Limit Cycle Oscillations in Drilling Processes: Simulation and Experimental Validation

Dennis Heyser & Bernhard Schweizer
Institute of Applied Dynamics, Technical University of Darmstadt, Germany

Motivation

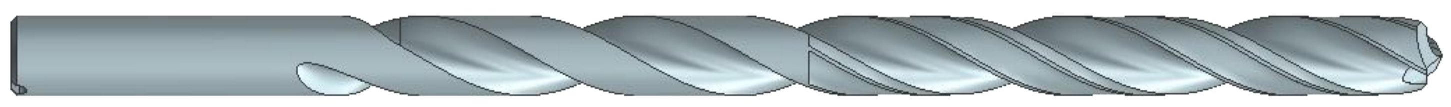
Task:

- Improved physical comprehension of nonlinear vibrations in drilling processes
- Prediction of limit cycle oscillations and experimental validation

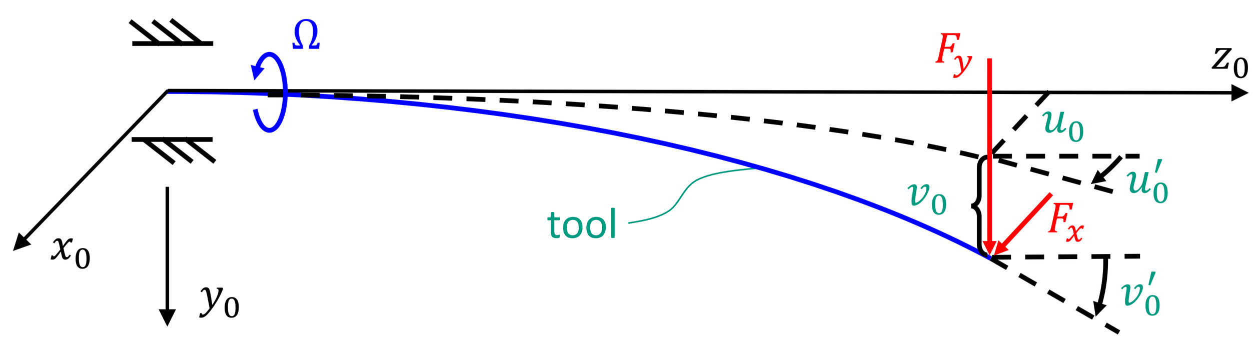
Mechanical Model

Mechanical Model:

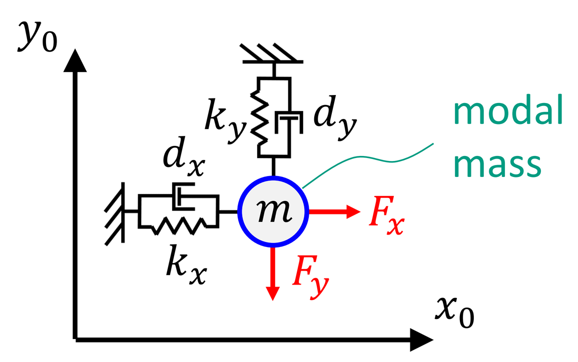
- Complex tool geometry



- Contact & tool stiffnesses: Beam model



- Equations of motion: Nonlinear modally reduced 2-DOF model

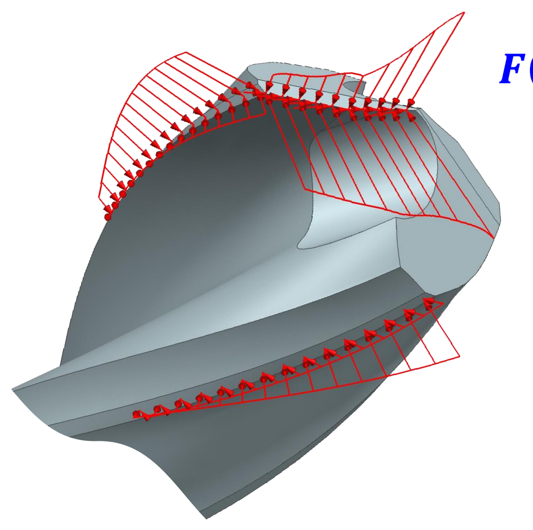


Equations of Motion in Rotating Frame:

