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A new calibration guideline for worm and worm-gear rolling testers

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Abstract

The evaluation and calibration of gear testers are considered as a key point to ensure the obtained results in gear metrology. Although ISO TC 60 working group has developed standards in this regard, the fact is that for the time being, there are not specific international standards for gear rolling tests. In this work, a periodical calibration guideline for gear rolling testers, particularly for worm gear transmission, is proposed, allowing the reduction of possible error sources in the measurement process. A series of tasks distributed over time are suggested in this work to maintain the accuracy of the gear rolling test machines.

Keywords: gear metrology; gear instrument calibration; rolling tester calibration; composite measurement tester evaluation

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1. Introduction

The need to improve gear metrology processes was proved in various studies, conducted by the gear industry in Europe and United States during the 1990s. The first verification and calibration guidelines for gear testers were defined by the British Gear Association (BGA) and the American Gear Manufacturers Association (AGMA) due to the lack of gear testers regulation [1]. These works settled the basis of the actual international standards for evaluation of gear instruments and testers, ISO 18653:2003 [2] and ISO/TR 10064-5:2005 [3] developed by the ISO TC 60/WG2 working group.

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Regarding gear rolling tests, AGMA decided that a similar standardization was necessary for double-flank rolling gear testers [4,5] but the equivalent ISO standards have not been developed yet. Concerning single-flank rolling testers, there is no existing specific standard available. Moreover, this situation is extremely critical for worm and worm gear inspections because the existing guidelines are mainly specified only for cylindrical gears.

In any case, in spite of the scarce existing recommendations relative to the verification of composite gear testers, the evaluation standards for gears measuring equipment propose not only complete periodical calibrations of the instruments but also their continuous inspection [3]. The periodical calibration is a key tool to assure and validate the results of the gears' verification maintaining the original accuracy of the rolling tester [1].

This work presents and develops a periodical calibration guideline for a worm and worm gear rolling tester. The guideline establishes the working routines to be carried out along the life cycle of the rolling tester. This calibration procedure has been developed to validate the equipment presented in the proceedings of the last MESIC 2015 [6], but it could also be adapted to calibrate any kind of rolling gear tester.

2. Gear rolling tests

Tangential composite and radial composite testing are the two types of gear rolling tests. They are known as single-flank and double-flank rolling test respectively. Although these tests can also verify a pair of production gears, generally the test gear is rolled against a master gear of better accuracy grade during an entire revolution. In this way, all deviations can be attributed to the test gear considering no error in the master gear, in comparison with test gear [7-9]. The main advantage of the rolling test is that it allows us to evaluate the gear's grade under its future working conditions.

Both tests, tangential and radial composite, must start at the nominal geometric position (height, axis angle and centre distance). In the single-flank test, the difference in the rotated angle between the master gear and test gear is compared, obtaining in this way the transmission error. In the double-flank test, the centre distance variation between both gears is measured, rolling them without backlash at a centre distance, achieved with a spring system, lower than the nominal. Although the configuration and sinusoidal graph obtained in both tests could be apparently very similar, the interpretation of the result data is different because the measuring principles are also different. The single-flank test allows us to obtain information on profile deviations, pitch and cumulated pitch errors, and runout of a gear, using the Fourier Transform. On the other hand, the double-flank test detects quickly damaged teeth, unsteady clamping and manufacturing process problems.

These measuring techniques can be used to verify the accuracy grade of cylindrical, bevel and worm gears [7]. In the normal configuration for worm gear transmission, the worm gear is rotated through a master worm that is turned on by a motor [10]. Figure 1a shows how, in the single-flank, test the rotation axis of the test gear must be perfectly aligned with the angular encoder's axis. Furthermore, in the double-flank test a dial indicator or a length gauge registers the constant swinging movement of the worm gear, which could be presumably generated by cutting defects in the tooth (Figure 1b).

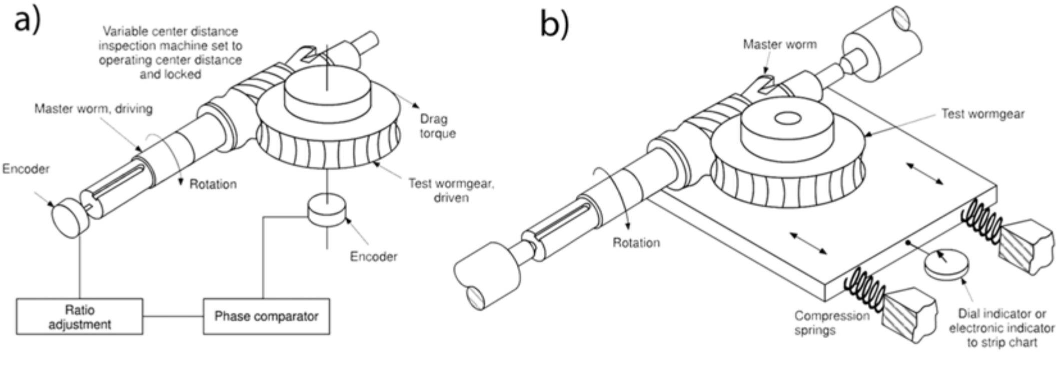

Fig. 1. Schematic of worm gear tester (source [10]): (a) Single-flank test; (b) Double-flank test.

