Machine Vision Based Techniques for Inspecting 3D-Printed Spur Gears

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Abstract

Spur gears are employed for transferring both motion and power from driver shaft to driven shaft. The performance of Spur gears largely depends upon its design and construction. Thus there is a need for inspecting spur gear before deployment. During the inspection, a spur gear will be checked for pitch circle, diametral pitch, center distance, outside diameter, etc. Many techniques have been proposed by researchers for the measurement of gear elements. Many of these techniques are contact-based and are fit for sampling inspection. These techniques are not amenable to automation. Sampling inspection techniques are not fool-proof. With the advent of 3D printing and Industry 4.0, there is a thrust is toward 100% inspection. This has necessitated the need for designing and developing new inspection techniques for measuring spur gear elements in real-time. In the present research, an attempt has been made to design and develop a new non-contact and online, technique for inspecting spur gears in real-time. The measurements made by using the proposed method are validated by standard methods and are in good agreement.

Keywords
Non-contact inspection, 3D-printing, Roughness evaluation, texture assessment, Image processing, Non-destructive testing

1. Introduction

In mechanical systems such as automobiles, machine tools, etc., different types of gears are used for transferring both motion and power. Spur gears are employed for transferring both motion and power from driver shaft to driven shaft. Gears of different sizes are being used in machine tools, Aerospace, Gear pumps, Automobiles, etc. The performance of spur gears largely depends upon their design and construction. Gears are being made by 3D printing. 3D printing mainly consists of construction of 3D model of the gear, slicing and final printing of gear (Zihong Wang, 2021). There is a need for inspecting spur gear before deployment. During the inspection, a spur gear will be checked for pitch circle, diametral pitch, center distance, module, circular pitch, etc. (ANSI/AGMA 2015). They are defined as follows.

$$module = \frac{\text{reference diameter (d)}}{\text{number of teeth (z)}} \tag{1}$$

$$diametral\ pitch = \frac{\text{number of teeth (z)}}{\text{reference diameter (d)}} \tag{2}$$

$$cicular\ pitch = \frac{circumference}{\text{number of teeth (z)}} \tag{3}$$

Different types of testing are carried out in industries, before releasing the gear for deployment. So that, the gear functions as per the expectations set by the designer. Accuracy of the spur gear elements determines the functional performance and service life.

2. Literature review

Traditionally, gear measurements can be broadly classified into analytical and functional. In the analytical method, gear elements are checked for compliance with the design specification (Ni et al., 2021). These techniques are mostly manual and make use of several instruments and they are time-consuming. Functional testing involves rolling the gear to be inspected in tight mesh with that of the master gear. If certain gear parameters of test gear are not as per design specifications, when the two gears are rolled, there will be variation in the center distance (Goch et al., 2003). This variation in the center distance is a composite effect of variation in tooth profile, pitch, tooth thickness, and runout error. The advantage of functional gear testing is that it is very quick (Goch et al. 2006, Martin et al., 2021). The limitation of this technique is that it requires further analysis. A traditional method for the measurement of gear size is by measurements over pins or balls with a micrometer. Micrometer reading gives the measurement of tooth thickness (figure 1). The method can be used for measuring the tooth thickness of any diameter gears, subjected to the maximum micrometer size Dudley (1984). Measurement of tooth thickness can be measured by using a gear tooth vernier caliper.

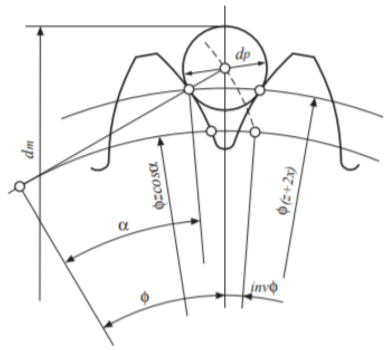

Figure 1.Tooth thickness measurement

Note (Figure 1):
d_m: over balls dimension (mms)
z: number of teeth
φ: pressure angle: Angle formed when center line and profile crosses pitch point upon the reference circle.
m: module (mms)
α: reference pressure angle
d_p: diameter over balls(mms)

