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Generalized modeling of drilling vibrations. Part I: Time domain model of drilling kinematics, dynamics and hole formation

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Abstract

This two part paper presents a comprehensive exercise in modeling dynamics, kinematics and stability in drilling operations. While Part II focuses on the chatter stability of drilling in frequency domain, Part I presents a three-dimensional (3D) dynamic model of drilling which considers rigid body motion, and torsional–axial and lateral vibrations in drilling, and resulting hole formation. The model is used to investigate: (a) the mechanism of whirling vibrations, which occur due to lateral drill deflections; (b) lateral chatter vibrations; and (c) combined lateral and torsional–axial vibrations. Mechanistic cutting force models are used to accurately predict lateral forces, torque and thrust as functions of feedrate, radial depth of cut, drill geometry and vibrations. Grinding errors reflected on the drill geometry are considered in the model. A 3D workpiece, consisting of a cylindrical hole wall and a hole bottom surface, is fed to the rotating drill while the structural vibrations are excited by the cutting forces. The mechanism of whirling vibrations is explained, and the hole wall formation during whirling vibrations is investigated by imposing commonly observed whirling motion on the drill. The time domain model is used to predict the cutting forces and frequency content as well as the shape of the hole wall, and how it depends on the amplitude and frequency of the whirling vibration. The model is also used to predict regenerative, lateral chatter vibrations. The influence of pilot hole size, spindle speed and torsional–axial chatter on lateral vibrations is observed from experimental cutting forces, frequency spectra and shows good similarity with simulation results. The effect of the drill–hole surface contact during drilling is discussed by observing the discrepancies between the numerical model of the drilling process and experimental measurements.

Keywords: Drilling; Lateral vibration; Chatter; Time domain simulation; Torsional; Axial

1. Introduction

Tool vibrations during drilling can cause errors in hole size and shape that may be unacceptable. Fig. 1 shows four different hole types generated by a regular twist drill. The hole shown in Fig. 1a was drilled with a very short drill bit, is perfectly round, and has a smooth surface without drill vibration marks. Fig. 1b shows a sunray pattern obtained from an unstable cut (chatter), due to coupled vibrations in axial and torsional directions [1]. The hole is round as in Fig. 1a. Fig. 1c shows a three-sided polygon shape at the bottom and a smooth surface, generated by lateral whirling vibrations.

Fig. 1d shows a three-sided hole with sunray pattern at the bottom, left by a drill undergoing torsional–axial chatter as well as lateral whirling vibrations. The holes shown in Figs. 1b–d were drilled with a slender drill bit. These photographs show that torsional–axial and lateral whirling vibrations can occur independently or at the same time. Detailed understanding of the mechanisms that cause these drill vibrations will allow for improvements in speed and precision of drilling operations. Accurate prediction of the cutting force system, the tool dynamic properties, the chip generation and hole formation mechanisms are essential for realistic numerical simulation of the drilling process.

