Analysis of Effects of Change of Gear Parameter Module on Transmission Error in Spur Gear using Interference Volume Method

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Abstract. Gear drives are the most used elements in power transmission systems. Any defect in the gear of these drives leads to noise and vibrations, which affect power/torque transmission. Transmission Error (TE) is one of the critical causes that arises due to the tooth geometry error, cracks in gear, profile error etc. Our work demonstrates, the consequences occurring due to the changes in gear parameter module on TE for spur gear pair of 1:1 gear ratio with pitch error, using the interference volume method. The spur gear without pitch error and with pitch error having the involute profile of standard tooth dimension system and stub tooth dimension system are modelled and assembled in CAD software SOLIDWORKS. The interference volume values obtained from the gear pairs are recorded for one mesh cycle. Various graphs plotted between the angle of rotation and interference volume values for one mesh cycle. It is found from the analysis that as the module and pitch error increase TE also increases. The effect of variation of module and pitch error is more in the standard tooth dimension system than the stub tooth dimension system.

Keywords: CAD, Gear Ratio, Pitch Error, No of Teeth, SOLIDWORKS, Geometry Error

1. Introduction

Gears drives are the most used elements employed to transfer power/torque. The condition to accurately transfer power/torque is that the drive elements such as gears should be free from any error else it could lead to noise and vibrations, which results in the development of Transmission Error (TE) despite of availability of world class manufacturing and design facilities. TE is a show of reading measured of angular or linear displacement by the side of activity on the base circle [1]. Hotait and Kahr [2] demonstrated experimentally the association connecting dynamic factor and transmission error measurement. The values were obtained from unabated and adapted spur gears using a gear dynamic test set-up. Kohler and Regan [3] concluded that TE has harmonic components of significant amplitude at tooth contact frequency spectrum. Chang and Tang [4] conducted theoretical analysis under the influence of single and cumulative pitch error to investigate the nonlinear vibration response in a double-helical gear set. Velex et al [5] established theoretically a relationship in the middle of active mesh agitation and transmission errors using 3D analysis modal of...
multi mesh gears. They demonstrated that the local confined TE is analogous with each individual mesh controls the dynamic mesh forces and provided a design criterion to minimize dynamic tooth loads by defining tooth shape modifications. Nina [6] developed equations of motion based on time varying mesh stiffness function, loaded quasistatic TE, and no-load or kinematic TE. Studied the effect of tooth pitch error and load on dynamic behavior of gear transmission. She also investigated the relationship between dynamic TE and mesh force or root stress. Sánchez et al [7] work is done to study the contact conditions of modified teeth under load. They widely explained the results by seeing the changes of various parameters of profile modification on actual load sharing quotient and TE. Palermo et al [8] in their work tried to calculate TE in comparison to the direct process which uses low-cost digital encoders, which are embedded on an accuracy gear pair test. Shwei et al [9] does work to find the change in conduct when a quality and light weight cylindrical gear meshes. An elastic multi body expressions which has hybrid approach in FE method in the background representation is used by them. Zhiying and Pengfei [10] proposed and validated, analytical mesh stiffness and quasi static TE models with finite element method to find the inner working of spur gear meshing pairs. Pleguezuelos et al [11] found out the effect of changes in symmetric long on high contact ratio spur. The change is represented empirically in the optimum length as a function of the contact ratio. Oswald [12] works found out the efficacy in modification of profile in ever changing reduced loads in gears having spacing errors. The analysis considers the modifications of both linear and parabolic profiles. Bruyere et al [13] presented a closed-form analytical formula of TE for helical and solid spur gears for minimizing time varying amplitudes of TE amalgamation of lead crouch and profile relief. They showed that the optimum tooth modifications depend on ratio of profile Vs face contact, the normalized depth and number of modifications in profile in continuation with the normalized lead crown amplitude. Handschuh [14] experimentally, empirically, and mathematically find out the consequences of tooth spacing error on TE and root stresses in spur gear pairs. Bartosova et al [15] uses finite element analysis to find out TE at variety of combination of load states, axial distant variation, and tooth shape elevation modification. Park [16] find out friction in tooth and TE in spur gears which occurs due to result of friction sliding in quasi static condition. Somani [17] worked in his doctorate thesis on studying the effect of changing the various gear parameters on TE in spur gear. Transmission through gears is used in every area of industry to convey power coming from shaft. A lot of research work is there in public domain in this area. Bruzzone et al [18] constructed model using multi-layered process in quasi-static state to find degree of deflection, tooth deformation and stiffness. Experiments results in terms of STE with different parameters has been found. TE is the main cause of vibration in gear box. Duan et al [19] established a test rig and made comparison between the result obtained theoretically and experimentally. Results shows that under heavy load conditions TE increases, but with the use of thin-walled housing it decreases considerably. A lot of study about the TE in gears is being done. Benaiach et al [20] in his work tries to develop a model which gives the insight efficient inaccurate working of gear TE. Results were compared with the earlier results obtained from classical techniques. Superiority of the model which is made was confirmed in his work. Backlash is also a type of TE which occurs due to the gap between the teeth at the pitch circles. This error is unavoidable as the time passes by. Ambaye et al [21] uses a Gear Trax software to model a gear with backlash with different degrees. In his experiments he uses plane strain analysis and finite element analysis to find mesh convergence for different contact pressure and stress. In this process he was able to predict backlash with a high degree of accuracy. Gearbox is used to transmit power from shaft to rotor in various machines. In case of wind turbine, it is important link to transmit power. Tao et al [22] uses Flank Pitch Error model to find gear faults. He proposed time varying meshing stiffness model to simulate meshing frequency and find severity of gear box vibration. Delay in drive which is popularly known as loaded TE is caused due to tooth deflection, manufacturing defects and assembly error in spur gear. Miguel et al [23] proposed a mathematical model to consider of meshing stiffness, load sharing ratio and TE for spur gears under minimal or varying load conditions. Gear TE causes vibration in moving parts. Chin et al [24] in his work find TE. His work is validated by readings.
obtained from encoder and tachometer from a drive gear wear experimental setup. Model prepared by him prove to be very robust under sever conditions also. From the available literature, it is observed that the researchers are working towards the determination of TE analytically, experimentally and or using finite element analysis for the gears having defects due to manufacturing, geometry error, crack, tooth breakage etc., in the standard tooth dimension system. In today’s scenario there is an urgent need of more simplified methods/procedure using CAD software to analyze the various manufacturing defects, geometry errors etc., in spur gears. A lot of work is to be done by considering the gears in both standard and stub tooth dimension system. Hence, the objective of the current work is to analyze the TE using interference volume method in stub tooth dimension system and standard tooth dimension system for spur gear having pitch error in a simplified procedure. The gears are modelled in SOLIDWORKS software. Various gear parameters used are the modules 3, 3.5, 4, 4.5, and 5 mm, pressure angle 20°, and the number of teeth 18. The pitch error of magnitudes 1% and 2% is deliberately introduced in all the teeth of gear. The gear without pitch error is meshed with a gear having pitch error using the assembly module of SOLIDWORKS software. The interference volume values are then recorded for one mesh angle of the gear pair. The graphs are plotted between angles turned vs. interference volume values, and for each change in module and pitch error, the effect on the TE is predicted for both standard as well as stub tooth dimension system. It is observed that TE is affected when module and pitch error magnitude is change but the effect is more in case of standard tooth dimension system than in stub tooth dimension system. The analysis is done using the procedure as described by the authors in [25]. The work of the paper/outcomes are in line with the work of researchers presented in [3, 4, 6, 12, 14, 17].