Runout inspection or measurement of gears is done using a dial indicator. Runout is measured always perpendicular to the reference surface. During runout measurement Dudley (1984), measurement is made using a dial indicator over the pins or balls or placed in the successive tooth spaces.
A profile represents the shape that is given to the gear tooth. The profile is measured from the root of the gear to its tip. Most of the spur gears are given the involute profile. During measurement, the probe starts scanning the gear face from the middle of the test gear. The profile so scanned is recorded for further analysis. In many gears measuring machines, the reference surface is created by the generative principle (Colbourne, 1985). Spacing represents the true or theoretical tooth position around the gear circumference (Ralf et al., 2015). Pitch inspection of spur gears is the measurement of the deviation of the actual tooth position from the ideal Dudley (1984). During measurement, a single probe fitted with a very precise indexing system. The indexing system can also be electronic as in the case of a CNC machine fitted with an encoder-controlled rotational axis. Pitch measurement is also made by using a pitch comparator and angular indexing. The proposed technique inspects a spur gear by non-contact approach, by making use of the Vision system. High measuring speeds are possible.

3. Research Methodology

3.1Setting up of Vision system

Figure 2 depicts the experimental set-up. Figure 3 depicts the gear specimen made from the 3D printing process. Likewise, 50 gears are made by 3D printing. Images of these gears are acquired by using a CCD camera. The images are stored in the hard disk of the computer.

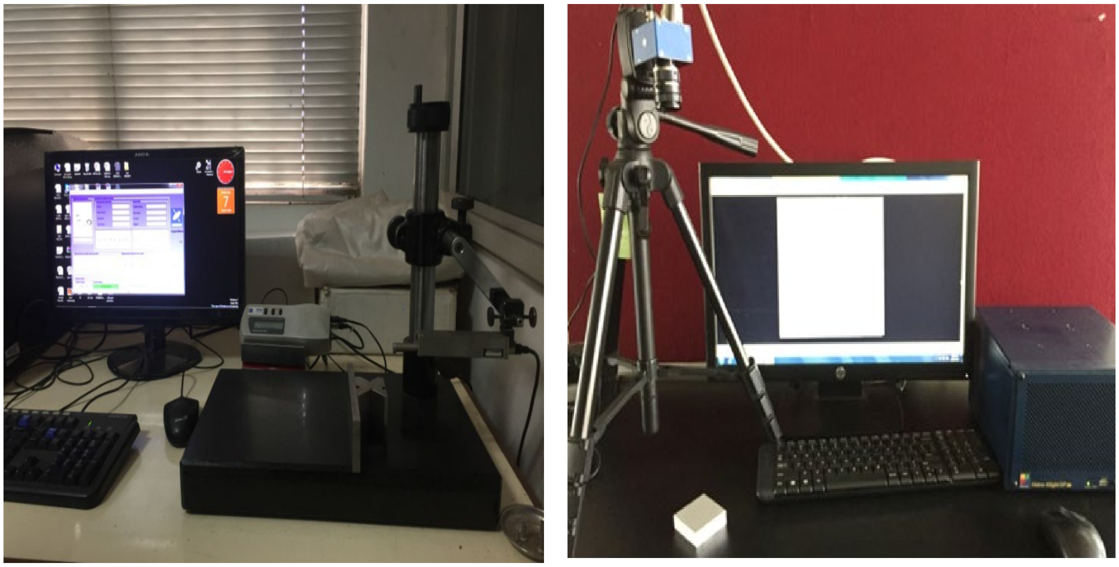

Figure 2. Experimental set-up of Vision System

Figure 3 shows the image of one such specimen acquired by a CCD camera. Figure 4 depicts the digital image of the specimen. The image is filtered for improving the quality of the image (Figure 5).

