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# A New Method for Contactless Measurement of Small Module Gears with Asymmetric Profile

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## Abstract

In the field of mechanical engineering, achieving precise measurements of small-module gears and transmissions is critical. This paper presents an innovative non-contact method for assessing the accuracy of these components, based on optic-electronic signal processing principles. It offers superior precision in evaluating gear geometry, pitch, and profile.

With recent advancements in gear manufacturing, there is a growing need for efficient and precise measurement methods to ensure optimal performance and durability. Traditional tactile methods and double-flank inspections have limitations, including potential subjective errors. This paper addresses these challenges by providing a comprehensive solution that not only enhances measurement accuracy but also sheds light on the relationship between production variables and gear precision.

This study is significant for delivering high-precision gear assessments, revealing production-precision links, reducing subjective errors, highlighting automation potential, and contributing to the discourse on mechanical precision in gear-dependent industries. Drawing from foundational research in gear measurement, optic-electronic signal processing, and manufacturing automation, its primary aim was to determine if non-contact methods improve small-module gear measurement. Through rigorous analysis, this study unequivocally affirms this question, advancing gear and transmission measurement and control.

**Keywords:** Small module gears; centroidal enveloping method; asymmetric cog profile; kinematic error; contactless measurement.

## 1. Introduction

Gears, integral components in a multitude of mechanical systems, play a pivotal role in ensuring the efficiency and functionality of machinery across various industries. Their manufacturing, however, is riddled with potential pitfalls stemming from the inherent challenges of achieving precise formations. Harmonic oscillations, a predominant concern, accumulate during manufacturing, leading to periodic errors that jeopardize the optimal functioning of the gears [1], [3], [10].

While radial errors are attributed to factors like product basing errors, tool inconsistencies, and the stability of the Machine, Adaptation, Tool, Detail (MATD) system, tangential errors often emerge from discrepancies within the kinematic chain's elements, such as worm pairs and dividing discs. The intricate interplay of these individual errors in the technological process manifests in various ways on the gear, affecting kinematic accuracy indicators like operational fluency, contact quality, and clearances. These complex errors, in turn, influence the gears' overall operational quality [2].

Moreover, understanding elemental errors is not just a theoretical exercise but has tangible implications for technological control.

Against this backdrop, this study seeks to address two fundamental questions:

How can we better understand the sources and implications of these harmonic oscillations and errors in gear manufacturing?

Is there a more accurate and efficient method for evaluating and mitigating these errors, particularly in the realm of small-module gears and transmissions?

In pursuit of these questions, we introduce a novel non-contact method and device, aiming to shed light on the relationship between manufacturing processes and resultant gear accuracy, while also offering potential solutions for improved production and control processes.

## 2. Discussion

Analyzing and controlling the precision of gears is an intricate endeavor. The intricate geometric configurations, multifaceted performance metrics, and rigorous precision criteria inherent to gears make their evaluation a formidable task. Typically, two predominant strategies dominate this sphere: the elemental evaluation techniques, which furnish direct insights into the functional proficiency of gears and transmissions, and those that present both technological and functional data regarding gear quality. Both streams of information are imperative to optimize the manufacture and functionality of gears. Hence, a pressing need arises for methodologies and tools that facilitate a seamless and intuitive bridging between these distinct data realms.

Small-module gears, defined by modules under 1 mm, intensify these challenges. Their minuscule dimensions and distinct tolerance ranges, juxtaposed with their medium and large-module counterparts, further amplify the complexity. This milieu catalyzed the inception of a comprehensive measuring instrument designed to amalgamate insights on both functional accuracy metrics and detailed technological discrepancies, along with underlying causatives. This invention took shape at the "Mechanical Engineering and Equipment" department of the Technical University - Gabrovo [11].

The said device harnesses the prowess of photoelectric technology, amalgamated with the computational capability of personal computers. As illustrated in Figure 1, the mechanism hinges on the modulation of a laser's light beam (laser 1) by the teeth of the gear under scrutiny (gear 3), which consistently rotates at a predetermined angular velocity. This modulated light, when channeled through an aperture (aperture 4), interacts with a photoelectric sensor, thereby being transmuted into a discernible signal. This signal, subsequently processed by the Analog-to-Digital Converter (ADC) 8, is relayed to a computer (computer 9). The unwavering angular velocity is upheld by a motor in conjunction with the photo raster converter (PRC) [9]. To mitigate potential positioning discrepancies, the gear under examination is meticulously positioned on a high-precision spindle system. The device's affinity for laser technology augments its resolution, thereby elevating the precision of the measurements. Moreover, the integration of a computerized system facilitates swift, real-time processing of the captured signals, proffering insights into functional viability, discernible inaccuracies, and the underlying technological rationale [12].

