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VALIDATION OF MICRO GEAR WHEELS

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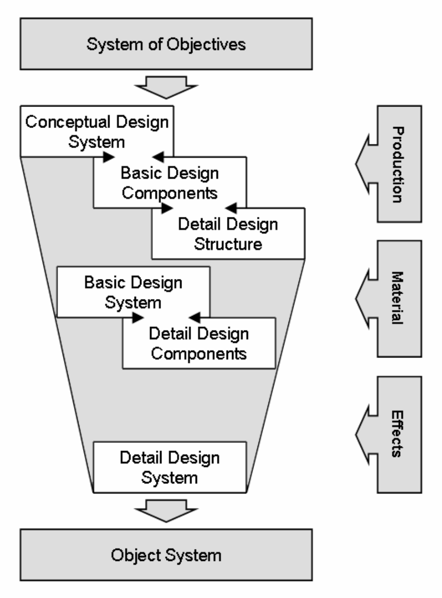
ABSTRACT
Micromechanical systems become more and more important. One of the central parts of those are gear wheels. They are used in most micromechanical systems, e.g. instruments for minimal invasive surgery, consumer electronics etc. Going on the one hand to smaller dimensions on the other hand to higher loads and suited operation conditions the testing of micromechanical systems and their components is more and more important. The approved validation techniques in macro dimensions cannot always be transformed down to micro – the uncertainties will rise and the testing machines can't be arbitrarily tiny. Thus there is a need for a new design of test rigs for micromechanical systems and for new methods to test them.
The following paper presents the results of an ongoing research that focuses on the validation of micro gear wheels. An extension to the methods that are common in the macro range is proposed thus they can be used in an adapted way for micro gear wheels too. Further a test rig is described which was developed and build to perform the proposed tests. Finally some results are presented as an example.

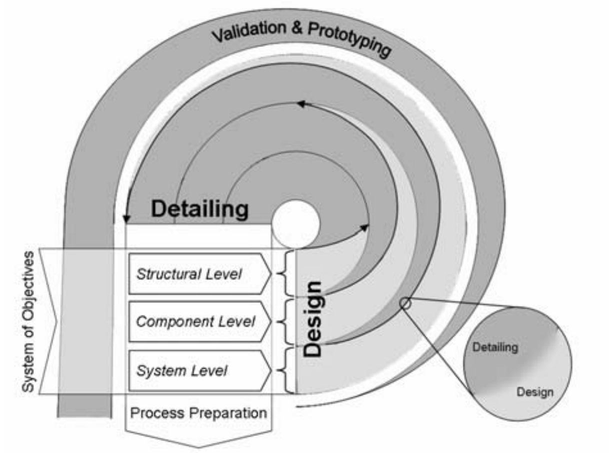
Keywords: Micro Technology, Micro Gear, Validation

1 INTRODUCTION
Today's technical systems become smaller and smaller but still should keep their performance. This leads to increasingly higher specific loads and hence higher demands to the quality of these systems. This can only be reached with a holistic view on the system. To regard this, an optimization on all levels of the product design is necessary. This can be done partly in theory e.g. with the help of design rules. But due to a lack of standards and practical experience, an accompanying testing is mandatory. One main component of most micro mechanical systems is a micro gear wheel. Therefore the quality inspection of micro gears will be considered in the presented paper.
A gear is regarded as "micro" if its module as a characteristic length is in the "micro-range", i.e. between 1µm and 1 mm.

2 DEVELOPMENT OF MICRO MECHANICAL SYSTEMS
A special process for the development of tool-based micro mechanical systems is described in [1, 2]. It suggests a sickle model which describes the simultaneous development in three levels of abstraction – on the system, component and structure level (fig. 1). Due to the limited possibilities of the manufacturing processes, these three levels cannot be defined sequentially but have much influence on each other. E.g. the minimal radius of a tool leads to a minimum module of a toothed gear wheel on the component level and therefore a required minimal diameter of the gear box or a changed arrangement of the gear wheels on the system level. These modifications do not only influence geometrical parameters but also functional, e.g. a transmittable torque or an accuracy of the movement.
Since there are no standards for the development of micro mechanical systems and few experiences with these new production technologies, the development is characterised by many loops between drafting the functional elements, developing the production and testing the system.