2. Modelling of Master Gear and Erred Gear

The spur gears are modelled with true involute curve from mathematical equation of involute curve in CAD software SOLIDWORKS. The following spur gears are modelled for the analysis. The designation of gears and their pairs are described below.

a) Spur Gear of standard tooth dimension system and stub tooth dimension system without any defect or error are designated as Master Gear [MG] and Stub Master Gear [SMG] respectively.
b) Spur Gear of standard tooth dimension system and stub tooth dimension system with pitch error are designated as Erred Gear [E] and Stub Erred Gear [SE] respectively. Gear with 1% and 2% pitch error are designated as E1 and E2 in standard tooth dimension system, SE1 and SE2 in stub tooth dimension system, respectively.

After modelling of the master gear, erred gears are modelled by inducing pitch error of 1% and 2% magnitude. The pitch error is created by increasing the tooth thickness to 1% and 2% of its original value. These deviations are sufficient deviation from the original value in manufacturing of any gear. A nominal face width of 10 mm is considered for the gears. The gears with and without pitch error in standard tooth dimension system and stub tooth dimension system of module 3, 3.5, 4, 4.5 and 5 mm, number of teeth 18 and pressure angle 20° are designated in table 1. For example as in table1, a gear of module 3 mm, number of teeth 18, pressure angle 20°, and without pitch error in standard tooth dimension system is designated as MG_m3_z18_phi20, and with pitch error of 1% and 2% is designated as E1_m3_z18_phi20 and E2_m3_z18_phi20 respectively (where MG is Master Gear, E1 is Erred Gear (1% pitch error), E2 is Erred Gear (2% pitch error), m is module, z is number of teeth and phi is pressure angle). Similarly a gear of module 3 mm, number of teeth 18, pressure angle 20°, and without pitch error in stub tooth dimension system is designated as SMG_m3_z18_phi20, and with pitch error of 1% and 2% is designated as SE1_m3_z18_phi20 and SE2_m3_z18_phi20 respectively (where SMG is Master Gear, SE1 is Erred Gear (1% pitch error), SE2 is Erred Gear (2% pitch error), m is module, z is number of teeth and phi is pressure angle). The various values of the spur gear parameters for the two tooth dimension systems are given in table 2 and table 3.
### Table 1. Designation of various spur gears in two tooth dimension systems

| Standard Tooth Dimension System | Master Gear / Gear without Pitch Error | Erred Gear / Gear with Pitch Error of 1% & 2% | Master Gear / Gear without Pitch Error | Erred Gear / Gear with Pitch Error of 1% & 2% |
|---------------------------------|----------------------------------------|-----------------------------------------------|----------------------------------------|-----------------------------------------------|
|                                | MG_m3_z18_phi20                        | E1_m3_z18_phi20                               | SMG_m3_z18_phi20                       | SE1_m3_z18_phi20                             |
|                                | MG_m3.5_z18_phi20                     | E1_m3.5_z18_phi20                             | SMG_m3.5_z18_phi20                    | SE1_m3.5_z18_phi20                           |
|                                | MG_m4_z18_phi20                       | E1_m4_z18_phi20                               | SMG_m4_z18_phi20                       | SE1_m4_z18_phi20                             |
|                                | MG_m4.5_z18_phi20                     | E1_m4.5_z18_phi20                             | SMG_m4.5_z18_phi20                    | SE1_m4.5_z18_phi20                           |
|                                | MG_m5_z18_phi20                       | E1_m5_z18_phi20                               | SMG_m5_z18_phi20                       | SE1_m5_z18_phi20                             |

#### 3. Meshing and Analysis of Gear Pair of Standard Tooth Dimension System

After modelling of various gears, it is required to form assemblies/pairs (meshing of Master and Master or Master and Erred Gear) for doing the analysis. The various assemblies or combinations formed, and their designations are shown in table 4. Each of these assemblies or combinations are taken one by one for determining the TE. The interference volume is determined for all these gear pairs/assemblies. From the values of the interference volume obtained, the TE variation is determined for all these spur gear pairs. The methodology to determine the TE is verified from the pair of master gear with master gear and then the master gear and erred gear pair is taken for the analysis. The two gears are meshed using the assembly module of SOLIDWORKS and interference volume between the two gears in mesh is checked for initial meshed position by invoking the command of finding interference volume and then the value of interference volume is recorded.

### Table 2. Values of Spur Gear parameters in Standard Tooth dimension System

| Parameters [26] | Module, mm | No. of Teeth | Pitch Circle Diameter, mm (m*z) | Pressure Angle, ° | Addendum, mm | Dedendum, mm | Base Circle Diameter, mm (m*z*co s(ϕ)) | Circular Pitch, mm | Tooth Thickness, mm (m/z/2) |
|-----------------|------------|--------------|---------------------------------|-------------------|--------------|-------------|----------------------------------------|--------------------|-----------------------------|
| Master Gear (MG) | 3.0        | 18           | 54                               | 20                | 3.0          | 3.750       | 50.7434                                | 4.7124             |
|                 | 3.5        | 18           | 63                               | 20                | 3.5          | 4.375       | 59.2006                                | 10.9956            | 5.4978                      |
|                 | 4.0        | 18           | 72                               | 20                | 4.0          | 5.000       | 67.6578                                | 12.5664            | 6.2832                      |
|                 | 4.5        | 18           | 81                               | 20                | 4.5          | 5.625       | 76.1151                                | 14.1372            | 7.0686                      |
|                 | 5.0        | 18           | 90                               | 20                | 5.0          | 6.250       | 84.5723                                | 15.7080            | 7.8540                      |
| Erred Gear (E1) | 3.0        | 18           | 54                               | 20                | 3.0          | 3.750       | 50.7434                                | 4.7124             |
|                 | 3.5        | 18           | 63                               | 20                | 3.5          | 4.375       | 59.2006                                | 10.9956            | 5.4978                      |
|                 | 4.0        | 18           | 72                               | 20                | 4.0          | 5.000       | 67.6578                                | 12.5664            | 6.2832                      |
|                 | 4.5        | 18           | 81                               | 20                | 4.5          | 5.625       | 76.1151                                | 14.1372            | 7.0686                      |
|                 | 5.0        | 18           | 90                               | 20                | 5.0          | 6.250       | 84.5723                                | 15.7080            | 7.8540                      |
| Erred Gear (E2) | 3.0        | 18           | 54                               | 20                | 3.0          | 3.750       | 50.7434                                | 4.7124             |
|                 | 3.5        | 18           | 63                               | 20                | 3.5          | 4.375       | 59.2006                                | 10.9956            | 5.4978                      |
|                 | 4.0        | 18           | 72                               | 20                | 4.0          | 5.000       | 67.6578                                | 12.5664            | 6.2832                      |
|                 | 4.5        | 18           | 81                               | 20                | 4.5          | 5.625       | 76.1151                                | 14.1372            | 7.0686                      |
|                 | 5.0        | 18           | 90                               | 20                | 5.0          | 6.250       | 84.5723                                | 15.7080            | 7.8540                      |