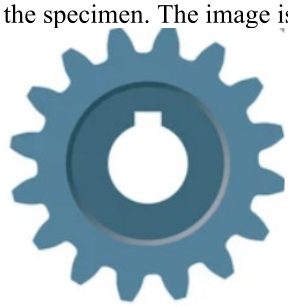

Figure 3. Spur gear

122	120	119	119	119	118	119
119	121	120	119	119	119	119
116	123	120	120	119	120	120
115	122	121	120	119	120	120
118	121	120	120	119	120	120
125	120	119	119	120	120	120
132	120	120	118	121	120	120
125	121	120	118	120	120	120

Figure 4. Digital image

Figure 5. Image after contrast enhancement

3.2 Image Quality Enhancement

In Figure 4 the values represent the pixel brightness in the image. The brightness value at each pixel depends upon the amount of light that is falling on the specimen. In a gray level image, ‘0’ represents dark and ‘255’ represents bright. The values between 0 and 255 represent various shades of gray. Figure 5 represents the same image after contrast enhancement operation. Contrast enhancement operation is done through Histogram equalization. Figure 6 represents the histogram before contrast enhancement. Figure 7 shows the Histogram after contrast enhancement operation. Figure 8 shows the effect of edge enhancement operation.

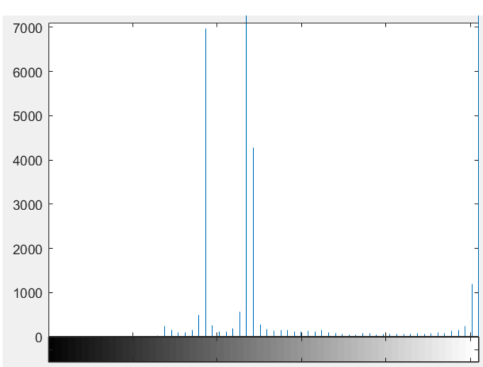

Figure 6. Histogram before contrast enhancement

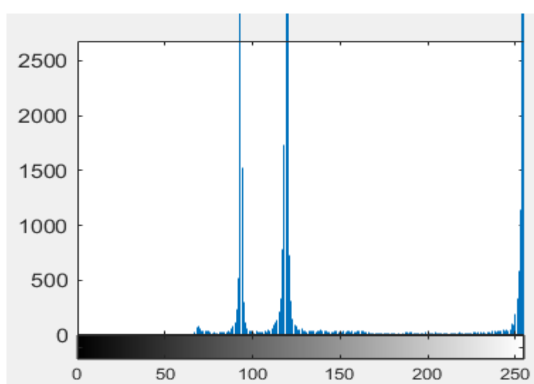

Figure 7. Histogram after contrast enhancement

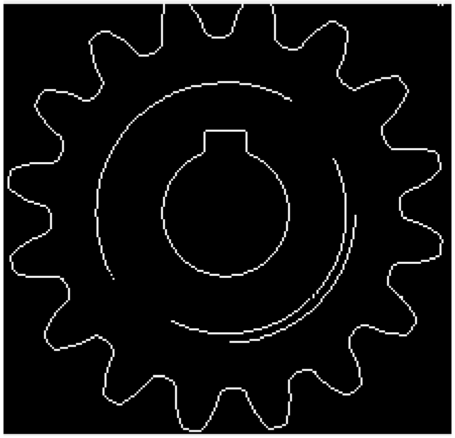

Figure 8. Image after edge enhancement

4. Gear tooth thickness and pitch measurement

During the experiment, gear image after edge enhancement is fed into the thickness computation module 10 times. The image is taken for 6 mm module gear. Table 1 shows the tooth thickness measurement details obtained for 10 iterations. The software also computes the 'Pitch' of the gear.