(a) Design stage



(b) Sickle-model

Figure 1: Development in tool-based microtechnology [2]

Due to the geometrical limitations especially of tool based micro manufacturing techniques it will often be not possible to produce a functionally optimal design. Therefore, even the nominal design of a micro system will have less functionality than a comparable macro system. Additionally the relative deviations in the production process are higher. These depend again on the production technique required by the nominal design. Those interactions are not fully researched yet. Hence it is not possible to develop such a system only in theory but it is necessary that this development process is accompanied by a testing process for each step. Therefore a testing method for micro gear wheels and for complete gear boxes is needed. It must be possible to test single components as well as whole systems.

3 TESTING OF GEAR WHEELS

3.1 Quality assurance by geometrical measurement

For the acquisition of the geometry of a gear wheel or any other part its shape is scanned and points on the surface are registered. They can either be fitted to a standard geometrical element (e.g. circle) or described as a curve (e.g. involute). Then the deviation from the designed values is determined and compared to the tolerances. Special values for gears can also be specified too. This can be a pitch error, the tooth thickness or the lead angle. There are specialized machines to measure these properties, so called gear measuring machines. They can scan the wheel with a touching probe tip. Often more general applicable coordinate measuring machines are used. These machines are limited to gear wheels with a minimum diameter of about 5mm since the diameter of the probe tip can only be in special applications smaller than 0.3 mm. To enlarge this size range there are currently some research projects. Since there are several with focus on miniaturized Coordinate Measuring Machines (CMM) and an enhanced accuracy only some works aiming especially on gear wheels will be mentioned.

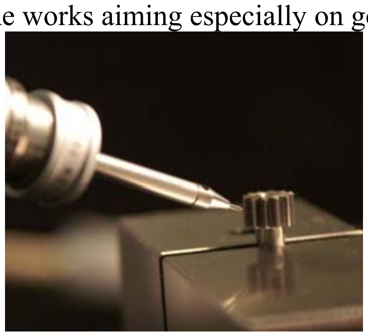
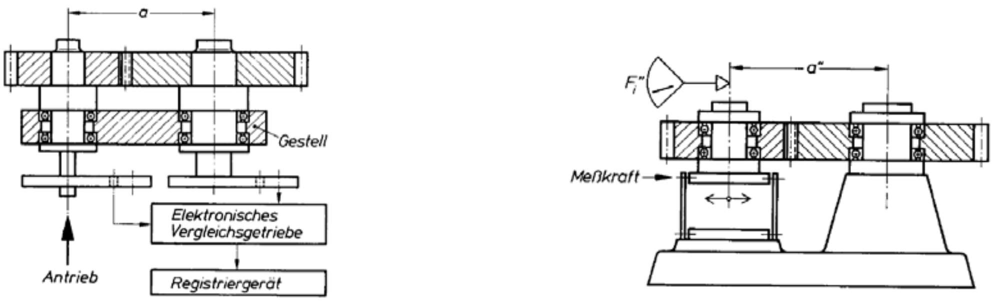


Figure 2: Scanning of a micro gear wheel by a Coordinate Measuring Machine (CMM)

The use of a special CMM built by the company Werth for micro gear measurement is described by [3]. It uses an optical-tactile probe developed by the PTB [4]. The stylus is a glass fiber with a sphere at its end. Its diameter can be as small as 25 µm. For measurement the sphere is moved until it touches the surface of the gear wheel. The actual position is measured optically [5]. With this equipment the geometry of a gear wheel with a module of 54µm was measured.
Different optical methods for measuring gears are explained by [6] but no statement on the required sizes or the potential for a miniaturization is given. Transmitted and reflected light measurements for micro gears are considered by [7]. But both are strongly limited with respect to the whole geometry of a part.