For obtaining the next value of interference volume, one of the gears of gear pair is rotated by 1° and due to the meshing, the other gear is also rotated by 1° in opposite direction. The interference volume between the two gears is checked again and the value is noted. In this way for 21 such positions the...
two gears are rotated and at every instance the interference volume is checked and noted (The interference volume cycle repeats after 20° of rotation for 18 number of teeth). All the interference volume values are recorded in table 5. Figure 1 shows one of the gear pair of master gear and erred gear 1 (MG_E1_m3.5_z18_phi20).

The detailed procedure for determining the TE for all the combinations is explained in the sections from 3.1 to 3.3

Figure 1. Assembly/Meshing of Master Gear and Erred Gear 1 of standard tooth dimension system having module 3.5 mm, number of teeth 18 and pressure angle 20° (MG_E1_m3.5_z18_phi20).

3.1. Meshing of Master Gear with Master Gear (MG_MG)
Two gears forming a pair with combinations as shown in table 4 are taken one by one for analysis. The two gears are meshed and for this initial position interference between them is checked. Then gear
pairs are rotated for contact angle (20° in case of 18 number of teeth). It is observed that the two gears are just touching each other, indicating that there is no interference occurring between them and hence the interference volume is zero. This also confirms the correctness of procedure.

3.2. Meshing of Master Gear with Erred Gear 1 (MG_E1)

In this case master gear is meshed with erred gear 1 (gear with 1% pitch error). The various combinations formed are represented in table 4. The same procedure as discussed in section 3.1 above is followed to determine the interference volume. Here it is observed that there is interference occurring in the two gears in mesh during rotation of contact angle (20° in case of 18 number of teeth). The values of interference volume are noted and tabulated in table 5 for plotting graph between interference volume vs rotation angle.

3.3. Meshing of Master Gear with Erred Gear 2 (MG_E2)

Now finally the master gear is meshed with erred gear 2 (gear with 2% pitch error). The various combinations are given in table 4. Here also similar procedure as discussed in section 3.1 is used to check the interference between the gears. It is again observed that there is an interference occurring in gears in mesh. The interference volume values for contact angle of 20° rotation is noted in table 5. Based on the interference volume values of table 5, various graphs are plotted between angle of rotation and interference volume values. These graphs are shown in the figure 2 and figure 3, respectively.