This expanded discussion provides a detailed and academic perspective on the complexities and solutions involved in gear measurement and control.

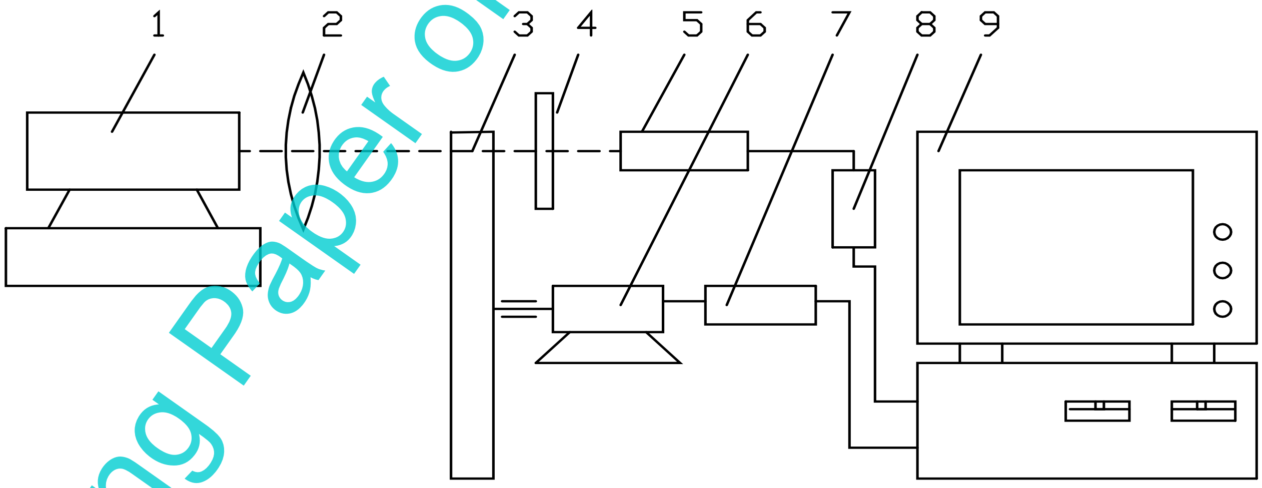

Fig.1. Principle of operation of a complex control device of small modular gears
1. Laser, 2. Optical system, 3. Controlled gear, 4. Aperture, 5. Optic-electronic receiver, 6. Motor, 7. Photo-raster converter, 8. Analog-to-digital converter, 9. Personal computer

The signal obtained on the Optic-electronic receiver as a voltage is proportional to the displacement of the tooth profile points on the line of engagement, so it is proportional to the accumulated error in the fundamental pitch. This signal can be measured either as time for passing points from two homonymous profiles of adjacent teeth or as pulses on the photoelectric converter 7.

In the first case, the controlled wheel must rotate at strictly constant angular velocity along the conditional working part of the tooth profile. While in the latter case, this is not necessary, but a high sensitivity PRC should be used. When the signal is measured as time, it represents a periodic function (voltage - time), or a period determined by the cog frequency. The envelope of this curve expresses the eccentricity of the gear, and the amplitude deviations inform about errors in the base step.

When the signal is received as a number of PRC pulses, the identification depends on the parameter measured. When determining the accumulated error in the base step **($f_{ptz}$)**, the expression is used for each part of the cog profile when the gear is reversible and requires a minimum dead stroke:

$$F_{ptz} = T_o - T_z = \frac{2\pi}{N} r_b j_z = q j_z; \; F_{ptz} = T_0^* - T_z^* = \frac{2\pi}{N} r_b^* j_z^* = q j_z^* \tag{1}$$

where:

**$T_o$ и $T^*_0$**- are the initial impulses of the PRC when passing the first cog of the gear with an asymmetric profile;
**$T_z$ и $T^*_z$** - the impulses of the PRC when passing the controlled homonymous profile;
**N** - the number of discrete PRC signals per rotation;
**$r_b$ и $r^*_b$** - the radii of the fundamental circles of the gear;
**$j_z$ и $j^*_z$** - the number of pulses counted by the PRC when measuring the gear with an asymmetric profile;
**q** - the value of the pulse in μm.