3.2 Determination of functional parameters

Some functional tests for macro gears are defined in the German standard [8], the tangential and the radial composite inspection (fig. 3). In both cases two gear wheels are meshing with each other at low rotational speed and loads. For the radial composite inspection the center distance is changeable. That means, one of the gear wheels is moveable along the center line. This leads to a rolling, which is free from backlash, and ensures always a contact on both the right-hand and left-hand flanks. The measured result is the variation of the center distance over the rolling angle. It depends mainly on the radial runout and variations in the tooth thickness.



(a) tangential composite inspection *(b) radial composite inspection*

Figure 3: Test rigs for tangential (a) and radial (b) composite inspection [8].
(a) Both wheels have a fixed center distance. The rotation angle of them is registered and compared to an ideal one.
(b) One gear wheel is movable in radial direction. Both are pushed together by a force F_i". The variations in the center distance are measured.

For the tangential composite inspection the gears are mounted normally, i.e. at the specified center distance and shaft angle. Unlike the radial composite inspection the gear wheels are measured close to their later operating conditions. Since there is only contact on either the left-hand or the right-hand flanks you can get two different results for each pair of gear wheels. 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 $i * \varphi_1$. [9]
In both inspections the measured result depends on both gear wheels. I.e. a “good” or “bad” test result only says nothing about one single gear but only about this pair of gears in their current mounting situation. To still get information only about one tested gear wheel you use a so called “master gear” as second wheel. This has a higher quality than the measured one and therefore produces only insignificant deviations in the functional test. All measured differences must hence infer from the other wheel.
Other tests can be carried out in complete mounted gear boxes. The regarded parameters are for example the maximal torque until the gears can be operated without fracture or other failures, the noise or the temperature reached in the housing. These all defer from geometric and material deviations in the used components. There are some works which investigate these links for macro gear wheels [10].
The testing of micro gear wheels leads to two main problems. There is a lack of adequate testing machines and of master gears. There are some research projects mostly concentrating on the load capability, noise, wear or fatigue of micro gear wheels. The Institute of Polymer Technology of the University Erlangen-Nuernberg operates a test rig for micro polymer gear boxes. They mainly investigate the tribological performance. Therefore the test rig can apply torque and rotational speed in

the range of 0.2 to 10 Nm and 50 to 8000 rpm, respectively [11]. The Faulhaber Group reports of a vibration test for micro power trains. It is used for a combination of a electric motor and a small gear box. The vibrations of the housing are measured by a laser vibrometer. After data acquisitions it is inferred to the generated noise of this system in real operations and hence the quality of it [12]. But no research work is found for the connection between the functional behaviour of single gear wheels, their geometry and their later behaviour in a operating system.

4 MICRO SPECIFIC TESTING OF GEAR WHEELS

4.1 Process

In the production process a quality is described by a difference of the nominal and the actual value of a mostly geometrical value. For a functional point of view, this definition is of little use. Since only a whole system can fulfil a function, single geometrical deviations are not convincing, their interaction is at least as important as the deviations themselves. A “good” system can fulfil its function, a “bad” one cannot. Hence the quality can be regarded as a measure how good the system can fulfil its function or to which part. The quality of a single part can therefore only be considered with respect to the system. You can regard the quality of a part as the quality of a system consisting of only perfect parts but the considered one. This leads to an idea of quality which can not be stated in general but is depending on the system of objectives for the micro mechanical system and has to be regarded in the whole development process and not only while testing the system or some components.
In extension to the sickle model you can add the validation of the newly developed part for every level of abstraction. After the detailing you must test the design. Since a function can only be fulfilled by the interaction of at least two parts, this will mainly take place on the component and system level. But also on the first level, the structure, a functionally important parameter could be for example the friction coefficient in a contact. This can be validated in a model test like the pin-disk-test. For the other levels a real testing close to the later purpose of the system is possible. E.g. a gear box can be tested on a component level (single gear wheels) and on the system level (completely mounted gear box). To test the design of a single gear wheel you can simply combine two each of them. The function of a housing must be fulfilled by the test rig. Then it is possible to measure interesting functional parameters like the backlash, efficiency of the toothing and the composite error. With these results a loop is made and the design on this level can be improved with respect to the production accuracy or function.