Likewise, Table I shows a sample of rolling parameters tolerance values for a worm gear of 280 mm pitch diameter and module 5. It could be considered as a representative worm gear size in the gear industry. The accuracy grade is assigned according to the more unfavorable rolling parameter. The error parameters obtained as a result of the rolling tests could be described as follows:

- Tangential and radial composite errors (Fi’ and Fi” respectively) are the difference between the maximum and the minimum value measured in the course of one revolution;
- Tooth-to-tooth tangential and tooth-to-tooth radial composite errors (fi’ and fi” respectively) are the difference between the maximum and the minimum value measured occurring within an angle of rotation corresponding to the pitch;
- Cumulative pitch deviation and runout (Fp’ and Fr” respectively) are the difference between the maximum and minimum value of the long-wave component of Fi’ and Fi” respectively using the Fourier Transform.

Despite the single flank rolling parameters (Fi’, Fp’, fi’) are angular deviations, the ISO standard expresses the limit value of the quality grades in term of a distance from the pitch diameter. This fact makes that Table 1 values will be expressed in micrometres instead of arc seconds.

Table 1. ISO accuracy grades according to rolling parameters for 280 mm pitch diameter and module 5 [11], [12].

Grade	Fi’ (μm)	fi’ (μm)	Fp’ (μm)	Fi” (μm)	Fi” (μm)	Fr” (μm)
6	45 (66”)	10 (15”)	36 (53”)	54	22	32
7	64 (94”)	14 (20”)	51 (78”)	77	32	46
8	91 (133”)	19 (28”)	72 (106”)	109	45	64

The fact of measuring continuously and dynamically these micrometer values implies not only the use of high precision measuring instruments but also to establish the appropriate verification and calibration procedures that will assure the test results along the testers’ life cycle. In this way, the following errors could be avoided:

- Deviations in the distance between centers that could generate different single flank rolling measurements.
- The lack of perpendicularity between the axes that would be equivalent to an error in the hobbing of the helix angle.
- Eccentricity in gear rotation, which would add runout or accumulated pitch deviation.

All of them could be considered as the most critical points affecting the test results; therefore it is necessary to minimize their effects by means of previously established calibration procedures.

3. Periodical calibration guideline

The measurement procedure requires a clear definition of the main tasks to be performed in all of its phases independently of the qualification of the operator. This fact is extremely important for precision measurement equipment. It includes tasks such as the performance of the test, the checking of the testing conditions, the alignment of the required testing elements and the maintenance of the equipment. Thus, the new procedure developed in this work assures the initial calibration of the equipment daily and includes a set of routines distributed along the time to minimize the variation of the measurement’s results due to accumulative errors.

3.1. Switch-on general procedure

The standard working procedure involves a number of preparation steps in the tester to simulate the initial calibration procedure. The gear manufacturing process is normally done in batches due to the high preparation costs for hobbing and grinding machines. For this reason, gear testers most often keep the same measuring configuration during several days or weeks. Nevertheless, depending on the lot size and the type of gear being manufactured, the rolling testers' parameters need to be frequently changed or adapted for their verification, even having different configurations during the same day.

The suggested sequence to be carried out in the rolling tester switch-on procedure should be the following:

Step 1. Check the environmental conditions of the verification area, mainly temperature and cleanliness. The calibration and the testing should be performed under identical working conditions.
Step 2. Switch on the rolling tester, start the measuring-software and carry out the first visual inspection.
Step 3. Adjust the zero setting of the measuring instruments and encoders moving the gear holder carriages. In this way, the correct working of the principal elements and measuring instruments can be assured.
Step 4. Set a gauge cylinder with known diameter between the centers in the worm position.