For the non-working part of the tooth profile, a dependency (1) is used, but the values of the non-working involute are placed in it. With a significant difference in the two profile angles (over 20°), it is recommended to use a different pitch of discretization and a different number of pulses for the two profiles, which ensures approximately equal accuracy.

In [4], [5], [6], [7], [8] the determination of the rectangular coordinates of the transitional curve for a symmetrical cog profile is given, solving the following system of partial derivatives for the instrument tip:

$$\begin{vmatrix} \dfrac{\partial f_1}{\partial t} \cdot \dfrac{\partial f_2}{\partial t} \\ \dfrac{\partial f_1}{\partial \gamma} \cdot \dfrac{\partial f_2}{\partial \gamma} \end{vmatrix} = 0 \tag{2}$$

where the coordinates **x** and **y** of the transition curve are functions of **t** – the wrapping angle and γ - the angle characterizing points from the rounding at the top of the instrument.

In the case of a preset classical instrument for making gears by the method of centroidal traversing, in a polar coordinate system, coinciding with the geometric center of the gear 1 or 2 and external engagement, the two evolvents are determined in the front section from:

- *First possibility of formation:*

$$\left|\begin{aligned} & inv\,\gamma_t = tg\,\gamma_t - \gamma_t \\ & r_{tb_{1,2}} = \frac{m_t . z_{1,2}}{2} . cos\ \ \alpha_t \\ & r_{te_{1,2}} = \frac{r_{tb_{1,2}}}{cos\ \ \gamma_t} \\ & \phi_{te_{1,2}} = \left(\frac{\pi}{2.z_{1,2}} + \frac{2.x_{1,2}.tg\,\alpha}{z_{1,2}}\right) + inv\,\alpha_t \end{aligned}\right. ; \quad \left|\begin{aligned} & inv\,\gamma_t^* = tg\,(-\gamma_t^*) + \gamma_t^* \\ & r^*_{tb_{1,2}} = \frac{m_t . z_{1,2}}{2} . cos\ \ \alpha_t^* \\ & r^*_{te_{1,2}} = \frac{r^*_{tb_{1,2}}}{cos\ \ \gamma_t^*} \\ & \phi^*_{te_{1,2}} = \left(\frac{\pi}{2.z_{1,2}} + \frac{2.x_{1,2}.tg\,\alpha^*}{z_{1,2}}\right) + inv\,\alpha_t^* \end{aligned}\right. \tag{3}$$