4.2 Testing equipment

For the testing of micro gear wheels special testing equipment is needed. As described above the geometrical measurement of micro parts is difficult because of the required small size of the probing elements. In a functional test a gear wheel is scanned by another gear wheel. Hence it is – in theory – possible to do this for arbitrary small gear wheels. But the influence of unknown errors in these gear wheels will make the measured result more and more uncertain, if the size decreases. Additionally the influence of the test rig and measurement equipment will increase too.
The tangential composite inspection has been identified as a good choice for a functional test for micro gear wheels. Its result is directly correlated to the functional quality of the gears and their later behaviour in a real system. And the measured physical property is an angle, the angles of rotation of both gear wheels. If the size of the gear wheels is reduced, the test rig will be too. But in opposite to lengths, angles will not. Thus they will be in the same size ranges as for macro gear wheels and have to be measured with a comparable accuracy. The main objective of the development of a micro gear test rig is therefore not the measurement technology but the test rig itself. It must have as little influence on the rolling of the gears as possible. This leads to high demands on the mechanical properties of it, mainly the friction and the moment of inertia. Both have to be as small as possible. Especially the friction may not lead to a “stick-slip-effect”, because that would directly disturb the angle measurement necessary for the tangential composite inspection.

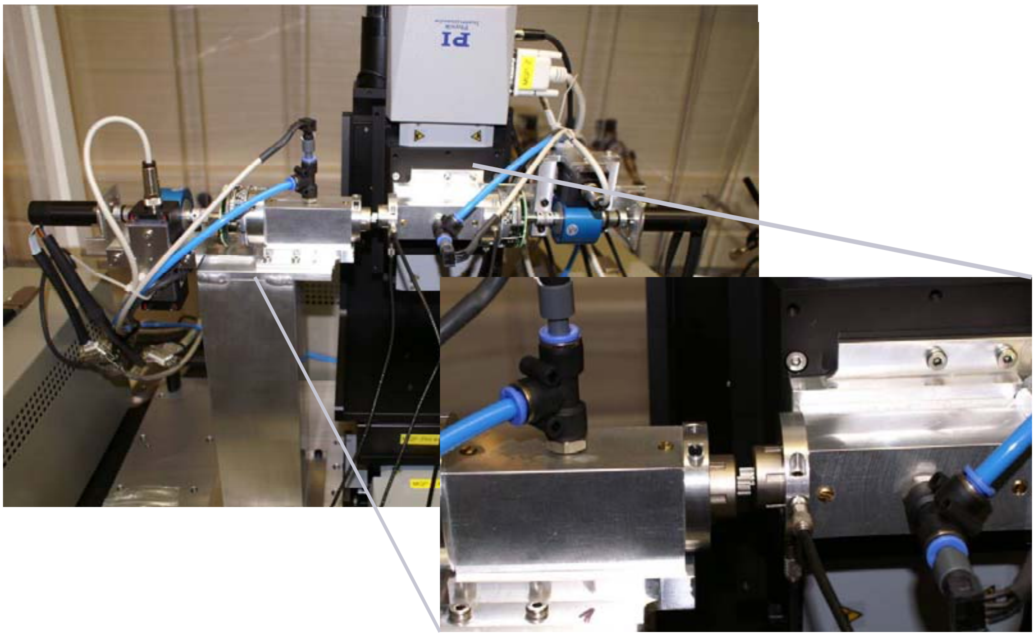


Figure 4: Micro gear test rig

Due to this reason, the shafts of the test rig are carried by aerostatic bearing which have nearly no friction at low rotational speed and absolutely no stick-slip-effect. A negative consequence is the rather big diameter of the shafts required for this type of bearing and the low stiffness. The gear wheels are fixed at the end of the shafts and these are arranged opposite of each other. Therefore no minimal center distance must be kept and arbitrarily small gear wheels can be mounted. To determine the exact position of the meshing gear wheels additional distance sensors are mounted around the shafts to measure their radial movement inside the bearings.
For a tangential composite inspection of two spur gear wheels it is necessary to adjust the center distance of both gear wheels according to their pitch diameter and their axial position so that they overlap completely. In addition to that the misalignment that can occur in a real gear box can be simulated, i.e. the angle between the axes in two directions and the spatial position of one gear wheel can be set.

