method was used to compare a high-resolution microscope image of the gear to determine the difference between actual profile and ideal profile:

1. An image is taken using a Zeiss Axio Imager optical microscope, with an objective lens of magnification 5x and 10x ocular lens in front of the camera. This has a resolution, calculated using a maximum of 700 nm for white light, of 2.69µm, while the camera has a resolution of 5MP (pixel size of 0.70µm).

Table 1
Profile Errors for Different Gears (D = Pitch Diameter, z = number of teeth).

z	D (mm)	Area of Teeth (Pix.)	Abs. Diff. (Pix.)	Error Factor	Error
12	6	18735	1466	0.078	7.8%
18	6	22004	3283	0.149	14.9%
18	8	23429	4069	0.174	17.4%
24	10	14061	1533	0.109	10.9%

2. The image is separated into red, green and blue planes. These are evaluated, visually, to determine the plane offering the most contrast between gear and background. The image is then converted to black and white, using a simple binary thresholding algorithm: pixel value is set to zero above a certain threshold (defined by the user) and set to 1 otherwise.
3. Using image dilation, the holes in the image are filled in. The value of the output pixel is the maximum value of all pixels in the neighbourhood. Thus in this case, a pixel is set to 1 if any of the neighbouring pixels have the value 1. A structuring element is defined, such that the neighbourhood of the pixel of interest was a square of dimensions 8x8 pixels. Thus, any pixel that was surrounded by a 1 in the neighbourhood was set to 1. The purpose of this was to remove noise.
4. An outline of the image is produced by a pixel to 0 if its 4-connected neighbours are all 1's, thus leaving only boundary pixels. This allows subjective appraisal of form errors quickly to identify whether errors such as runout or burring have occurred.
5. Either the gear is filled, using image dilation or the image in (c) is inverted.
6. The image a, from the CAD file, and b, from the actual gear, are each subtracted from on another. This shows both areas where material outside the gear boundary is seen, and where material missing from the expected boundary is seen.

Green background returned the worst result, due to the difficulty discerning between gear and background (Figs. 3 and 4). For a brass gear, the red plane is the most successful in thresholding. The overall volume of the measured gear is calculated in pixels. This is then compared to the number of pixels in the CAD image, to determine an area difference, in Pixels. The error factor (*EF*) describes the difference as a proportion of the expected tooth area.

Number of pixels counted, N_D, was taken to be the absolute difference between the binary images. This value was divided by the total number of pixels of the teeth (and only these) in the file N_t. The analysis process used is depicted in Fig. 5. N_T is used as difference between the images returns almost no pixels from the centre of the gear since this is area is almost identical for both. Dividing N_D by total number of pixels in file N_T would give an artificially low error. Thus gear profile error can be calculated by

$$\text{ErrorFactor} = \frac{N_D}{N_t} \quad (1)$$

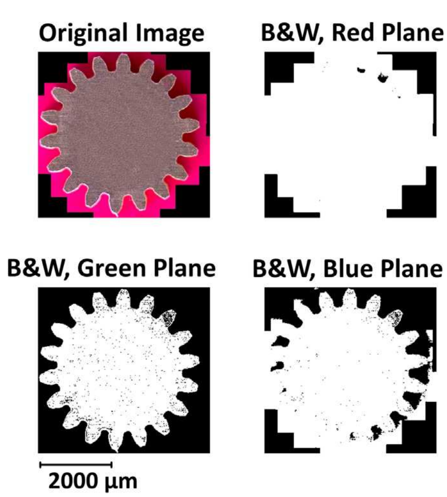


Fig. 3. Thresholding in the red, green and blue planes with red background. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

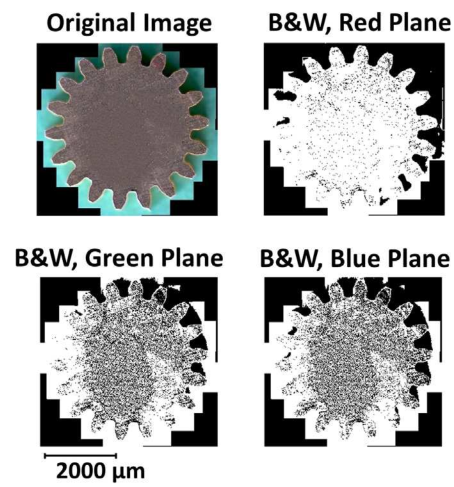


Fig. 4. Thresholding in the red, green and blue planes with green background. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results

Values obtained using image processing for several different gears are given in Table 1. Error in profile appeared relatively high when compared with typical requirements from DIN standards [22]: for a gear with 12 teeth and pitch diameter 6, approximately 7.8% of the total tooth volume was either missing or added to the expected profile (i.e. line of tooth lies outside the expected outline).