| Angle of Rotation (°) | Master Gears [MG] | MG_E1 z18 phi 20 | MG_E1 z18 phi 20 | MG_E1 z18 phi 20 | MG_E1 z18 phi 20 | MG_E1 z18 phi 20 | MG_E1 z18 phi 20 | MG_E1 z18 phi 20 | MG_E1 z18 phi 20 |
|-----------------------|-------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| 0                     | 0                 | 0.4000           | 0.5400           | 0.7000           | 0.8800           | 1.1000           | 1.1000           | 1.4800           | 1.9400           |
| 1                     | 0                 | 0.3700           | 0.5000           | 0.6500           | 0.8200           | 1.0000           | 1.0500           | 1.4300           | 1.8700           |
| 2                     | 0                 | 0.3600           | 0.5000           | 0.6300           | 0.8100           | 1.0000           | 1.0100           | 1.3800           | 1.8000           |
| 3                     | 0                 | 0.3600           | 0.4900           | 0.6500           | 0.8200           | 1.0100           | 1.0300           | 1.3900           | 1.8200           |
| 4                     | 0                 | 0.3600           | 0.5000           | 0.6500           | 0.8200           | 1.0100           | 1.0400           | 1.4000           | 1.8300           |
| 5                     | 0                 | 0.3700           | 0.4900           | 0.6600           | 0.8200           | 1.0100           | 1.0400           | 1.4000           | 1.8300           |
| 6                     | 0                 | 0.3600           | 0.5000           | 0.6500           | 0.8200           | 1.0100           | 1.0300           | 1.4000           | 1.8300           |
| 7                     | 0                 | 0.3600           | 0.4900           | 0.6500           | 0.8200           | 1.0100           | 1.0200           | 1.3900           | 1.8200           |
| 8                     | 0                 | 0.3600           | 0.4900           | 0.6300           | 0.8100           | 1.0000           | 1.0100           | 1.3800           | 1.8000           |
| 9                     | 0                 | 0.3700           | 0.5000           | 0.6500           | 0.8200           | 1.0100           | 1.0600           | 1.4500           | 1.9000           |
| 10                    | 0                 | 0.4000           | 0.5500           | 0.7000           | 0.9000           | 1.1000           | 1.1000           | 1.5200           | 1.9800           |
| 11                    | 0                 | 0.3700           | 0.5000           | 0.6500           | 0.8200           | 1.0100           | 1.0600           | 1.4500           | 1.9000           |
| 12                    | 0                 | 0.3600           | 0.4900           | 0.6300           | 0.8100           | 1.0000           | 1.0100           | 1.3800           | 1.8000           |
| 13                    | 0                 | 0.3600           | 0.5000           | 0.6500           | 0.8200           | 1.0100           | 1.0200           | 1.3900           | 1.8200           |
| 14                    | 0                 | 0.3600           | 0.4900           | 0.6500           | 0.8200           | 1.0100           | 1.0300           | 1.4000           | 1.8300           |
| 15                    | 0                 | 0.3700           | 0.5000           | 0.6600           | 0.8200           | 1.0100           | 1.0400           | 1.4000           | 1.8300           |
| 16                    | 0                 | 0.3600           | 0.4900           | 0.6500           | 0.8200           | 1.0100           | 1.0300           | 1.4000           | 1.8300           |
| 17                    | 0                 | 0.3600           | 0.5000           | 0.6500           | 0.8200           | 1.0100           | 1.0300           | 1.3900           | 1.8200           |
| 18                    | 0                 | 0.3600           | 0.4900           | 0.6300           | 0.8100           | 1.0000           | 1.0100           | 1.3800           | 1.8000           |
| 19                    | 0                 | 0.3700           | 0.4900           | 0.6500           | 0.8200           | 1.0000           | 1.0500           | 1.4300           | 1.8700           |
| 20                    | 0                 | 0.4000           | 0.5400           | 0.7000           | 0.8800           | 1.1000           | 1.1000           | 1.4800           | 1.9400           |
4. Meshing and Analysis of Gear Pair of Stub Tooth Dimension System

In this case the various gear pairs formed are listed in table 6. First the master gear is meshed with the master gear and the interference volume values obtained by rotation of gear pair for one mesh cycle is listed in table 7. Next using the same procedure, the interference volume values are obtained for master gear - errored gear 1 and master gear - errored gear 2 pair. All these values are listed in Table 7. Using these values various graphs are plotted between the interference volume values and angle of rotation. These are represented in figure 4 and figure 5 respectively.

Table 6. Combinations/Assemblies of Gears (Stub Tooth Dimension System)

| Module, mm (m) | No. of Teeth, z | Pressure Angle, ° | Meshing of Master Gear with Master Gear | Meshing of Master Gear with Errored Gear 1 | Meshing of Master Gear with Errored Gear 2 |
|----------------|-----------------|------------------|--------------------------------------|----------------------------------------|----------------------------------------|
| 3              | 3.5             | 18               | SMG_SMG_m3_z18_phi20                  | SMG_SE1_m3_z18_phi20                   | SMG_SE2_m3_z18_phi20                   |
| 4              | 3.5             | 20               | SMG_SMG_m3.5_z18_phi20                | SMG_SE1_m3.5_z18_phi20                 | SMG_SE2_m3.5_z18_phi20                 |
| 4.5            | 5               | 18               | SMG_SMG_m4.5_z18_phi20                | SMG_SE1_m4.5_z18_phi20                 | SMG_SE2_m4.5_z18_phi20                 |
| 5              | 5               | 18               | SMG_SMG_m5_z18_phi20                  | SMG_SE1_m5_z18_phi20                   | SMG_SE2_m5_z18_phi20                   |