5 FUNCTION ORIENTED QUALITY INSPECTION OF MICRO GEAR WHEELS

5.1 Quality of a system

Micro gears can have multiple functions in different systems. In general they have to transmit and change a rotation and a torque. Most gears are either used for positioning issues, e.g. in a micro position stage or a clock, or for power transmission, e.g. in a dental application. In the first case it is important that the rotational movement of the driving wheel is exactly followed by the driven wheel, that means the rotation angle of the driven wheel φ_2 must not differ more from the ideal position i * φ_1 given by the driving wheel than a certain tolerance $\Delta\varphi$.

$$|\varphi_2 - i * \varphi_1| = \Delta\varphi \qquad (1)$$

Since both rotational angles can be measured directly on the presented test rig and the transmission ratio is know for a pair of gear wheels, these quality check can be performed without any additional efforts.
If the torque capability and the efficiency of the spur gear pair have to be determined, it is possible to test it under the same conditions as in operations, i.e. at the same speed, center distance and possible misalignments. But due to the position of the torque sensors on the test rig, the torque on the gear wheels cannot directly be measured. Because of the inertia of the shafts each change in the rotational speed results in an additional torque registered by the sensors. This has to be corrected in the measured data. Since the moment of inertia, the rotational speed and acceleration is known, this additional torque can be calculated and subtracted from the logged values. To compare both measured torques of

the driving and driven side, the latter has to be corrected by the gear ratio. The ratio of these corrected values is the efficiency.
Since there are no standardized values and tolerances for micro gears, these have to be defined by the designer for each application separately. Then they can be controlled by the method described above for single components, like a spur gear pair, and for complete systems.

5.2 Quality of a single gear wheel

The quality of a single gear wheel like defined above cannot be measured on this test rig. Since there are no “perfect” gear wheels, also called master gears, it is not possible to measure only the influence of one gear wheel. It can only be inferred to it based on an extension of the tangential composite inspection described in [8] and [9].
The deviations caused by an eccentricity of the tooth profile can be found by a frequency analysis. For two different numbers of teeth on each gear you will find two fundamental frequencies in the acquired signal corresponding to the two rotational speeds. But there is no possibility to split the measured short-wave component (meshing) and hence no way to identify the quality of one gear wheel in such an inspection if the second wheel is unknown too. The problem is to divide one signal in two components, one characteristic for each meshing gear wheel.
The solution to this problem should be described by a model. Since the tangential composite deviation is describing a function, it is a direct result of basic elements – working surface pairs (WSP), channel and support structures (CSS) and their interaction. This model, the Contact and Channel Model (C&CM) is detailed explained in [13]. Transferred to a system of gear wheels, each flank can be regarded as a working surface (WS). Two flanks that can mesh together form a working surface pair. Dependent on the gear ratio this can be any combination of flanks or just one per flank (equal number of teeth). I.e. only regarding the meshing contact gear wheels consist of one WS per flank. With z_1 and z_2 being the number of teeth, you have a system of z_1+z_2 working surfaces. Since they can mesh in any combination by mounting them differently, they can form $z_1 \cdot z_2$ working surface pairs.

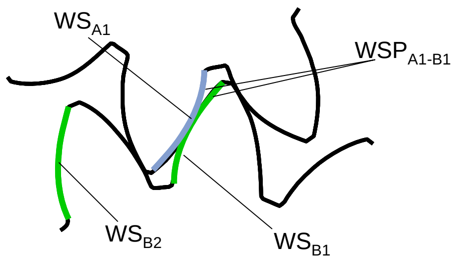


Figure 5: Tangential composite inspection with a master gear wheel. The working surfaces WS_{B1} and WS_{B2} have the same properties. Hence the WSP_{A1-B1} and WSP_{A1-B1} will produce the same deviations which are fully caused by WS_{A1}.