The profile errors measured for three other gears were higher still, ranging from 10.9 to 17.4%. Due to the simplicity of the method, it is likely that over-estimation of errors occurs since the size of the pitch error factor relates to overall tooth volume. Although it is appropriate to over-estimate errors in terms of producing adequate quality, rejection of gears unnecessarily is problematic and thus a margin of error appropriate to the required application of the user should be used.

4. Repeatability of method

There are three primary sources of uncertainty in calculating the "Error factor" (*EF*) used in this method. The first derives from the thresholding value chosen: this is determined based on the point at which the pixels of the gear (light grey) transition to the pixels of the background (dark grey). The gear is lighter due to the higher reflection of the brass as compared to the matt background. The second derives from the size of the gear, or number of teeth, which has significance since it is important to allow for

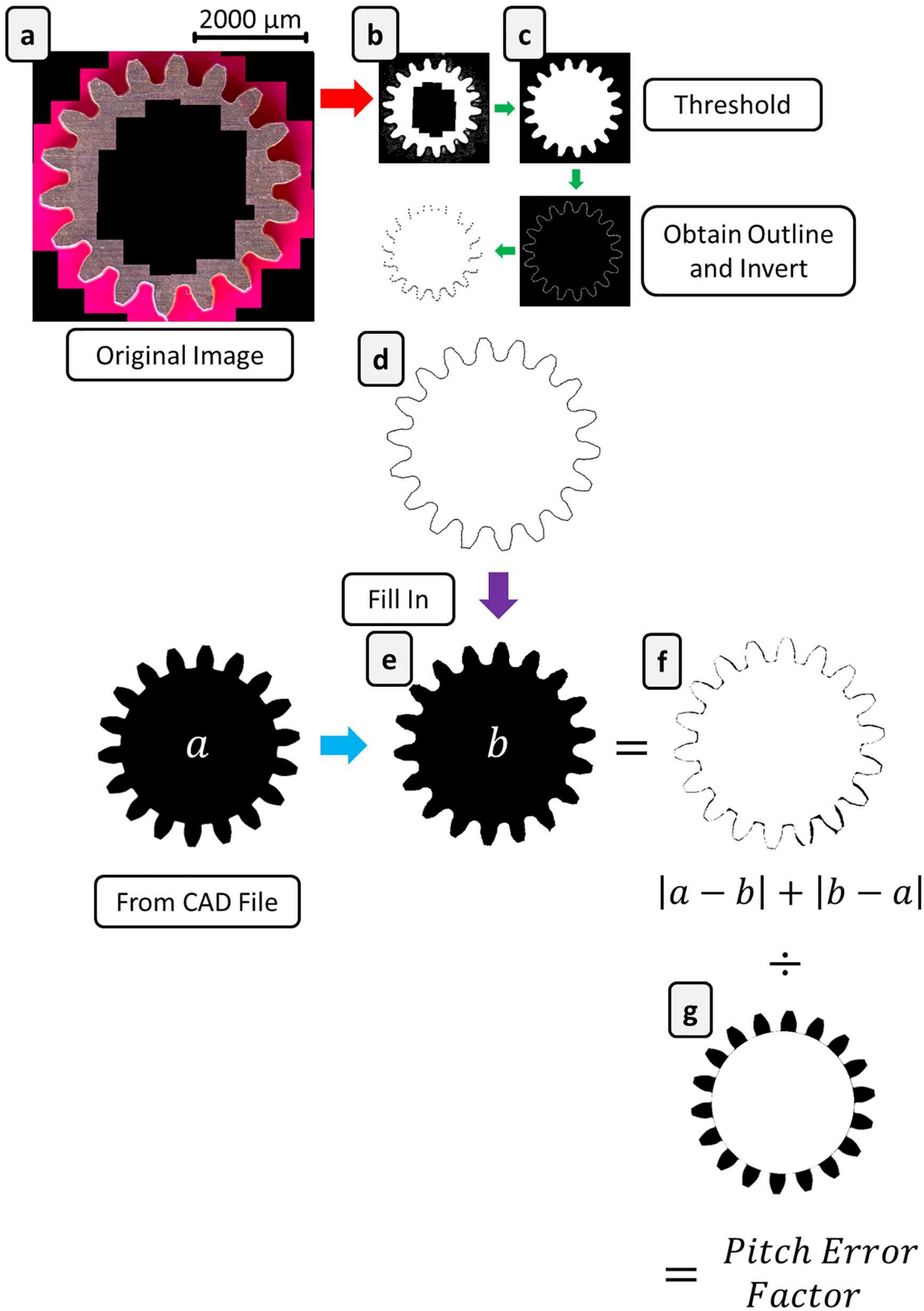


Fig. 5. Image analysis method for determining profile errors in gears.

