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TECHNICAL PAPER

Validation of micromechanical systems

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Abstract For a reliable function of micro-mechanical systems the behavior of the used gear wheels is of extreme importance. But up to now there is no general available method for quality assurance of them. In this paper an adoption of the tangential and radial composite inspection as defined in standards for macroscopic gear wheels to the special needs and boundary conditions in micro technology is proposed. It is based on an examination of the differing results if the same gear wheels are mated with varying angles of rotation. Additionally special test rigs are presented which are able to test micro gear wheels. Finally some exemplary results are shown.

1 Introduction

Micromechanical systems become more and more popular. Going on the one hand to smaller dimensions and on the other hand to higher loads the testing of micromechanical systems and their components gains increasingly in importance. The approved techniques in macro dimensions cannot always be directly scaled down to micro—the uncertainties will rise and the testing machines cannot be arbitrarily tiny. Thus there is a need for a new design of test rigs for micromechanical systems and for new methods of testing.

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A very common mechanical system is a gear box, in the macro scale as well as in micro. Thus, there are many standards and guidelines for the design and testing of gear wheels and gear boxes, which are only valid in the macro size range. For precision engineering the references are significantly fewer and there are no standards for real micromechanical systems. The authors define micromechanical systems as mechanical systems, in which at least one structural element relevant for function has dimensions in micrometer range.

The presented research work focuses not only on the testing process and methods for gear wheels in micro scale but covers also the test rigs needed to perform the proposed tests. The testing methods for gear wheels in "common" size ranges cannot be used in this special case. On the one hand, the testing specifications and tolerances are only defined down to a certain size, in the German standards DIN 3960 (1987), etc. down to a module of 1 mm, on the other hand the test rigs or measuring machines are limited due to their probe size or due to their whole construction. The DIN 3960 standard describes together with VDI/VDE 2608 (2001) the so-called radial (Fig. 1b) and the tangential (Fig. 1a) composite inspection. For both two gear wheels are meshing with each other at low rotational speed and loads. For the radial composite inspection the center distance is variable. That means one of the gear wheels is moveable along the center line, which leads to rolling which is free from backlash and ensures always a contact on the right-hand and left-hand flanks. The measured result is the variation of the center distance. It depends mainly on the radial run-out, eccentricity and variations in the tooth thickness (Figs. 1, 2).

Since both inspections measure effects that are caused by both rolling gear wheels, the result is only significant for

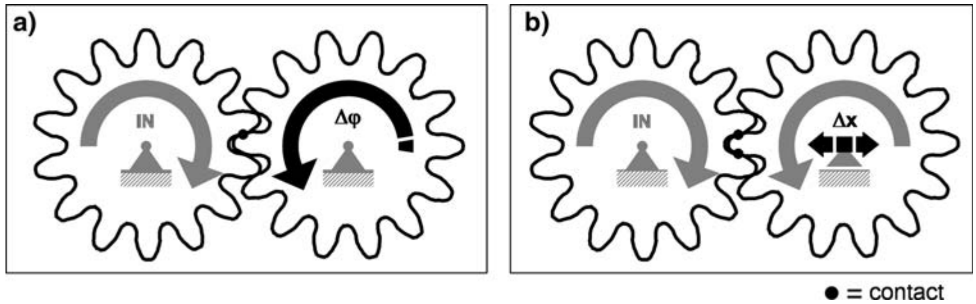

Fig. 1 Principles of tangential composite (**a**) and radial composite inspection (**b**)

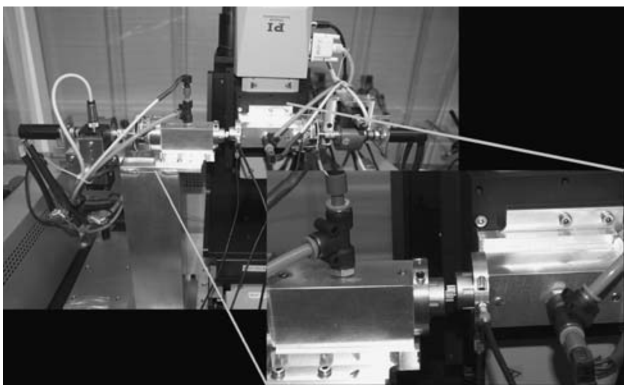

Fig. 2 Test rig for tangential composite inspection

this single pair of gear wheels in the applied arrangement. To get information for only one gear wheel independent of the other, so-called master gears are used. They have very small geometrical deviations compared to the product gears and therefore have no influence on the result. This is now characteristic for the measured product gear.