Table 1. Tooth thickness measurement details of 6mm module gear

Tooth	Mean (mms)	σ (mms)	Range (mms)
1	8.3831	0.00151	0.0111
2	8.4422	0.00142	0.0122
3	8.3783	0.00131	0.0125
4	8.3882	0.00132	0.0118
5	8.4231	0.00134	0.0122
6	8.2862	0.00128	0.0092
7	8.2582	0.00121	0.0125
8	8.4561	0.00138	0.0129
9	8.3091	0.00133	0.0133
10	8.1792	0.00136	0.0138
11	8.2302	0.00137	0.0127
12	8.5452	0.00135	0.0126
13	8.6232	0.00133	0.0124
14	8.4622	0.00141	0.0135

5. Gear Profile & texture Measurement

During profile measurement, actual profile is compared with the standard profile and measures deviations. During the texture measurement, the software computes the GLCM using the digital image. The method then computes Haralick's (1973) texture features for classification purposes. Figure 9 shows a sample GLCM calculated for the digital image.

0	0	0	0	0	0	0	0
0	1	3	0	0	0	0	0
0	3	7922	259	11	4	0	0
0	0	264	16009	314	111	25	2
0	0	10	318	496	130	105	37
0	0	0	122	152	167	65	135
0	0	0	38	103	78	77	192
0	0	0	1	24	152	219	19504

Figure 9. Co-occurrence matrix

6. Result and Discussion

Figure 10 depicts the plot of the co-occurrence matrix. The plot shows how the relationship between the pixel brightness and the region of interest (32 X 32). Table 2 shows the feature values obtained for different specimens.

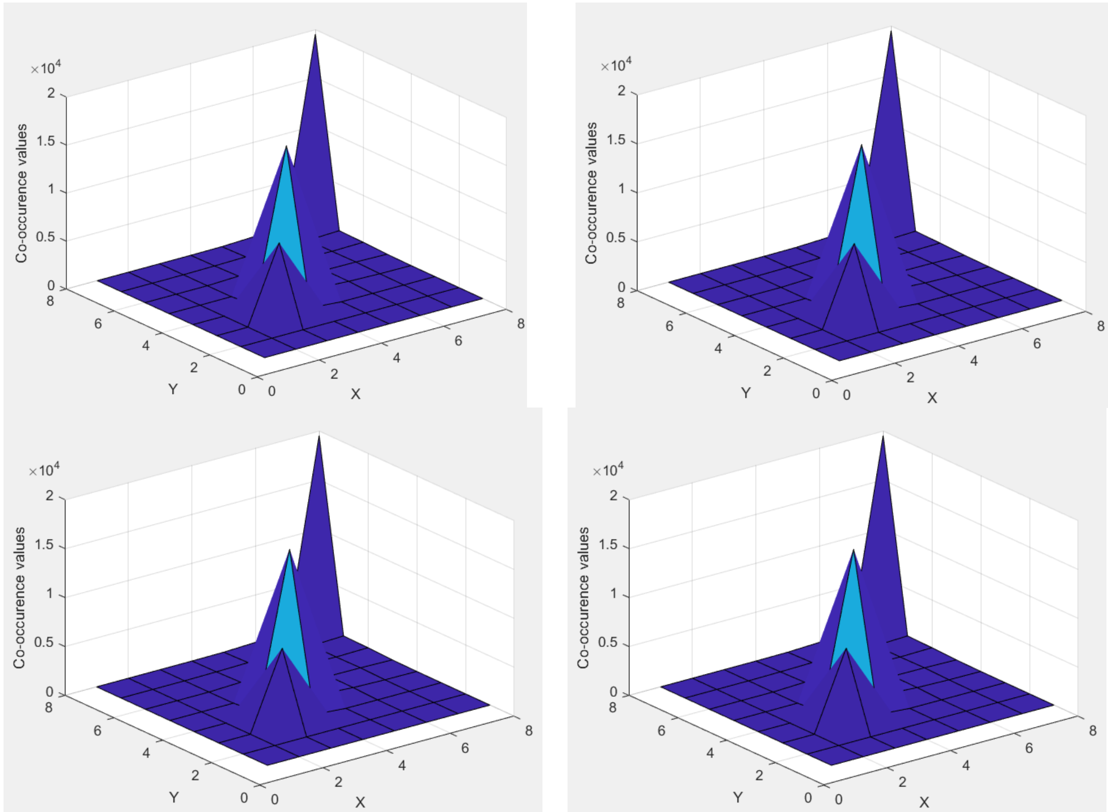

Figure10. Plot of Co-occurence matrix (a) 0^0 (b) 45^0 (c) 90^0 (d) 135^0

Feature set reduction
All the features are evaluated and only those features are used for classification, which are required in the classification by singular value decomposition method. This will improve computational efficiency.