In a test according to [8] a product gear meshes with a master gear. The latter has a significantly more accurate geometry. That means in comparison to the product gear, all working surfaces of the master gear are identical. Deviations in the functions of the pair, which is in general a property of the working surface pair, arise therefore only from the first working surface. Figure 5 shows the different flanks of the product gear “A”, for example WS_{A1}, whereas all working surfaces of the master gear “B” have the same properties. I.e. the function of the working surface pair WSP_{A1-B1} and WSP_{A1-B2} are the same.

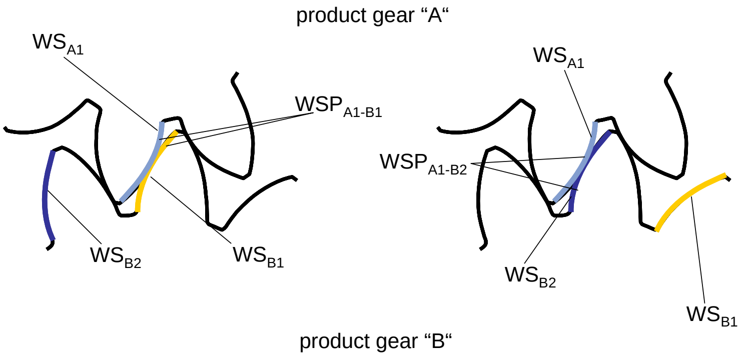


Figure 6: Both gear wheels “A” and “B” are product gears and therefore have deviations in the same size range. The working surfaces WS_{B1} and WS_{B2} are significantly different and the $WSP_{A1\text{-}B1}$ and $WSP_{A1\text{-}B2}$ will produce different deviations.

If you mate two product gears as shown in figure 6 there is indeed a difference between both working surface pairs. If the single working surfaces WS_{B1} and WS_{B2} have different properties, it will be the same with the working surface pairs $WSP_{A1\text{-}B1}$ and $WSP_{A1\text{-}B2}$. In this case you will get varying results for all working surface pairs and cannot directly distinguish which part of the deviation is influenced by the first working surface and which by the second one of the pair. But instead you can measure much more working surface pairs than there are unknown working surfaces.

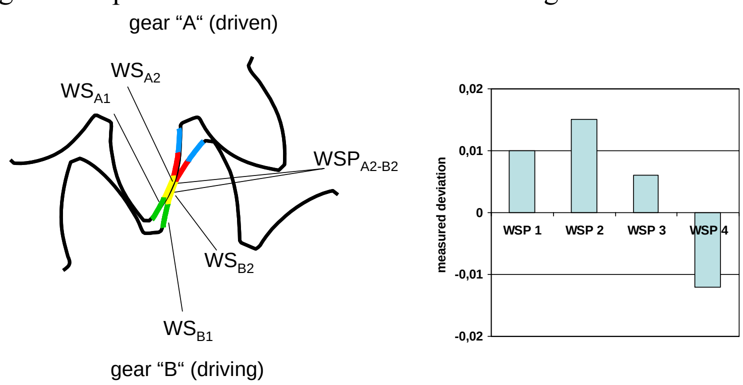


Figure 7: Dividing the tooth flank in several working surfaces. The so formed working surface pairs hold the functional contact successively.

Due to the special character of the C&CM it is possible to regard a tooth flank not as a single working surface but as several parallel working surfaces that are sequentially in contact. You can adjust this resolution of the model to the resolution of a real measurement so that each sample corresponds to exactly one working surface pair and therefore directly is caused by the two working surfaces in the pair and their properties (fig. 7).