To transfer these testing methods in the micro range two main challenges have to be solved: a test rig is needed that is able to bear micro gear wheels. It must permit center distances that are smaller than 1 mm and may not have a major influence on the result due to, e.g., friction or inertia. Furthermore master gears are not available with a module smaller than approximately 0.3 mm. That means that another evaluation process is necessary, which can separate the influence of each rolling gear wheel.

To perform the radial and the tangential composite inspection two test rigs were developed and built. Up to now they are intended to test only a pair of micro gear wheels. They are assembled within as a spur gear pair.

2 Tangential composite inspection

For the tangential composite inspection the gears are mounted normally, i.e., at the specified center distance and shaft angle. The gear wheels are measured in the same contact situation as in the later operation. Dynamic effects like vibrations or the disengagement of flanks are not supposed to occur during testing, so the rotational speed of the gears is in a low range and the driven gear wheel is loaded by a small braking torque to ensure a continuous contact. This contact is on either the left-hand or the right-hand flanks depending on the direction of the torque and rotation. As results of a tangential composite inspection the transmission errors of the tested gear set are obtained. The measured value, the tangential composite deviation, is the difference $\Delta\varphi_{21}$ of the rotation angle of the second gear wheel φ_2 and its ideal angle which is calculated by the gear ratio and the angle of the first gear $i\varphi_1$. The evaluation of these results gives a diagram, in which the tangential composite deviation is plotted against the number of test gear revolutions. It is common to scale it not to the deviation angle but to a length measured on the pitch circle.

The test rig for the tangential composite inspection consists of two identically arranged drive trains. One is used as input, the other as output shaft of the gear system. The shafts are supported by aerostatic bearings to reduce friction and driven or retarded by a brushless DC-motor. Additionally the torque and the rotation angle are measured. Both gear wheels are fixed in collets. This arrangement allows to place both gear wheels at an arbitrarily small center distance. Additionally it is possible to move one side with five degrees of freedom in any position relative to the other. Hence it is possible to adjust and test deviations in the center distance, the axial alignment and the angular alignment. Due to the low stiffness of the aerostatic bearing a displacement of the shafts and the gear wheels can be caused by the forces of gravity and meshing. Therefore each bearing is equipped with four distance sensors to measure the angular and translational offset.

Measured parameters of both interacting gear wheels, mainly torque and rotation angle, enable a direct conclusion on properties of the gear pair. It is possible to calculate the power transmitted in and out of the gears and therewith the efficiency of them. Since the shafts due to their inertia can store energy themselves, the measured values have to be corrected. To calculate a mean efficiency it is sufficient to integrate the power transmitted in and out of the system for several revolutions. Another possibility is to get the tangential composite error by evaluating the difference of the rotation angle of both shafts. This is an indicator for the quality of the gear pair. In literature the law of error propagation is proposed to get the allowed tangential composite error of a gear pair if only the value for a single gear is known (VDI/VDE 2608).

As mentioned above the direct results of the measurement are only characteristic for the applied gear pair and the actual mounting situation. But for the purpose of a quality assurance for the single manufactured gear wheel, a value, which is only depending on one gear wheel, is needed. It can be derived from a test of two product gears if they are tested repeatedly with different combinations of flank contacts.

Figure 3 shows the results for a gear pair. Since both wheels have a non-integer gear ratio, different teeth mate in each revolution. Therefore the measured result shows some similarities but also significant differences. Since the diagram is plotted for the angle of rotation of the first gear wheel, you can say that the effects that can be seen exactly each revolution (2π) depend on the first wheel, the varying effects on the second wheel or on any special interaction of both.

Neglecting the latter effects caused by the first and the second wheel can be calculated out of these results and lead to a characteristic measure for the single gear wheels (Albers et al. 2007). To prove this theoretical approach a test series was performed. One gear was mated with several others. Figure 4 shows some results. It becomes obvious that the deviations for the pairs are quite different. But the separation into the effects caused by the wheels leads to a diagram, which shows only the influence of the second wheel, which was always the same (cp. Fig. 5). These results are nearly independent of the mating of the gear wheels and therefore characteristic for one gear wheel. The deviations and so the error is less than 5% of the maximum value.