Table 7. Interference Volume values (mm³) when Master Gear meshes with Master Gear, Errored Gear 1, and Errored Gear 2 for Stub Tooth Dimension System

| Angle of Rotation (°) | Master Gear [SMG] | SMG_SE1_m3_z18_phi20 | SMG_SE1_m3.5_z18_phi20 | SMG_SE1_m4.5_z18_phi20 | SMG_SE1_m5_z18_phi20 | SMG_SE2_m3_z18_phi20 | SMG_SE2_m3.5_z18_phi20 | SMG_SE2_m4.5_z18_phi20 | SMG_SE2_m5_z18_phi20 |
|-----------------------|-------------------|----------------------|------------------------|------------------------|----------------------|----------------------|------------------------|------------------------|----------------------|
| 0                     | 0                 | 0.2590               | 0.3526                 | 0.4604                 | 0.5828               | 0.7194               | 0.7310                 | 0.9950                 | 1.2994               |
| 1                     | 0                 | 0.2583               | 0.3517                 | 0.4594                 | 0.5814               | 0.7178               | 0.7495                 | 1.0202                 | 1.3324               |
| 2                     | 0                 | 0.2935               | 0.3995                 | 0.5219                 | 0.6605               | 0.8154               | 0.8449                 | 1.1499                 | 1.5020               |
| 3                     | 0                 | 0.3476               | 0.4731                 | 0.6181                 | 0.7822               | 0.9658               | 0.9557                 | 1.2989                 | 1.6992               |
| 4                     | 0                 | 0.3651               | 0.4969                 | 0.6492                 | 0.8215               | 1.0143               | 1.0238                 | 1.3937                 | 1.8201               |
| 5                     | 0                 | 0.3665               | 0.4988                 | 0.6516                 | 0.8246               | 1.0181               | 1.0306                 | 1.4028                 | 1.8323               |
| 6                     | 0                 | 0.3651               | 0.4971                 | 0.6492                 | 0.8217               | 1.0144               | 1.0261                 | 1.3965                 | 1.8242               |
| 7                     | 0                 | 0.3497               | 0.4759                 | 0.6216                 | 0.7867               | 0.9713               | 0.9646                 | 1.3124                 | 1.7150               |
| 8                     | 0                 | 0.2963               | 0.4032                 | 0.5267                 | 0.6666               | 0.8229               | 0.8558                 | 1.1641                 | 1.5215               |
| 9                     | 0                 | 0.2585               | 0.3518                 | 0.4592                 | 0.5816               | 0.7181               | 0.7556                 | 1.0279                 | 1.3433               |
| 10                    | 0                 | 0.2588               | 0.3522                 | 0.4602                 | 0.5824               | 0.7190               | 0.7300                 | 0.9936                 | 1.2978               |
| 11                    | 0                 | 0.2585               | 0.3518                 | 0.4624                 | 0.5816               | 0.7181               | 0.7556                 | 1.0289                 | 1.3677               |
| 12                    | 0                 | 0.2963               | 0.4032                 | 0.5402                 | 0.6666               | 0.8229               | 0.8558                 | 1.1656                 | 1.5215               |
| 13                    | 0                 | 0.3497               | 0.4759                 | 0.6303                 | 0.7867               | 0.9713               | 0.9646                 | 1.3137                 | 1.7150               |
| 14                    | 0                 | 0.3650               | 0.4971                 | 0.6495                 | 0.8217               | 1.0144               | 1.0261                 | 1.3968                 | 1.8242               |
| 15                    | 0                 | 0.3664               | 0.4988                 | 0.6514                 | 0.8246               | 1.0181               | 1.0306                 | 1.4029                 | 1.8323               |
| 16                    | 0                 | 0.3655               | 0.4969                 | 0.6490                 | 0.8215               | 1.0143               | 1.0238                 | 1.3934                 | 1.8201               |
| 17                    | 0                 | 0.3548               | 0.4731                 | 0.6074                 | 0.7832               | 0.9658               | 0.9557                 | 1.3003                 | 1.6992               |
| 18                    | 0                 | 0.3043               | 0.3995                 | 0.5090                 | 0.6605               | 0.8154               | 0.8449                 | 1.1493                 | 1.5020               |
| 19                    | 0                 | 0.2602               | 0.3517                 | 0.4595                 | 0.5814               | 0.7178               | 0.7495                 | 1.0198                 | 1.3324               |
| 20                    | 0                 | 0.2590               | 0.3526                 | 0.4604                 | 0.5828               | 0.7195               | 0.7310                 | 0.9950                 | 1.2994               |