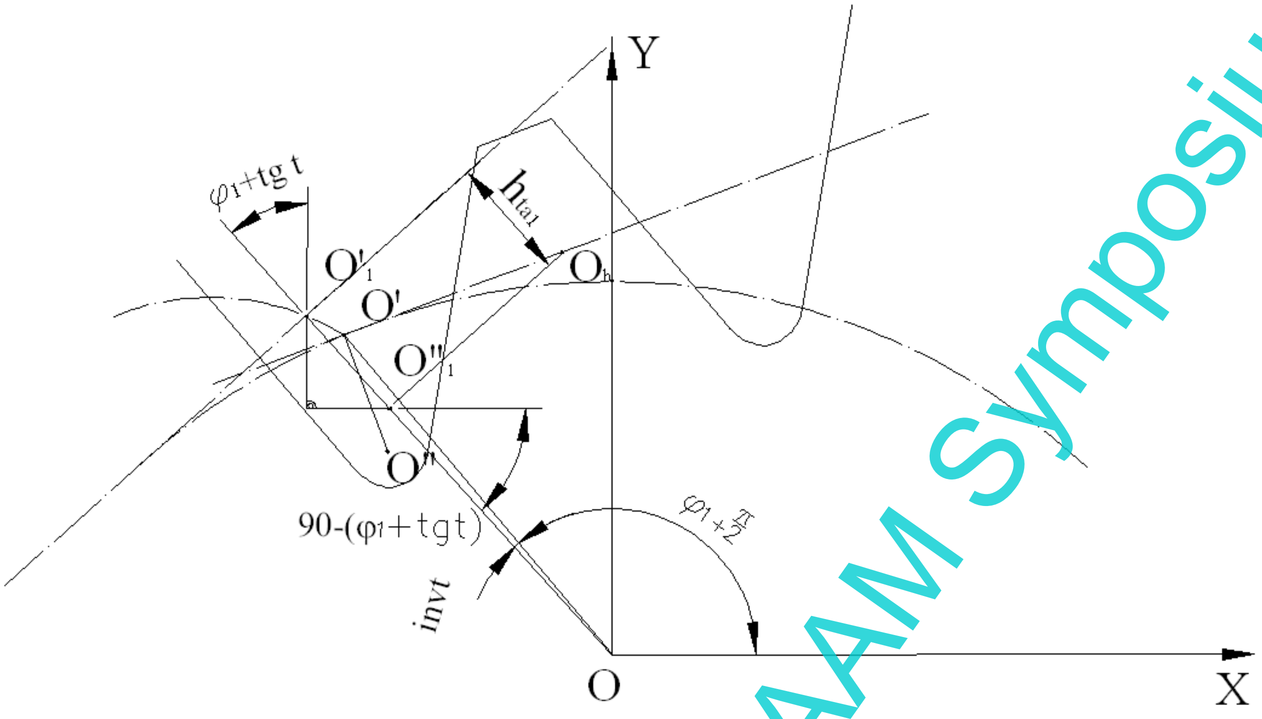

Fig. 2. Computational scheme for determining the parameters of the transitional curve

- *Second possibility of formation:*

$$\left|\begin{array}{l} inv\,\gamma_t = tg\,\gamma_t - \gamma_t \\ r_{tb_{1,2}} = \frac{m_t.z_{1,2}}{2}.\cos\ \alpha_t \\ r_{te_{1,2}} = \frac{r_{tb_{1,2}}}{\cos\,\gamma_t} \\ \phi_{te_{1,2}} = \left(\frac{\pi}{2.z_{1,2}} + \frac{2.x_{1,2}.tg\,\alpha}{z_{1,2}}\right) + inv\,\alpha_t \end{array}\right. ; \quad \left|\begin{array}{l} inv\,\gamma_t^* = tg\,(-\gamma_t^*) + \gamma_t^* \\ r_{tb_{1,2}}^* = \frac{m*_t.z_{1,2}}{2}.\cos\ \alpha_t^* \\ r_{te_{1,2}}^* = \frac{r_{tb_{1,2}}^*}{\cos\,\gamma_t^*} \\ \phi_{te_{1,2}}^* = \left(\frac{\pi.m_{t_{1,2}}^*}{2..m_t.z_{1,2}} + \frac{2.x_{1,2}.tg\,\alpha^*}{z_{1,2}}\right) + inv\,\alpha_t^* \end{array}\right. \tag{4}$$

$$m_{t_1}^* + m_{t_2}^* = 2.\,m_t$$

where $\mathbf{r_{te1,2}}$ and $\mathbf{r^*_{te1,2}}$ are radius-vectors of the involutes in the polar coordinate systems, on **3K 1** and **2** of the gear transmission;

$\boldsymbol{\varphi_{te1,2}}$ and $\boldsymbol{\varphi^*_{te1,2}}$ – the initial angles of the involutes on the base circles, in the frontal section;

$\boldsymbol{\gamma_t}$ and $\boldsymbol{\gamma^*_t}$ – the wrap angles when the lines of engagement roll without slipping on the base circles of the gears of the transmission;

$\boldsymbol{\alpha_t}$ and $\boldsymbol{\alpha_t^*}$ - profile angles of the tool with which the gears are made by the method of centroidal wrapping in the frontal section;

$\mathbf{z_{1,2}}$ – the number of teeth on gear 1 or 2 of the transmission;

$\mathbf{m^*_t}$ - is the frontal module of the output contour with non-uniform thickness, corresponding to the profile angle αt;

The obtaining of Cartesian coordinates xte1,2, x*te1,2, yte1,2 and yte1,2 in the absolute coordinate system of the theoretical involutes is performed by:

$$\left|\begin{array}{l} x_{te_{1,2}} = r_{te_{1,2}}.\sin\left(inv(t) + \frac{\pi}{2} + \phi_{te_{1,2}}\right) \\ y_{te_{1,2}} = r_{te_{1,2}}.\cos\left(inv(t) + \frac{\pi}{2} + \phi_{te_{1,2}}\right) \end{array}\right. ; \quad \left|\begin{array}{l} x_{te_{1,2}}^* = r_{te_{1,2}}^*.\sin\left(inv(t^*) + \frac{\pi}{2} + \phi_{te_{1,2}}^*\right) \\ y_{te_{1,2}}^* = r_{te_{1,2}}^*.\cos\left(inv(t^*) + \frac{\pi}{2} + \phi_{te_{1,2}}^*\right) \end{array}\right. \tag{5}$$

For better accuracy, it is recommended to calculate 100 points in Cartesian coordinates for each of the two dissimilar involutes.