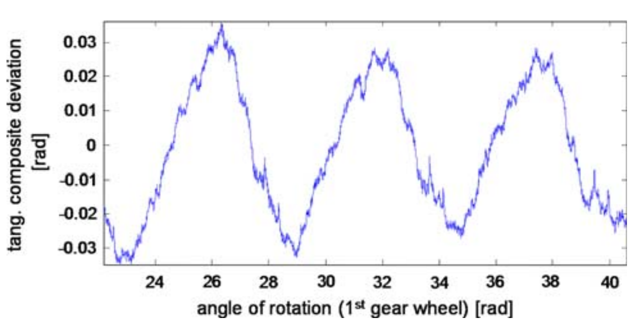

Fig. 3 Results of tangential composite inspection for three revolutions of the first wheel

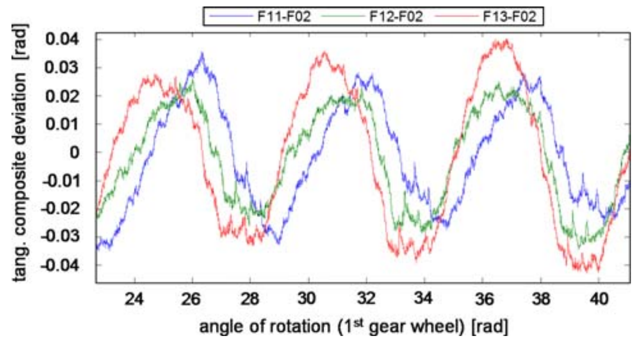

Fig. 4 Results of tangential composite inspections for three revolutions of the first wheel and three different matings of the same second wheel F02

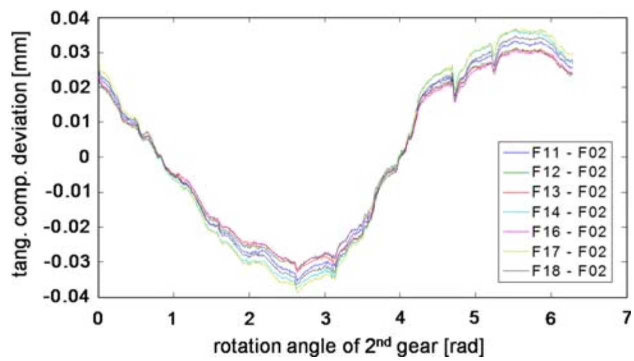

Fig. 5 Calculated results for the gear wheel "F02"

3 Radial composite inspection

For radial composite inspection, both gears are rolled free of backlash while the variation of the center distance is measured, which results in the radial composite deviation. Zero backlash is ensured by preloading the gears in direction of the center distance. Thus, left- and right-hand flanks mate at the same time. Basically, there are two possibilities of measuring such gears: on the one hand two product gears, i.e., specimens are mated; on the other hand a product gear and a master gear (cp. DIN 58420; for precision gears) are mated. Such a master gear usually needs to be of higher quality. DIN 3960 (1987) recommends the master gear to be three levels of quality [as defined for precision gears in DIN 58405 (NaFuO 1972a) for example] better than the nominal quality of the specimen gear. Thus, when meshing a product and a master gear, the deviations measured within one revolution can be directly assigned to the product gear. In microtechnology, a master gear is not available in general. Therefore, only product gears can be rolled and thus the measured superposed deviations of center distance cannot be assigned to a single gear. However, long wave components can be calculated by displacing the gears several times and then assigned to the single gear wheel (cp. VDI/VDE 2608).

