# Tool tip to spindle-integrated sensor transfer function prediction using receptance coupling

Prof. Christian Brecher, Prateek Chavan, Anton Strachkov*, Dr.-Ing. Marcel Fey, WZL der RWTH Aachen, Aachen, Germany
*Corresponding author

## Executive summary

The force applied to the tool tip of the machine tool as a central and important parameter for machining enables detailed insight into the milling process. The process force is important for different applications such as a virtual workpiece quality monitoring, condition monitoring of the main spindle and machine tool components, tool wear, etc. A method to measure the process force uses spindle-integrated displacement sensors (SIDS).
Non-contact displacement sensors integrated in the housing of a milling machine main spindle can measure the relative displacement between the spindle shaft and the housing during machining. For this paper, eddy-current displacement sensors are integrated into the main spindle. Six displacement sensors (three radial, three axial) form a measurement system to capture relative displacement between the rotating shaft and the housing of the main spindle of the machine tool. With this measurement system the three translational displacements x, y, z, and two rotational displacements $\Theta_x$, $\Theta_y$ are measurable. If the dynamic transfer function between a force at the milling tool tip and the high-resolution displacement measured at the sensors is known, dynamic process forces can be computed based on the measured deflections. Dynamic characteristics of the mechanical spindle-tool structure depend significantly on the tool properties. However, gathering the dynamic characteristics requires the measurement of the transfer function between the tool tip and SIDS for each milling tool. A disadvantage of this approach is the amount of time needed to the experimental estimation and analysis of the measured dynamic characteristics of the spindle-tool structure.
This paper provides an approach for predicting the tool tip-SIDS transfer function for different milling tools by extending an exsisting receptance coupling framework to include the coupling plane of the SIDS. By modeling the dynamic properties of each tool this way, the time consuming measurement of the transfer function for each tool can be avoided. In the proposed approach, a one-time measurement of the transfer function between the spindle-holder interface and the SIDS is required in addition to the receptance matrices necessary for conventional tool coupling. Due the spatial separation (non-collocation) between the spindle-holder interface and the SIDS, a reduced signal to noise ratio is expected. Therefore, the quantification and propagation of the measurement uncertainty from the measured transfer function to the predicted tool tip-SIDS transfer function are also considered in this paper. The proposed approach is implemented on a 5-axis machine tool with spindle-integrated sensors and an HSK-A63 interface. The validation of the approach conducted by comparing the predicted and measured frequency response functions for four different holder-tool assemblies (two tools and two appropriate blanks 10 mm and 16 mm diameter) in the frequency range relevant for milling. The accurate prediction of the transfer functions for end mill shrink-fit holders shows the potential of the proposed approach for process force estimation.

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