the fact that different sized gears are measured. The third error of importance is the rotational accuracy of positioning of the gear when taking a measurement. If the gear is significantly rotated as compared with the CAD image, the result is that the error appears higher than it actually is, leading to unnecessary rejection. Thresholding error is calculated by evaluating the data with a number of thresholding values.

The *EF* achieved is calculated in each case, both for different thresholding values and different sizes of gear. Similarly, size error was calculated by evaluating several different sizes of gear at a single threshold. Finally, the gear was rotated through 0.5, 1.0, 1.5 and 2.0 degrees to assess the change in *EF* over this range. The data produced was tested using the Anderson–Darling test for normality and found to meet assumption of normality, and thus the errors were calculated as follows:

$$E_T = \sqrt{\left(\frac{2\sigma N_T}{\bar{N}_T}\right)^2 + \left(\frac{2\sigma T}{\bar{T}}\right)^2 + \left(\frac{2\sigma R}{\bar{R}}\right)^2} \tag{2}$$

where $E_T$is total error, $\sigma N_T$is standard deviation in result for different numbers of teeth, $\bar{N}_T$is mean values for different numbers of teeth, *T* denotes a given thresholding value and *R* denotes angle of rotation (degrees).

The method has been tested using three different sizes and numbers of teeth of gear, and 7 different thresholding values (from 0.05 to 0.35). This resulted in a nominal error of 0.12, which supports the proposal that the method should be used for preliminary assessment of gears only. The method is eminently reproducible since it requires only a small gear, the original dimensions in CAD file (such as DXF), an optical microscope (such as the Zeiss Axio Imager) and red card (in the region of R:255, G:0–50; B:0–50 when compared with the RGB colour scale).

5. Advantages of new technique to improve efficiency

A major advantage of the image processing method used is the output image which allows the user to instantly identify profile and form errors. Primarily, simple profile errors were seen (the shape of the gear often did not quite follow the involute curve). For all gears there was evidence of tooth spacing error as can be seen in Fig. 6. Thus, this method provides two outputs: information on overall error volume, and information on type of error. This is useful in that it enables manufacturing modifications to be determined. In spite of high profile errors, there was little evidence of runout, but in some gears there was suggestion of pitch error.

Further to the described approach, it is possible to measure topography optically using optical profilometry. This can be used to augment the data arising from optical images. It is assumed that where gears have failed geometrical specifications, there is no need to test for surface topography. Thus, topography measurement can take place as a secondary measurement.

5.1. Future work

The method described here arose from a need to measure gears easily and quickly during machining, where no specialist equipment was available. As a result, it was not possible to provide data from machines such as CMMs, optical comparators and height gauges. Currently this method has two benefits:

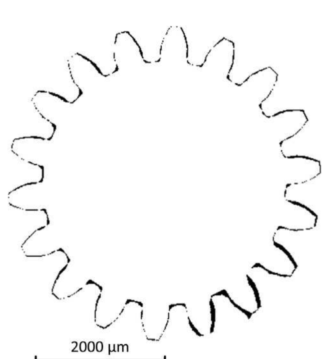


Fig. 6. Graphical representation of the profile error for a gear with pitch diameter 6 mm and 18 teeth.

1. To allow basic measurement of gear where access to more sophisticated equipment is unavailable.
2. To eliminate gears with severe (as defined by the specification) form or profile errors that cannot easily be seen by eye.

To further support the method, it would be useful to carry out bench-marking comparisons with established techniques such as CMM and profilometry, and with more sophisticated techniques such as interferometry. In doing so, the situations in which those methods are superfluous could be determined, allowing this tool to be used more widely.

6. Conclusions

Using the gears produced for this study, it was possible to quickly identify an overall profile difference between the produced gears and a CAD file, using only an optical microscope with appropriate coloured background, and Matlab software. Additionally, types of errors could be identified. The latter can be used to inform future measurement.

The method described is particularly useful in the case of smaller manufacturing operations where specialist gear measurement is not readily available. It also provides a rapid tool on a large scale for pre-inspection of gears. Finally, it allows larger-scale production to carry out time-saving pre-inspection before more complex gear measurement.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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