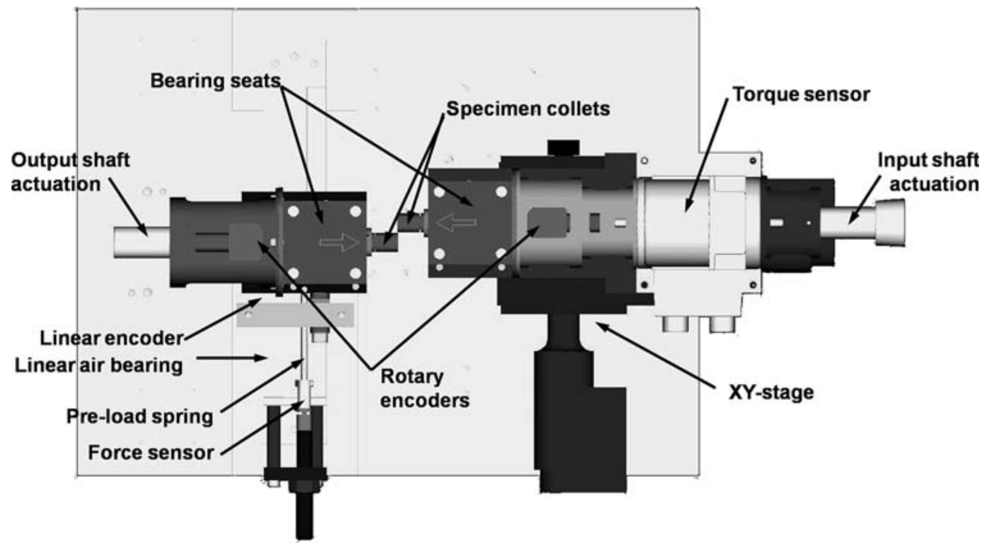

Fig. 6 Test rig layout

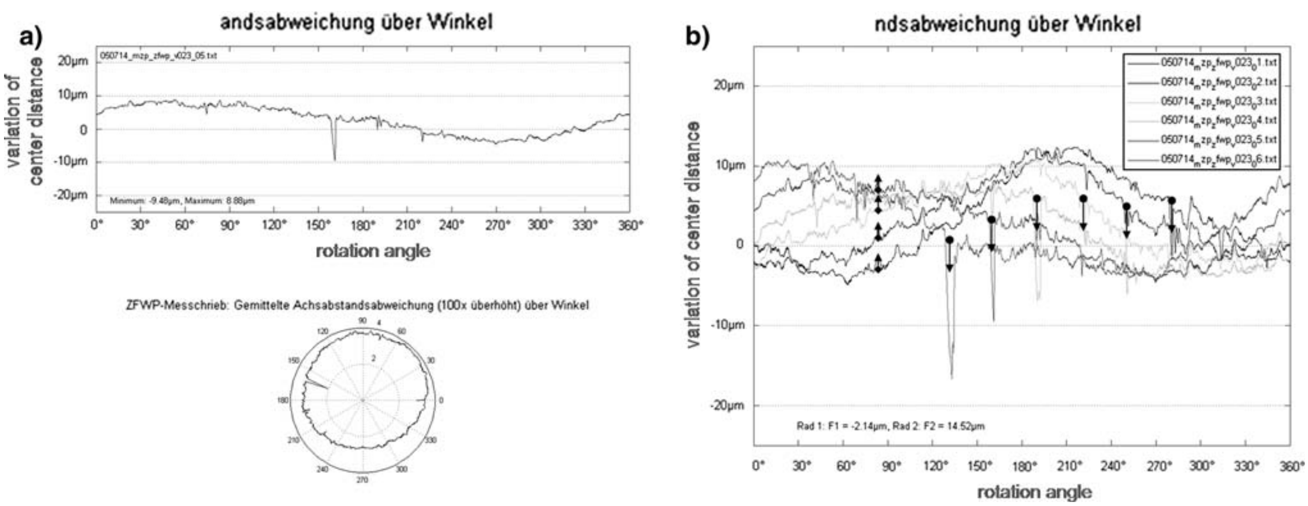

Fig. 7 Measurement of variation of center distance: **a** single mating; **b** several matings of product gears

Regarding the test rig, DC motors are used for applying driving and retarding torque to the tested pair of gears, which are attached by collets. Measurement of radial deviation is enabled by an aerostatic linear bearing and an exposed linear encoder based on a glass scale. Onto this linear bearing the bearing block of the output shaft is attached. In order to identify correlations of radial deviations and rotation angle, rotary encoders on input and output side are used, which are mounted before the bearing blocks (cp. Fig. 6).

Measurement of microgears results in graphs as depicted in Fig. 7a. The long-term component, an effect of eccentricity, can be seen. On short-wave level, smaller deviations can be identified; noticeable is a higher deviation peak at 160°. Obviously, the deviations cannot be assigned to a single gear by this single measurement and thus one cannot make a statement regarding the quality of single gears. However, when systematically displacing one of the gears, one can conclude with respect to a single gear wheel. Figure 7b. represents six measurements whereas the output gear wheel was displaced tooth by tooth. Once again, the deviation at 160° is obvious. Now, keeping that distinctive deviation in mind, one can see the movement of that deviation (marked by points) with the steps of the output gear. Thus, this deviation can be assigned directly to a known tooth of the output gear wheel. Another deviation appears at the same position at all six measurements (marked by diamonds). So, this deviation is characteristic for the gear on the input shaft. This approach allows to assign distinctive short-wave deviations to a single tooth.

4 Conclusion

Both the radial and tangential composite inspection can only be conducted for two product wheels since there are no master wheels in the regarded size range. Current research is going on to identify the deviation caused by each single gear wheel. Based on a linear consideration it is not only possible to associate single effects with the accordant wheel, but also to calculate a curve comparable to the result of a tangential or radial composite inspection according to the standards.

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