5. Result and Discussions

Based on the values of interference volume values for different cases of change of module and pitch error as reported in table 5 and table 7 for standard tooth dimension system and stub tooth dimension
system respectively, various graphs are plotted between the angle of rotation on x axis and the interference volume values on y axis, respectively.

a. Figure 2 and Figure 3 shows the graph between interference volume values and rotation angle of gear pair for 1% and 2% pitch error cases with module changes from 3 to 5 mm respectively for standard tooth dimension system. The x axis contains the rotation angle in degree (°) and the y axis represents the interference volume values in cubic mm.

b. Similarly, the graph between interference volume values and rotation angle of gear pair for 1% and 2% pitch error cases with module changes from 3 to 5 mm for stub tooth dimension system is shown in Figure 4 and Figure 5, respectively. The x axis contains the rotation angle in degree (°) and the y axis represents the interference volume values in cubic mm. The angle of rotation is 20° since the curve repeats after 20° for 18 number of teeth.

c. In this paper the effects of variation of module on TE along with pitch error in gear is considered for the analysis purpose.

![Figure 2](image1.png)  
**Figure 2.** Graph between interference volume in cu. mm and angle of rotation (°) for analysing the effects of change of Module (3, 3.5, 4, 4.5 and 5) on TE with pitch error of 1% (Master Gear & Erred Gear 1). [Standard Tooth Dimension System]

![Figure 3](image2.png)  
**Figure 3.** Graph between interference volume in cu. mm and angle of rotation (°) for analysing the effect of change of Module (3, 3.5, 4, 4.5 and 5) on TE with pitch error of 2% (Master Gear & Erred Gear 2). [Standard Tooth Dimension System]
Figure 4. Graph between interference volume in cu. mm and angle of rotation (°) for analysing the effects of change of Module (3, 3.5, 4, 4.5 and 5) on TE with pitch error of 1% (Master Gear & Erred Gear 1). [Stub Tooth Dimension System]

Figure 5. Graph between interference volume in cu. mm and angle of rotation (°) for analysing the effects of change of Module (3, 3.5, 4, 4.5 and 5) on TE with pitch error of 2% (Master Gear & Erred Gear 2). [Stub Tooth Dimension System]

Following are the observations drawn from the graphs of interference volume values and angle of rotation (figure 2 to figure 5):

1. There is a fluctuation in the values of interference volume, when angle of rotation changes from 0 to 20° (start and end of mesh cycle), there are some points having peak values of interference volume. This means that the TE is not constant for angle of rotation. The points having peak values are the point of concerned for the noise and vibrations in gears. This is observed for both the tooth dimension system i.e., standard tooth dimension system and stub tooth dimension system.

2. As the module changes from 3 to 5 mm, the interference volume values increases and hence the TE increases in standard as well as in stub tooth dimension system.

3. The interference volume values are found to be more in case of 2% pitch error than 1% pitch error and consequently the TE is more in 2% pitch error case. This is also observed in both tooth dimension system.
4. The graph is identical about its mid-point. i.e., it repeats after 10° for 18 number of teeth for both standard tooth dimension and stub tooth dimension system.

5. It is also observed that the interference volume or TE is more in standard tooth dimension system than stub tooth dimension system.

The work of the paper/outcomes are in line with the work of researchers presented in [3, 4, 6, 12, 14, 17]

6. Conclusions

In this work the consequences occurring due to the changes in gear parameter module on TE for spur gear pair with pitch error, using the interference volume method is presented. The spur gear without pitch error and with pitch error consisting of involute profile for standard tooth dimension and stub tooth dimension systems are modelled and meshed/assembled in SOLIDWORKS software. The interference volume values obtained from the meshing of gear pairs are recorded for one mesh cycle. Various graphs were plotted between the angle of rotation and interference volume values. It is found from the analysis that, as the module increases the TE also increases, TE also increases as the pitch error increase from 0 (no pitch error) to 2%. The effect of variation of module and pitch error is more in the standard tooth dimension system than that in the stub tooth dimension system.

References

[1] Beghini M, Presicce F and Santus C 2004 A method to define profile modification of spur gear and minimize the transmission error Technical Paper American Gear Manufacturers Association (Alexandria, Virginia) pp 1-9

[2] Hotait M A and Kahraman A 2013 Experiments on the relationship between the dynamic transmission error and the dynamic stress factor of spur gear pairs Mech Mach Theory 70 116–128

[3] Kohler H and Regan R 1985 The Derivation of Gear Transmission Error from Pitch Error Records Proc. Inst. Mech. Eng. Part C 199 195-01.

