Potentials and challenges of integrated optical deformation sensors with TIR Prism Rods

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Integrated TIR prism rod sensors allow for the direct and compact monitoring of torsion and bending in highly stressed shafts. These sensors offer high potential in terms of integration, precision, and environmental resistance. The most significant challenges are ensuring optical accuracy, reliable energy and data transmission, and effective signal evaluation.

1 Motivation and Objective

Optical sensors based on total internal reflection (TIR) in prism rods offer a promising solution for the integrated detection of mechanical deformations. Unlike conventional concepts, which are constrained by limited space or indirect measurement, TIR-based systems enable direct, localized sensing in closed or rotating structures.

Structure-integrated condition monitoring is a key enabler in the development of intelligent and durable mechanical systems. Conventional sensor concepts often reach their limits, particularly in dynamically loaded components such as drive shafts, due to limited installation space, difficult mounting conditions or environmental interference. Moreover, they typically provide only indirect information about the internal mechanical state.

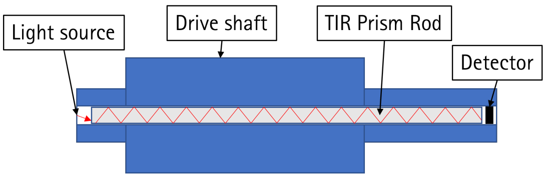

***Fig. 1** Concept of an integrated TIR prism rod sensor for in-situ deformation measurement within a drive shaft.*

In the context of "gentelligent" systems [1], which autonomously record and store condition data throughout production and operation to enable technical inheritance in future product generations, integrated, real-time measurement solutions are gaining importance.

A promising approach is the use of optical deformation sensors based on TIR prism rods, as shown conceptually in Fig. 1. Positioned near the neutral axis, where material contribution to strength is minimal, these sensors enable direct, internal stress detection without significant impact on structural integrity.

This article highlights the potential of this sensor concept with respect to integrability, measurement accuracy, and environmental robustness. Key challenges are also addressed, particularly in terms of geometric tolerances, energy and data interfacing, and signal evaluation.

2 Working principle of the Prism Rod sensor

The sensor is based on a transparent prism rod into which light is coupled at a defined angle. Inside the rod, the light beam undergoes total internal reflection at the lateral surfaces, creating a helical propagation path determined by the rod's geometry. The light path under TIR conditions is illustrated in Fig. 2.

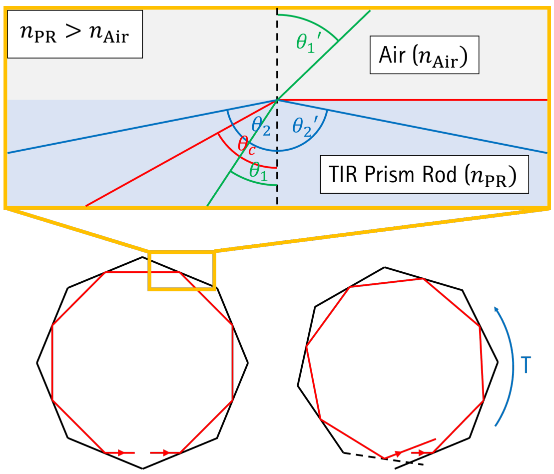

***Fig. 2** Reflections in the projected cross-section of the TIR prism rod with polygonal base. **Left**: without torsion, **right**: with deformation of the lateral surfaces caused by torsion.*

Mechanical deformation of the host structure, such as bending or torsion, alters the geometry of the embedded rod and the angles at the reflection interfaces. These changes affect the beam trajectory, leading to a shift in the position, angle, and intensity of the outgoing light. This behavior is shown in Fig. 3, which illustrates output projections under different torsional states.

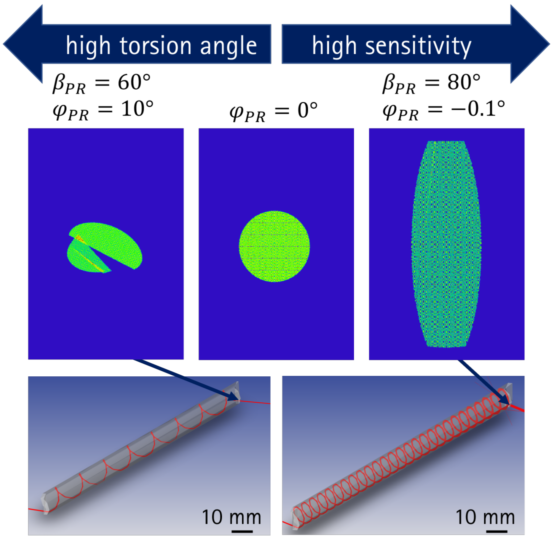

Fig. 3 *Representation of the application range. High pitch angles β_{PR} enable high sensitivity at small negative torsion angles φ_{PR}, while high torsion angles in the positive direction can be monitored.*

Initial experimental validation with a PMMA prism rod has confirmed the sensor's functional principle using intensity-based signal evaluation. Variations in mechanical loading produced consistent, measurable changes in the total light intensity at the detector, demonstrating the feasibility of deformation detection through optical coupling effects. Future work will extend the evaluation to include spatial characteristics of the output signal.

3 Potential and Challenges

The TIR prism rod sensor offers several advantages over conventional deformation measurement technologies. Its full integration into mechanical components enables condition monitoring without additional installation space or external attachments. Positioned near the neutral axis, the sensor minimally affects structural integrity. [2]

Unlike surface-mounted systems, the optical principle allows internal, deformation-sensitive measurements with more accurate and localized information about the mechanical load state. The internal light path is protected against dust, humidity, and electromagnetic interference, which enhances robustness in harsh environments.

A key advantage is the sensor's high optical sensitivity. [3] Even small geometric changes from torsion or bending produce measurable signal shifts, enabling early detection of stress accumulation or fatigue and supporting predictive maintenance.

However, several technical challenges remain. Sensor function depends on precise geometry and surface quality of the prism rod. Small deviations during manufacturing, especially at coupling and reflection points, can impact beam guidance and signal consistency.

Energy supply and data transmission must be integrated without compromising mechanical performance. This requires compact, robust solutions for wireless energy transfer and optoelectronic readout.

Finally, the output must be reliably interpreted under variable mechanical and environmental conditions. This calls for calibration strategies that link optical signals to specific load states. Addressing these challenges is key to unlocking the sensor's full potential, especially in the context of intelligent and gentelligent systems.

4 Conclusion and outlook

This work presented an integrated optical deformation sensor based on total internal reflection in prism rods. The concept enables internal, contactless stress detection with high sensitivity and minimal structural impact. Initial experiments confirmed functionality using intensity-based signal evaluation.

The approach shows strong potential for condition monitoring in demanding applications. Future work will focus on spatial signal analysis, calibration under defined loads, and integration of energy and data interfaces. The sensor will also be implemented in a real component to assess performance under practical conditions.

5 Acknowledgement

This research is funded by the German Research Foundation (DFG) under Germany's Excellence Strategy within the Cluster of Excellence PhoenixD (EXC 2122, Project ID 390833453).

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