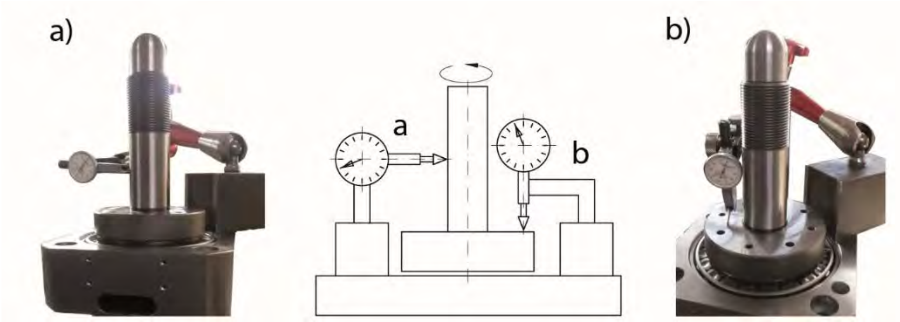

Fig. 2. Worm gear shaft verifications; (a) Eccentricity; (b) Reference surface flatness.

Step 5. Check the eccentricity of the worm and worm gear axis (Figure 2a) as well as the flatness of the reference surface (Figure 2b). They are usually verified using a micrometric dial indicator.
Step 6. Check the tester's axis perpendicularity measuring the two maximum points of the gauge cylinder's sides when the worm gear shaft is rotated. (Figure 3).

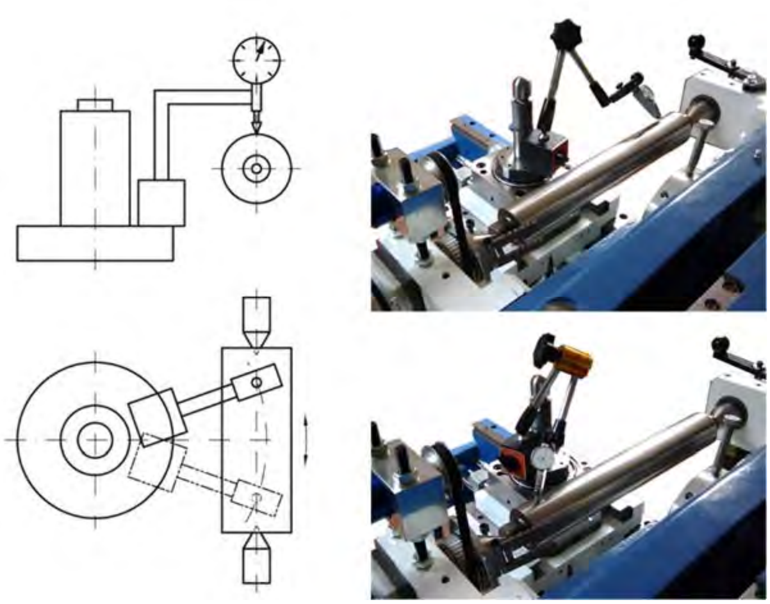

Fig. 3. Perpendicularity of the axis verification.

Step 7. Verify with gauge blocks (Figure 4a) or by direct contact (Figure 4b) that the instrument's readings (centre distance and height) appearing on the display are correct. Several control points should be established along the displacement so as to verify the test readings in different measuring positions.

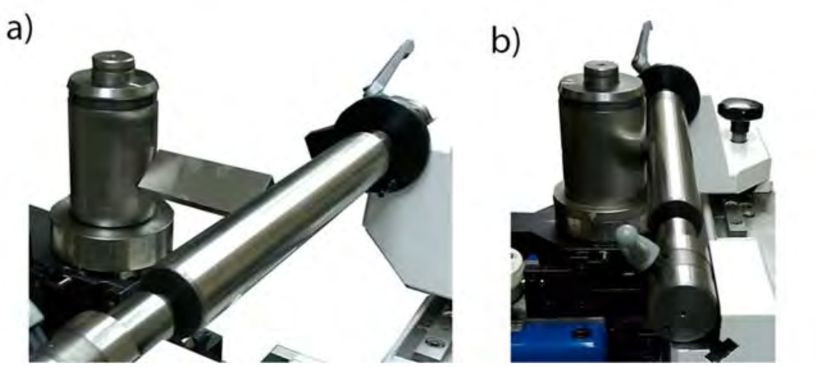

Fig. 4. Centre distance calibration procedure: (a) Static method; (b) Dynamic method.

Step 8. Replace the gauge cylinder with a master gear, if no problems are detected in the previous steps, mount the test worm gear on its corresponding shaft. Afterwards, worm and worm gear are placed at the nominal centre distance to initiate the rolling test.

Step 9. As a final step, rotate the set several revolutions in both directions to check the operation. During the rotation, the elastic system should be unlocked several times to verify its proper functioning.

In case certain discrepancies between display and verification values could be observed in step 7, a second calibration of the measuring instruments would be necessary. In this case, two calibration methods denoted as static and dynamic can be considered. In the static method, the centre distance is validated using gauge blocks. The value shown in the tester display must coincide with the sum of cylinders' radii plus the gauge blocks measurement (Figure 4a). The main advantage of this procedure is that calibration is carried out in a position very similar to the test position. On the other hand, in the dynamic method also called automatic calibration, the system "automatically" detects the contact between both cylinders considering the centre distance as the sum of cylinders' radii (Figure 4b). The length gauge of the double-flank test is used for that purpose, capturing the contact point position. This procedure could be considered as more accurate and precise than the static one because it avoids the operator's influence. Nevertheless, it adds other error sources, such as the worm gear carriage displacement to the nominal test position, due to the calibration is carried out in a different position that measuring position.