[4] Siyu C. and Jinyuan T. 2017. Effects of staggering and pitch error on the dynamic response of a double-helical gear set J. Vib. Control 23 1844-56.

[5] Velex Ph, Chapron M, Fakhfakh H, Bruyère J and Becquerelle S 2016 On transmission errors and profile modifications minimising dynamic tooth loads in multi-mesh gears J. Sound Vib. 379 28–52.

[6] Nina Sainte-Marie 2016 A transmission-error-based gear dynamic model: Applications to single- and multi-mesh transmissions (Doctoral dissertation, Université de Lyon)

[7] Sánchez Miryam B, Pleguezuelos M and Pedrero J 2019 Influence of profile modifications on meshing stiffness, load sharing, and transmission error of involute spur gears Mech Mach Theory 139 506–25

[8] Palermo A, Britte L, Janssens K, Mundo D and Desmet W 2018 The measurement of Gear Transmission Error as an NVH indicator: Theoretical discussion and industrial application via low-cost digital encoders to an all-electric vehicle gearbox Mech Syst Signal Process 110 368–89

[9] Shweiki S, Rezayat A, Tamarozzi T and Mundo D 2019 Transmission Error and strain analysis of lightweight gears by using a hybrid FE-analytical gear contact model Mech Syst Signal Process 123 573–90

[10] Zhiying C and Pengfei J 2020 Research on the variation of mesh stiffness and transmission error for spur gear with tooth profile modification and wear fault Eng. Fail. Anal. 122 2020 105184

[11] Pleguezuelos M, Sánchez Miryam B, and Pedrero JoséI 2020 Control of transmission error of high contact ratio spur gears with symmetric profile modifications Mech Mach Theory 149 103839
[12] Padmasolala G., Lin H.H., Oswald F.B. 2000 Influence of tooth spacing error on gears with and without profile modifications (NASA/TM-2000-210061 PTG14436)
[13] Bruyere J, Velex P, Guilbert B, and Houser D R 2019 An analytical study on the combination of profile relief and lead crown minimizing transmission error in narrow-faced helical gears Mech Mach Theory 136 224-43
[14] Handschu M J 2013 An Investigation into the impact of random spacing errors on static transmission error and root stresses of spur gear pairs (Master of Science Thesis, The Ohio State University)
[15] Bartosova D, Otipka V and Rehak K 2018 Determination of transmission error in spur gear by numerical approach Vib. Proced. 19 284-88
[16] Park C I 2019 Tooth friction force and transmission error of spur gears due to sliding friction J. Mech. Sci. Technol 33 1311-19
[17] Somani S K 2004 Transmission Error in Spur Gear (PhD Thesis, Institute of Engineering & Technology, Devi Ahilya University, Indore)
[18] Bruzzone F, Maggi T, Marcellini C and Rosso C 2021 2D nonlinear and non-Hertzian gear teeth deflection model for static transmission error calculation Mech Mach Theory 166 104471
[19] Duan T, Wei J, Zhang A, Xu Z and Lim T C 2021 Transmission error investigation of gearbox using rigid-flexible coupling dynamic model: Theoretical analysis and experiments Mech Mach Theory 157 104213
[20] Benaïcha Y, Joël P-L, Beley J-D, Rigaud E, Thouverez F 2021 On a flexible multibody modelling approach using FE-based contact formulation for describing gear transmission Mech Mach Theory 167 104505.
[21] Ambaye, G.A. and Lemu, H.G. 2020 Effect of backlash on transmission error and time varying mesh stiffness Proc. Int. Work. of Advanced Manufacturing and Automation (Springer, Singapore) pp18-28.
[22] Tao L, Tian D, Tang S, Wu X and Li B 2021 Dynamical modelling and simulation of spur gears with flank pitch error Res. Sq. 1 (Preprint rs.3.rs-534359/v1)
[23] Pleguezuelos M, Sánchez M B and Pedrero J I 2021 Analytical model for meshing stiffness, load sharing, and transmission error for spur gears with profile modification under non-nominal load conditions Appl. Math. Model. 97 344–65
[24] Chin Z Y, Smith W A, Borghesani P, Randall R B and Peng Z 2021 Absolute transmission error: A simple new tool for assessing gear wear Mech Syst Signal Process 146 107070
[25] Karma V K, Maheshwari G and Somani S K 2020 Analysis of effects of pressure angle and pitch error variation on transmission error in spur gear using interference volume method Int. J. Adv. Eng. Sci. Technol. 15-22
[26] Maitra Gitin M 2001 Handbook of Gear Design 2nd Edn (Tata McGraw Hill Publishing Company Limited New Delhi)