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Nomenclature

b_1, b_2	radial depth of cut flute 1, flute 2 (mm)
Δb	elemental width of cut (mm)
b_t	back taper of drill (reduction of flute diameter) (μm)
C	damping matrix of drill bit (N s/m)
D	drill diameter (mm)
e	amplitude of imposed circular whirling motion (μm)
F_x, F_y, F_z	cutting forces acting on tool tip (N)
$F_{t_i}, F_{r_i}, F_{z_i}$	tangential, radial and axial force acting on drill flute i (N)
F_{wi}	contact force between drill and hole wall (N)
f_c	chatter frequency (Hz)
f_r	feedrate (mm/rev)
Δf_r	feedrate increment (mm)
f_s	spindle frequency (Hz)
h_f	chip thickness (mm)
f_w	whirling frequency in fixed coordinate system (Hz)
$\overset{r}{f}_w$	whirling frequency in coordinate system rotating with the tool (Hz)
h_{lip}	distance from drill tip to start of cutting flutes (mm)
K	stiffness matrix of drill bit (N/m)
k	time step (—)
k_{cz}	specific thrust force (N/mm^2)
k_{cp}	specific torque force (N/mm^2)
k_{ct}	specific tangential force (N/mm^2)
k_{cr}	specific radial force (N/mm^2)
k_i	stiffness (N/m)
k_m	number of modes included in vibration direction (—)
k_{ZFz}	direct axial stiffness of drill bit (axial due to thrust) (N/m)
k_{ZTc}	cross axial stiffness of drill bit (axial due to torque) (Nm/m)
$k_{\theta Tc}$	direct torsional stiffness of drill bit (torsional due to torque) (N m/rad)
$k_{\theta Fz}$	cross torsional stiffness of drill bit (torsional due to thrust) (N/rad)
$k'_{f,1}$, $k_{f,2}$	estimate location of cutting edge 1,2 with respect to workpiece grid (—)
k_{f1}, k_{f2}	discrete location of cutting edge 1,2 with respect to workpiece grid (—)
L	drill length (mm)
L_f	flute length measured from drill tip (mm)
L_1	drill dimension (mm)
M	mass matrix of drill bit (kg)
m	number of elements along the cutting edge (—)
N	number of teeth on drill/reamer (—)
N_g	number of grid points along the hole circumference (—)
N_r	number of revolutions passed in simulation (—)
r	radial distance from drill axis to midpoint of element on flute (mm)
r_r	radial drill runout (in direction of cutting lips) (mm)
r_t	tangential drill runout (perpendicular to cutting lips) (mm)
r_z	axial drill runout (lip height difference) (mm)
Δt	time step (s)
$t_1(i, k)$	chip height for cutting edge point i on edge 1 at timestep k (mm)
T_c	cutting torque acting on tool tip (N m)
$2W$	web thickness of drill bit (mm)
$W_{x,1}, W_{y,1}, W_{z,1}$	workpiece surface coordinate matrices for surface generated by flute 1 (mm)
x_c, y_c, z_c	lateral and axial tool tip deflections (mm)
$x_{i,1}$, $y_{i,1}$	coordinates of intersection points of cutting edge with grid circles (mm)
$x_{fi,1}$, $y_{fi,1}$	coordinates of intersection point of flute with wall grid circle (mm)
$x_{p,1}$, $y_{p,1}$	coordinates of the peripheral point of drill flute 1 (mm)
$x_{p,2}$, $y_{p,2}$	coordinates of the peripheral point of drill flute 2 (mm)
$\vec{x}_{t,1}, \vec{y}_{t,1}, \vec{z}_{t,1}$	coordinates of tool tip points on cutting edge 1 (mm)
z_d	height of whirling grid layer in global coordinate system (mm)
$z_{i,1}(i,k)$	height of cutting edge at intersection points with grid (mm)
$q_1, q_2, \dot{q}_1, \dot{q}_2$	state space variables (m, m/s)
β_0	drill bit helix angle at drill periphery (deg)
ζ_i	damping ratio (—)
θ_c	torsional tool tip deflection (rad)
$2_{\kappa t}$	drill tip angle (deg)
$w_{\kappa t}$	tip angle grinding error (deg)
$\Phi(s)$	transfer function (N/m)
ω_0	web angle at drill periphery (rad)
ω_{ni}	natural frequency mode i (Hz)
Ω	angular speed of the tool (rad/s)

2. Literature review

There has been significant research effort in modeling the drilling forces as a function of tool geometry, grinding errors, material properties, structural dynamics of the drill, and initial penetration of the chisel edge into the material since Galloway's experimental results relating the tool geometry with hole accuracy [2]. Galloway attributed experimentally observed hole accuracy (oversize) to the drill point symmetry. A lip height error r_z on a drill with tip angle $2\kappa_t$ caused a hole roundness error of $r_z \tan\kappa_t$, as the drill would rotate about an axis displaced $0.5r_z \tan\kappa_t$ from the spindle axis, creating equal chip areas on each flute.