The significance of the profile error $(\mathbf{f_{fri}})$ is determined within the active section of the line of engagement at a given angle of rotation separately for the both parts of the gear profile:

$$\varphi = 2\pi j_i/N;\ \varphi^* = 2\pi j^*_i/N^* \tag{6}$$

The error is determined as the difference between the nominal and actual displacement for each of the two different profiles:

$$f_{fri} = T - T_{gi} = q(j_i - j_{gi}) \quad ; \qquad f^*_{fri} = T^* - T^*_{gi} = q^*(j^*_i - j^*_{gi}) \tag{7}$$

where $\mathbf{j}_i$ and $\mathbf{j}^*_I$ are the initial values, equal to the number of pulses on the RPM at the start signal;
$\mathbf{j}_{gi}$ and $\mathbf{j}^*_{gi}$ - the number of pulses on the RPM between the initial pulse and the actual passage of the corresponding gear profile.

The discrete value of the kinematic error is determined, consecutively for the two profiles, from the expression:

$$F_{iz} = F_{ptz} + f_{fri} = q[j_z + (j_i - j_{gi})]; F^*_{iz} = F^*_{ptz} + f^*_{fri} = [j^*_z + (j^*_i - j^*_{gi})] \tag{8}$$

Post-processing of the signal can be carried out by computer analysis of frequency characteristics, rapid Fourier Transformation, Cepstral Analysis, in order to seek the influence of the technological process on the accuracy of gears.

## 3. Conclusion

The advancement and introduction of the proposed non-contact method and device for gauging the accuracy of small-module gears and transmissions mark a pivotal evolution in the domain of precision engineering. The significance of this innovation can be enumerated in the following facets:

Enhanced Precision and Dependability: At its core, the method transcends conventional paradigms, offering unparalleled accuracy in gauging the geometrical intricacies of gears. This isn't limited to mere pitch and profile discernment but spans the realms of kinematic precision and operational fluidity. Such meticulousness not only underscores its potential but sets a precedent in measurement standards.

Technological Insights: By bridging gear manufacturing processes with their resultant accuracy metrics, the method lends itself to a profound analytical prowess. This capability doesn't just illuminate the intricacies of gear production but paves the way for iterative enhancements in both production and quality assurance protocols.

Mitigating Human-induced Anomalies: One of the perennial challenges in precision measurements has been human-induced errors. The contactless nature of the method, juxtaposed against conventional contact and double-flank methodologies, drastically reduces these anomalies, thereby bolstering the reliability quotient of the results.

Advancing Automation: Automation isn't merely about efficiency but about repeatability and consistency. The new device, by virtue of its design, elevates automation standards in measurement processes, translating to enhanced throughput, consistency, and resource optimization.

Versatility in Application: Beyond its intrinsic merits, the method's adaptability across diverse industries, be it automotive, aerospace, or heavy machinery, underscores its universal relevance. This wide applicability augments its value proposition, hinting at its potential ubiquity in the coming times.

Holistic Measurement Capability: The device, in its essence, isn't just about passive measurement. It actively processes signals to discern gear pitch, profile, and kinematic fidelity. Moreover, its ability to draw correlations between technological facets and gear accuracy, all the while negating the need for reference gears and specialized apparatus, is laudable.

In retrospection, this groundbreaking method and apparatus don't just represent an incremental addition to the gear and transmission measurement cosmos. They signify a paradigm shift, providing tools that are not only precise and reliable but are poised to redefine manufacturing and control processes for gears and transmissions.

### Future Directions:

As industries evolve and the demand for precision grows, the implications of the findings in this study present several exciting avenues for further research:

Integration with Machine Learning and AI: Leveraging artificial intelligence could further optimize the process, allowing for predictive analyses, anomaly detection, and self-calibration.

Scalability: Exploring how this technology can be scaled or adapted to measure larger module gears or other complex mechanical components would be beneficial.

Material Interaction Analysis: It would be interesting to see how different gear materials interact with the non-contact method, potentially leading to tailored measurement techniques for diverse materials.

Interdisciplinary Applications: The potential of applying this method to realms beyond gears, possibly in sectors like microelectronics or nanotechnology, could be explored.

These prospective directions not only stem from the core findings of this research but are a testament to the profound impact the study could have on the broader scientific community.Acknowledgments

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