Prediction of Limit Cycles of Lateral Oscillations in Drilling Processes: Numerical Analysis and Experimental Validation

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Summary. Several experimental investigations have shown that drilling processes are likely to develop limit cycles at approximately integer multiples of the tool rotation frequency. As a consequence, the whirling oscillations generate N-lobed holes. In literature, linear models are presented to explain the onset of the instability and to analyze the exponential growth or decay of this whirling phenomenon. However, to predict the orbit of the limit cycles, more involved models are required, which take the relevant nonlinearities into account [1,2,3]. This work deals with a nonlinear drilling model. The cutting forces involve the so-called regenerative effect, which leads to a delay differential equation (DDE). Nonlinear rubbing effects, which occur at the contact under the cutting edge, are considered. Also, the contact at the bore hole wall is taken into account and its stabilizing effect on the drilling process is shown. The presented drilling model is able to predict the bore hole shape as well as the circularity of a real drilling process with high accuracy. The model can be used to optimize the drilling parameters and the shape of the tool in order to improve real drilling processes.

Motivation

Basically, two phenomena are distinguished in cutting tool vibrations: (i) Chatter which appears approximately at the tools torsion natural frequency and (ii) lateral oscillations at odd multiples of the tool rotation frequency.
Currently, often two machining steps are necessary to create bore holes with high precision: Drilling and finishing afterwards, for example by reaming, to reach the required accuracy.
To analyze and clearly understand the physical effects occurring in drilling processes and to optimize these processes (i.e. reducing the amplitudes of the lateral oscillations by optimization of the tool shape and cutting parameters), a nonlinear two degree of freedom model is applied in the current work. The model yields a system of coupled delay differential equations, which is solved numerically.

Physical Model

The drilling model includes the mass, structural damping and stiffness of the tool as well as external forces due to the contact with the workpiece. The external forces consist of the cutting force, the rubbing force and the contact force at the bore hole wall.
The cutting force is assumed to be proportional to the uncut chip area and obtained experimentally similar to an experimental setup introduced by *Bayly et al.* [1]. Since the uncut chip area depends on the current position of the tool and the position at the previous cutting-edge passage, a time delay is generated in the differential equations.
Rubbing occurs due to material compression under the cutting edge. *Chiou* and *Liang* [4] suggested a linear rubbing force model for turning processes. Their approach is extended to a nonlinear model and adapted to oblique cutting, which leads to a dependence on the feed rate, cutting velocity, current tool vibrations and tool wear.
Previous experimental investigations by *Volz et al.* [3] have shown a strong correlation between the land width of the tool, which supports it against the bore hole surface, and the amplitude of the lateral oscillations. Therefore, a model for the wall contact is introduced. On one hand, this contact model takes elastic effects into account. On the other hand, a nonlinear damper - similar to the rubbing force model - is integrated, which incorporates the energy dissipation in the contact.

Experimental Investigations

The cutting force model is based on experimental data. The drilling tests were conducted in aluminum alloy (AlSi7Mg0.3) using a 10 mm diameter sold carbide twisted drill with four lands, a TiAlN top coating and a ZrN deck layer. Since the uncut chip area increases linearly with the feed rate, cutting force tests with different feed rates were performed. The measured cutting forces are plotted over the corresponding uncut chip areas and the slope of this plot yields the approximately linear relation of the change in force per change in uncut chip area. In the numerical simulations, this slope is used as proportionality factor to calculate the cutting force on cutting lip segments with the aid of the current and the delayed tool position.

Simulation

The DDE is discretized with an implicit integration scheme, namely with a variable-step size, variable-order BDF solver. In order to handle the time delay, the following strategy has been applied.
The simulation time is split into equal intervals, where the interval length corresponds to the time delay. In each interval the simulation results (displacements and velocities) from the previous interval are known and used to take the delay part in the equations of motion into account, which may then be interpreted as an external time function. The problem is

the initialization of the simulation, because the initial conditions must be known as a function of time over one delay period. Therefore, the simulation is firstly started with the trivial solution of the DDE. In a second step, a rectangular-shaped external force is applied in order to initialize the lateral vibrations.

Results and Conclusions

In the simulations, the contact stiffness parameters used in the bore hole wall contact model as well as for the rubbing force model are adopted from a turning test presented by *Chiou* and *Liang* [4]; the parameters have been slightly modified and adapted to fit the drilling process. The feed rate, cutting velocity and pre-hole diameter are varied and the damping is increased successively to describe the behavior of chip flow and coolant water in the drilling process. The damping has no significant influence on the amplitude of the appearing limit cycles, but on the frequency of the oscillation and therefore on the bore hole shape.

A comparison between a simulation and measurements is depicted in *Figure 1*. In this case, the ratio between the limit cycle frequency and the tool rotational frequency is approximately three. A transformation from the tool tip movement to the outer cutting edges represent the emerging bore hole contour as a three-lobed hole. The shape and magnitude of the simulated bore holes (blue) show a high accordance with the experimental results (red) with respect to the circularity. For a better visualization, the plot is stretched by the factor 41 around the gauss circle of the simulated data (black solid line). The drilling experiments have been carried out with a pre-hole diameter of 4 mm. Note that the circularity is defined as radial distance between the outermost (outer blue dashed line) and innermost (inner blue dashed line) circles.

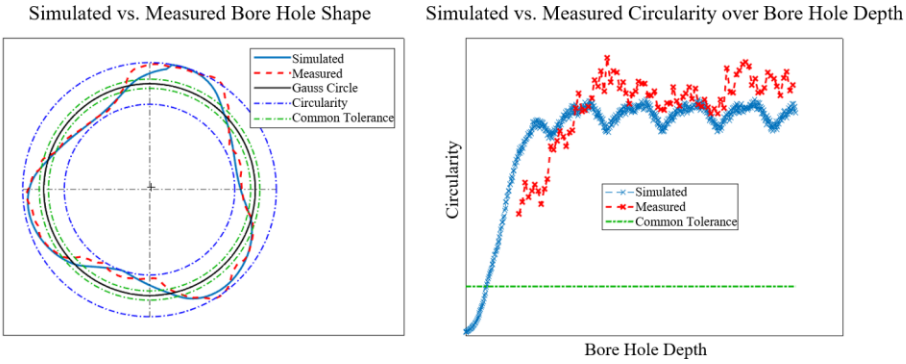

Figure 1: Left: Simulated (blue) vs. measured (red) bore hole shape at a specific bore hole depth. Right: Simulated (blue) vs. measured (red) circularity over bore hole depth and a common tolerance for drilling processes (green).

Summarizing: The presented drilling model is able to predict the circularity of drilling processes with a special consideration of lateral oscillations of the drilling tool tip. Within the validation of the implemented model, a high agreement of the results from the simulation with those from the machining tests could be achieved.

In a following step, a great range of parameter studies, including the cutting parameters and the shape of the tool, can be conducted with the numerical model to identify the most important parameters for improving the drilling process. Possibly the process can be optimized to reach a specified tolerance without an additional reaming step.

References

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