

Hao Zhang

## Laser Interference Sensor for 4D Shape and Vibration Measurement with Camera Based Uncertainty Reduction

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Vibration Measurement with Camera Based  
Uncertainty Reduction**

**Hao Zhang**

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献给我的母亲

*To my mother*



## Abstract

The measurement of absolute shape, deformation and vibration of fast moving objects for instance turning shafts, rotating workpieces and milling tools in CNC machines is a significant task for the development of manufacturing technology and process monitoring in Industry 4.0. These measurements can be achieved by using the laser Doppler distance sensor with phase evaluation (PLDDS), as the sensor enables simultaneous axial distance and lateral velocity measurement of moving rough surfaces with micron uncertainty and with a single sensor head.

In this dissertation, the PLDDS based measurement technique for the in-situ measurement of absolute 4D shape and tool tip vibration are investigated. The measurement uncertainty and uncertainty budget are investigated with numerical simulation and experiments. It is shown that the achievable measurement uncertainty is limited by the speckle effect and temperature drifts. To overcome the uncertainty limitation due to the speckle effect, a speckle separation technique by using cameras instead of single photo detectors is proposed. Thus, the speckle signals can be detected separately by using a proposed image-processing algorithm and the velocity and distance uncertainty decreases with the square root of the speckle number. A fringe spacing calibration method that can be conducted in-situ is realized to eliminate the fringe spacing uncertainty resulting from temperature drifts. Coherent fiber bundles are employed to forward the scattered light towards the cameras. This removes the cameras from the sensor head and therefore enables a compact and passive sensor head with keyhole access. Compared with a photo detector based sensor, the camera based setup allows to decrease the measurement uncertainty by the order of one magnitude, which is verified by numerical simulations and experimental results. As a result, the absolute shape uncertainty of rotating workpieces can be reduced to about 100 nm.

By extending the measurement volume, a non-scanning, 4D laser line PLDDS is designed. Compared to the conventional PLDDS, the measurement range in a single measurement is increased by a factor of 40. A 4D shape measurement of a rotating workpiece is achieved by employing the proposed sensor without scanning along the rotational axis. This means the sensor can perform simultaneous 3D absolute shape and time resolved deformation measurements at multiple surface segments along the rotational axis. Meanwhile, the measurement uncertainty and position deviation due to mechanical scanning of the sensor are completely avoided.

Moreover, a measurement system for investigating the tip vibration inside of a CNC milling machine under different rotational speeds is developed. It consists of an automated impact unit generating vibrations with a known force and a PLDDS. A signal processing algorithm is proposed. It enables simultaneously bi-directional vibration measurements at non-continuous surface of tool tip with measurement rates up to 50 kHz combined with the measurement system. The dynamic behavior parameters of the tool are estimated depending on the geometric relationship of the displacement in two directions and can be used for machine modelling. Furthermore, the sensor can be used for detecting undesirable milling tool eccentricity, thermal deformation and cutter deterioration in the future.



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