3.2. Time-based routines definition

Section 3.1 describes the switch-on and start up procedure for the worm and worm gear rolling testers. These tasks should be complemented with a definition of the principal routines and actions to be applied in the medium-long term. Thus, a general periodical calibration protocol is proposed to define all the routines to perform (Figure 5), which currently do not exist. In any case, it has mainly been developed to calibrate worm and worm gear rolling testers, in particular to calibrate rolling tester presented in the proceedings of the last MESIC 2015 [6].

Fig. 5. Calibration guideline for gear rolling tester.

As a result of this work, a written document has been prepared including all the tasks and activities that define an entire calibration procedure in order to assure reproducible and accurate results. A summary of the routines' distribution over time is following described:

- Daily routine (steps 1 to 3 and 9): switch-on basic routine will include the zero setting of the measuring instruments and the checking of the correct working of the main elements of the tester, providing there is no change in the type and size of the gear to be tested.
- Size change routine (steps 1 to 9): every time the gear size changes, a complete checking of all the elements and measuring instruments must be carried out, as well as a verification of the nominal system distances and positions.
- Weekly routine (steps 1 to 9): every weekly cycle will mean carrying out the entire switch-on procedure, even though identical gears have been tested last week. Moreover, cleaning and maintenance of the tester should be performed at the end of the week, focusing on the critical elements.
- Monthly routine: weekly routines will be complemented with the testing of gear pairs previously characterized, at least once a moth. The gears to be tested should have several sizes to cover all measuring range of the tester. Furthermore, a thorough inspection of gauge blocks, gauge cylinders, artifacts and master gears should be included in the monthly routine. This task could avoid calibration errors due to possible damages occurred in the daily handling of these elements.
- Bi-annual routine: a complete calibration of the rolling tester, reference pair of gears and reference artifacts is recommended every two years, even when the previously described routines could ensure the original tester accuracy. In this way, stability over time could be observed and the tester measurement uncertainty could be recalculated again.

3.3. Measurement uncertainty

Both the ISO 18653:2003 [2] "Evaluation of instruments for the measurement of individual gears" and the ANSI/AGMA 2116-A05 [4] "Evaluation of Double Flank Testers for Radial Composite Measurement of Gears" standards include a list of the potential error sources to be considered in the uncertainty estimation process. They propose an uncertainty expression according to a surrogate method that is normally applied in national calibration laboratories, and a second approach based on the comparator method used by the gear industry to verify the measuring instrument performance. Nevertheless, in secondary calibration laboratories or industrial facilities that require a more accurate estimate of their measurement process capability, the uncertainty budgeting method outlined in the ISO Guide to the expression of uncertainty of measurement (GUM) [13] is often applied. In this way, we propose in this work a general uncertainty budget expression (see equation (1)) following the GUM guideline. It enables to recalculate single-flank and double-flank equipment's' uncertainty according to the previously established bi-annual routine.

$$U_{95} = k\left[\left(u_0^2 + u_{dis}^2 + u_{gear}^2 + u_{test}^2\right)^{0.5}\right] \qquad (1)$$

The errors in the measurement of the rolling parameters (Fi', Fi", fi', fi", Fp', Fr") could be derived from the preparation or the execution of the test. This includes concepts such as the initial calibration uncertainty (u_0), the displacement uncertainty of the axis till the nominal testing position due to the residual errors of the numerical compensation (u_{dis}), the uncertainty derived from the mounting and clamping repeatability of the gears (u_{gear}) and finally the rolling test execution uncertainty (u_{test}). In order to carry out a proper calculation it is necessary to break down each uncertainty term and assess its individual influence out of the experimental values obtained in the calibration of the rolling tester. The uncertainty budget allows determining and modelling the most influencing error sources affecting the measuring results, making this information essential for future improvements or corrections of the calibration process.

4. Conclusions

The new periodical calibration guideline developed in this work for worm and worm gear rolling testers fills an existing void in the gears' guidelines and standards. A series of routines have been established to minimize the effects of the different error sources on the measuring process. Proposed tasks have been distributed over time based on its relevance and difficulty of implementation in order to assure the measurement repeatability along the life cycle of the rolling tester. Added to this, a general uncertainty budget expression according to the GUM guideline is proposed for this type of tests so as to estimate the measurement uncertainty and to identify the main error sources of influence.

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