Method of texture classification
A software designed in-house will use KNN method for performing image classification. The software will assign a sample to be tested based on Euclidean distance. Here, the distance should be minimum. From Table 3 it is clear the minimum classification accuracy is 95%. That is, out of 50 Good samples, the classifier identified 45 as Good; 3 as reworkable; and 2 as Bad.

Table 2. Feature values for different specimens.

Feature No.	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15
F1	0.35	0.43	0.58	037	0.43	0.56	0.37	0.47	0.57	0.35	0.46	0.38	0.47	0.37	0.46
F2	4.50	4.6	3.79	3.50	3.57	3.15	4.57	4.57	4.19	4.04	3.38	3.54	3.54	4.07	4.12
F3	1.45	1.74	1.68	1.63	1.64	1.68	1.62	1.78	1.67	1.70	1.64	1.79	1.67	1.69	1.68
F4	0.96	1.13	1.22	1.48	0.96	1.39	1.52	1.02	1.07	1.33	1.37	1.58	148	1.26	1.34
F5	11.1	11.2	11.3	11.2	11.5	11.28	1.29	1.43	11.2	1.51	1.26	1.47	1.37	1.30	1.34

F6	1.38	1.27	1.28	1.22	1.24	1.19	1.30	1.27	1.20	1.19	1.29	1.25	1.23	1.27	1.29
F7	79.2	75.52	75.21	75.28	75.35	75.24	75.31	74.47	74.93	73.67	74.78	72.14	73.14	75.50	75.6
F8	0.23	0.24	0.27	0.25	0.26	0.26	0.29	0.23	0.22	0.24	0.27	0.20	0.30	0.26	0.22
F9	0.42	0.43	0.45	0.45	0.48	0.48	0.40	0.44	0.40	0.45	0.44	0.42	0.45	0.46	0.47
F10	0.81	0.82	0.93	0.79	0.73	0.86	0.76	0.74	0.77	0.75	0.92	0.84	0.74	0.82	0.82
F11	14	11	15	18	19	19	20	18	12	11	16	13	13	10	13
F12	0.98	0.97	0.97	0.98	0.97	0.96	0.96	0.95	0.94	0.94	0.93	0.92	0.91	0.91	0.98

Table 3. Confusion Matrix

Training				Testing			
Good	Re-work	Bad	Classified as	Good	Re-work	Bad	Classified as
50	0	0	Good	47	1	2	Good
0	50	0	Re-work	0	49	1	Re-work
0	0	50	Bad	0	0	50	Bad

The accuracy of the proposed method is 94%. The method was tested for repeatability and has shown a repeatability error of ± 5.14%. This is a considerable improvement when compared to the existing methods of Gear inspection techniques. Many existing techniques are time consuming and fit for post process inspection of Gears.

7. Conclusion

The present research work demonstrates a novel technique for the inspection of Spur gears. The method makes use of a Vision system for acquiring images of the Gears. These images are then processed for image quality enhancement. Then the images are used for computing the following Gear parameters.

a. Gear tooth thickness
b. Gear pitch
c. Gear profile

The method also does gear profile as well as texture analysis through GLCM. The method is also capable of classifying gears into Good/Bad/Rework categories.

Thus, the proposed method is a non-contact means of comprehensively inspecting a Spur gear, in a single set-up. The method finds application in the online inspection of Gears. The classification accuracy was 94%. The method was tested for repeatability and has shown a repeatability error of ± 5.14%.

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