With the assumptions that the composite deviation of a working surface pair is just the linear addition of the deviations of the mated working surfaces, there is a possibility to infer from the pair to the single surface. You can describe the deviation measured for a working surface pair $\Delta(WSP_{1\text{-}2})$ as the sum of the deviations caused by the single working surfaces $\Delta(WS_1) + \Delta(WS_2)$. As it is possible for gear wheels to measure each combination of working surfaces you can generate a set of linear equations.

$$\Delta(WSP_{i\text{-}j}) = \Delta(WS_i) + \Delta(WS_j) \qquad (2)$$

Transferred to the real measurement this means, the measured deviation of the gear pair Δs for a rotation angle φ_1 and φ_2 of the rolling gear wheels is the sum of the deviation Δs_1 that would be measured if gear wheel 1 is paired with a master gear wheel and Δs_2 corresponding.

$$\Delta s(\varphi_1, \varphi_2) = \Delta s_1(\varphi_1) + \Delta s_1(\varphi_1) \qquad (3)$$

These deviations $\Delta s(\varphi_1, \varphi_2)$ can be measured for several combinations of angles. Unfortunately the resulting equations are linear dependent in such way, that you cannot solve this system without further conditions. These can be for example a minimum square sum of the deviations, resulting in the most "smooth" teeth that can produce the measured result. Or the geometry of one tooth flank is known. Then the tangential composite deviation of this flank mated with a master gear can be determined by a simulation [14] and finally the set of linear equations can be solved.

6. RESULTS OF THE TEST RIG

Some exemplary results found on the micro gear test rig will be presented. The tested gears have a module of 0.5 mm, 12 and 13 teeth respectively and are made of steel. They are mounted as a spur gear pair with the nominal center distance and no misalignment. For low rotational speeds the rotation angle of both gear wheels can be measured. Figure 8 shows the deviations on the pitch circle.

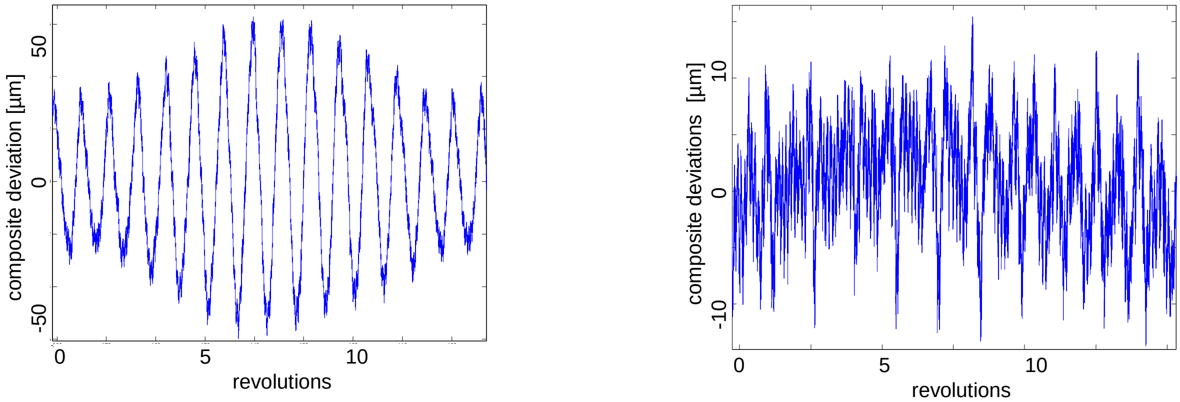


Figure 8: Measured signal (left) and residuum after subtraction of the eccentricity according to equation (5)

The most significant deviation has a period of 2π and therefore defers from an eccentricity of the gear wheels and not an error of the profile line. For the function this will result in no difference. But for improvement of manufacturing a correction will require other measures. For example an injection moulded gear wheel with a milled mould just needs a correction of the center axis and no change of the profile.

$$f' = e \cdot (\cos \alpha_0)^{-1} \cdot \sin(\varphi + \alpha_0) \; [9] \qquad (5)$$

If you subtract the deviation caused by the eccentricity of both gear wheels, the residual signal is characteristic for this combination of the both gear profiles. Further on the signal can be averaged synchronously to eliminate noise.