$$M\ddot{x}(t) + (D + 2M\Omega)\dot{x}(t) + (K + D\Omega - \Omega^2 M)x(t) = F(x(t), \dot{x}(t), t, \tau)$$

tool properties & process parameters — tool / workpiece interaction

Tool / Workpiece Interaction Considering Real Tool Geometry:



$$F(x(t), \dot{x}(t), t, \tau) = \sum_{i=1}^{N} K_{ci}\left(x(t) + x(t-\tau)\right) + F_R(v(t)) + F_{W,elastic}(x(t)) + F_{W,dissipative}(v(t))$$

- delayed time $t - \tau$
- $\sum_{i=1}^{N} K_{ci}\left(x(t) + x(t-\tau)\right)$: cutting force
- $+F_R(v(t))$: process damping
- $+F_{W,elastic}(x(t))$: elastic contact
- $+F_{W,dissipative}(v(t))$: dissipative contact

Absolute Velocity of Tool Tip:

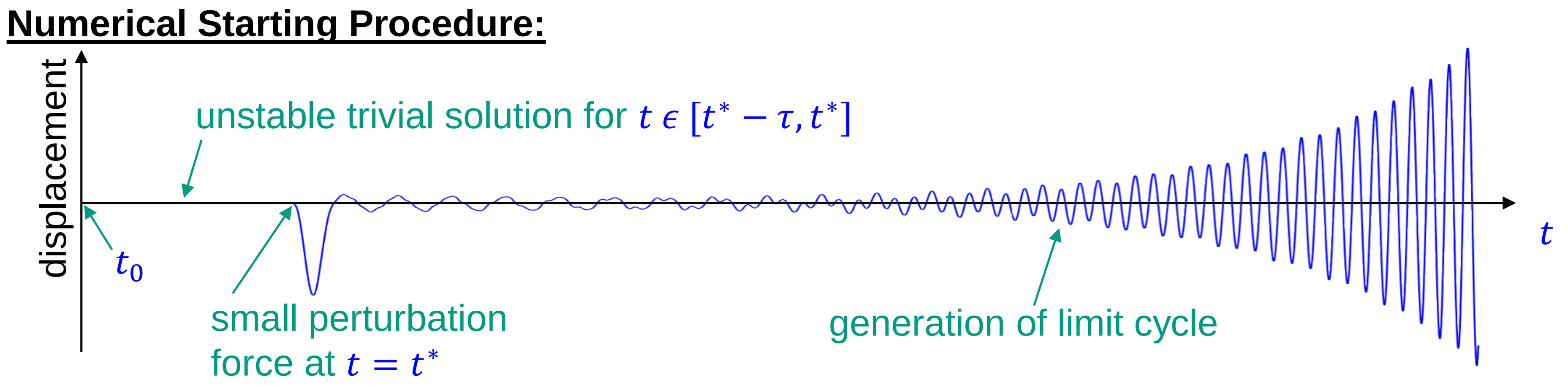
$$v(t) = \dot{x}(t) + \Omega\, e_z \times \left(R e_r + x(t)\right) + \frac{f\Omega}{2\pi} e_z$$

Numerical Approach

Time Integration of Numerical Model:

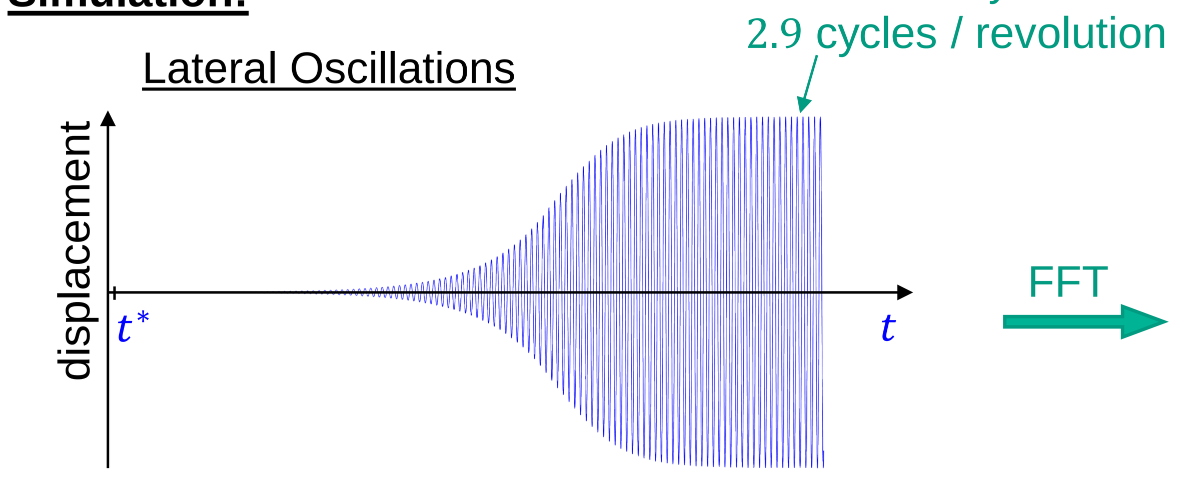
- Equations of motion:
  System of nonlinear **D**elay **D**ifferential **E**quations (**DDE**)
- Solve **DDE** by implicit time integration scheme:
  Appropriate initialization procedure at $t = t_0$

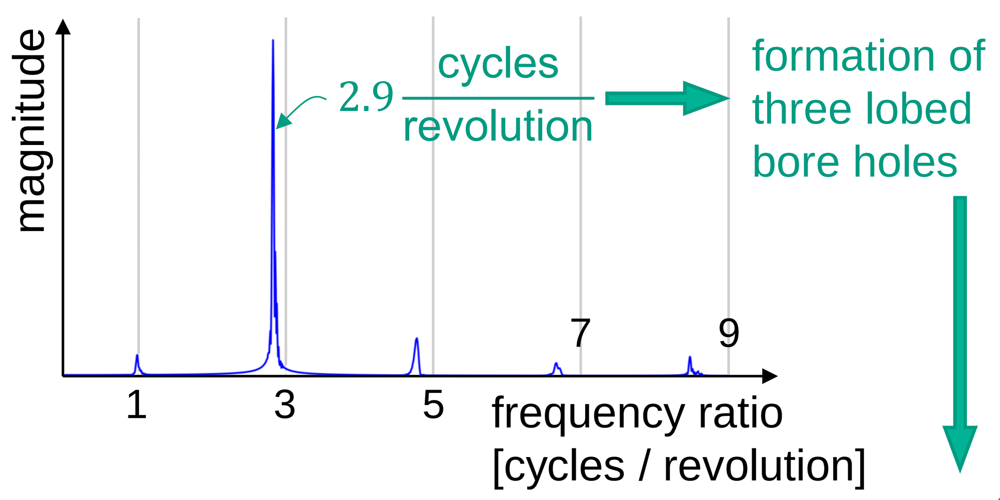
Numerical Starting Procedure:

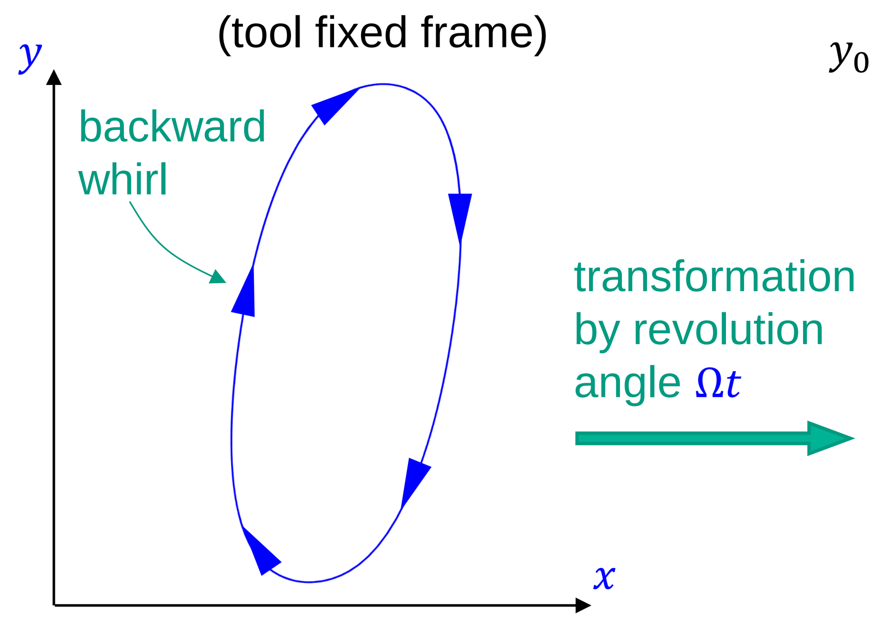


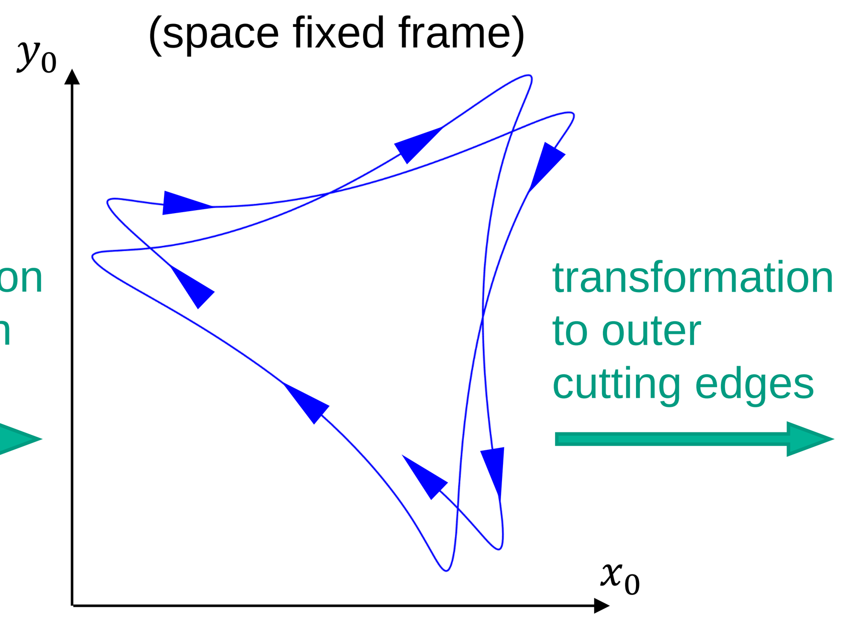
Results and Experimental Validation

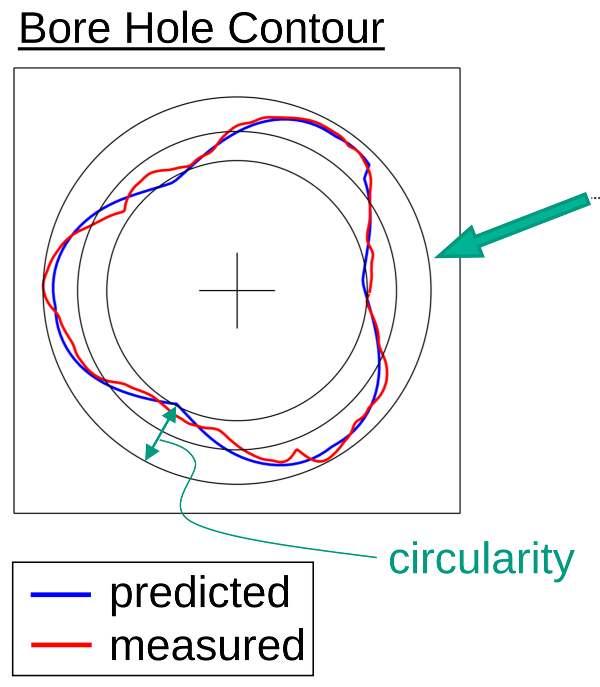
Simulation:



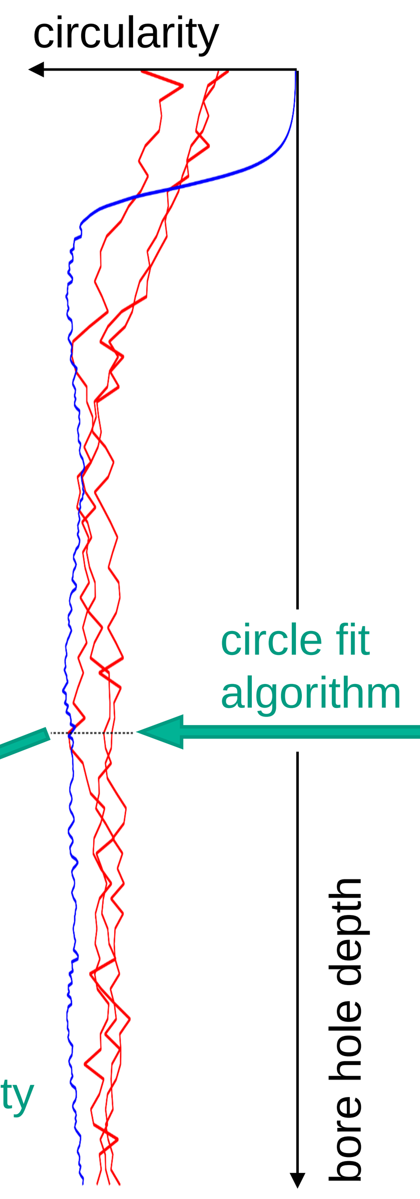




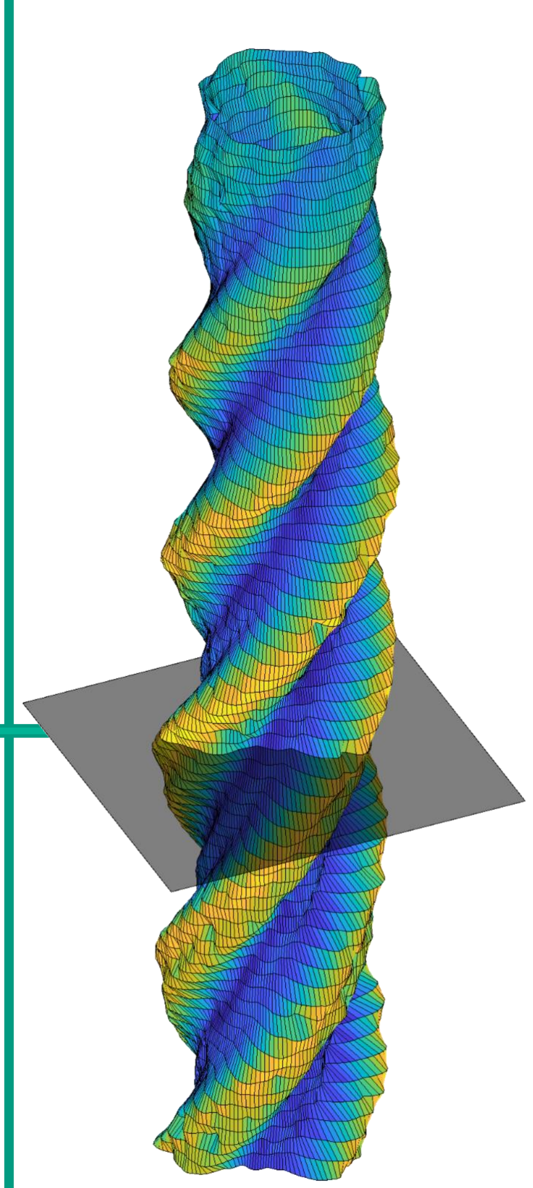




Simulation vs. Measurement:



Measurement:



[1] Altintas, Y.: Manufacturing Automation; Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design, 2nd Ed.; Cambridge University Press: New York, 2012.
[2] Bayly, P.V.; Lamar, M.T.; Calvert, S.G.: Low-Frequency Regenerative Vibration and the Formation of Lobed Holes in Drilling. Journal of Manufacturing Science and Engineering, 2002, Vol. 124, pp. 275–285.
[3] Heyser, D.: Spiralbohrer (patent submitted: June 2021, expected release: December 2022); German Patent No. 10 2021 115 315.8; Deutsches Patent- und Markenamt, 2022.