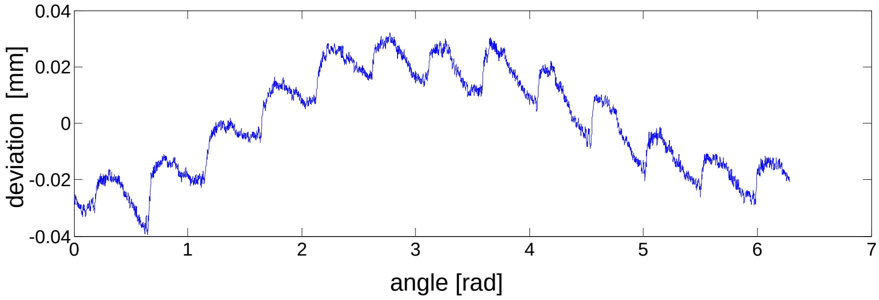
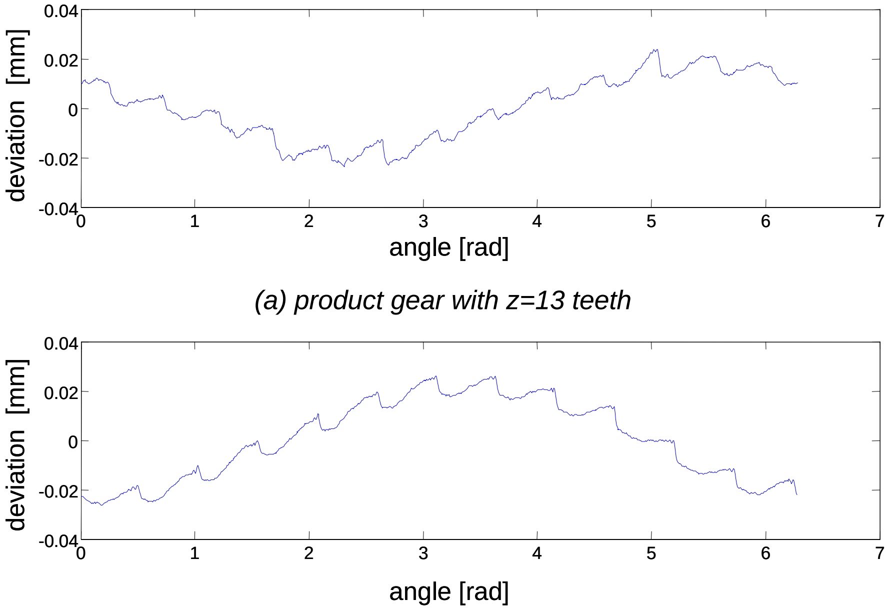


Figure 9: Measured tangential composite deviation for the gear pair



(a) product gear with z=12 teeth

Figure 10: Separated tangential composite deviations for both gear wheels

To get the separate signal for both gear wheels equation (4) can be applied (fig. 10). For this the scanned data points have to be transformed to equally spaced angles φ_1 and φ_2. As additional condition the solution with the smallest norm should be used. In general this will lead to "better" results, i.e. smaller deviations, than a measurement with master gears according to [8, 9] but still to a characteristic curve for each gear wheel. These can be compared to other diagrams obtained in the same way.

7. CONCLUSION

In the development process of micro mechanical systems it is extremely important to have a sufficient validation potential. That means that the consequences of decisions in the design cannot always be foreseen. Hence it is necessary to add validation steps at the end of some stages of the process. With the aid of the presented method and testing equipment it is now possible to determine the quality of micro gear wheels. Any deviations from the desired behaviour can be considered in an early design phase and adequate measures can be taken. Although the testing process for a single component is performed with two unknown product gears it is possible to derive characteristic values for each of them. Thus you can measure the quality of a single gear wheel by a functional test on a micro gear test rig.

8. ACKNOWLEDGMENT

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