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Frequency domain identification of grinding stiffness and damping

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ABSTRACT

As equivalent stiffness and damping of the grinding process dominate cutting stability, their identification is essential to predict and avoid detrimental chatter occurrence. The identification of these process constants is not easy in large cylindrical grinding machines, e.g. roll grinders, since there are no practical ways to measure cutting force normal component. This paper presents a novel frequency domain approach for identifying these process parameters, exploiting in-process system response, measured via impact testing. This method adopts a sub-structuring approach to couple the wheel-workpiece relative dynamic compliance with a two-dimensional grinding force model that entails both normal and tangential directions. The grinding specific energy and normal force ratio, that determine grinding stiffness and damping, are identified by fitting the closed loop FRF (Frequency Response Function) measured during specific plunge-grinding tests. The fitting quality supports the predictive capability of the model. Eventually, the soundness of the proposed identification procedure is further assessed by comparing the grinding specific energy identified through standard cutting power measurements.

1. Introduction

In grinding, multiple abrasive particles of the grinding wheel — with different size, distribution and orientation — act together to produce a complex and stochastic grinding force signature [1]. Several force models, ranging from physical to empirical/statistical, have been proposed in grinding literature, as reported in this exhaustive survey from CIRP [2]. Despite generality of physical approaches is theoretically broader, mixed analytical-empirical models are mostly used, thanks to their easy calibration in real cases with simple experimental setups. Different formulations have been proposed over the years for improving modelling accuracy: those based on specific energy concept [3] are the simplest and most used to cope with force estimation and cutting stability issues.

Cylindrical grinding stability is usually strictly related to normal — i.e. radial — dynamic compliance between wheel and roll. For this reason, grinding dynamics is often studied reducing system behavior to the solely normal direction [4]. Normal force component does not generate cutting power but just a load on machine structure that provokes a relative displacement between wheel and workpiece. In regenerative chatter stability analysis the cutting process is typically described by means of a “grinding stiffness” (or “cutting stiffness”), i.e. the ratio between normal grinding force and actual infeed [5], and a “grinding damping”, relating force to vibrational velocity in normal direction.

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Nomenclature

a [mm]	actual infeed
b [mm]	grinding (cutting) width
$\mathbf{C}(\omega_j)$ [mm^3/N^2]	coefficient matrix of the identification system
$\mathbf{c}_n(\omega_j)$ [mm^3/N^2]	column of $\mathbf{C}(\omega_j)$ associated to k_n
$\mathbf{c}_t(\omega_j)$ [mm^3/N^2]	column of $\mathbf{C}(\omega_j)$ associated to k_t
δt, δn [mm], $\delta\dot{t}$, $\delta\dot{n}$ [mm/s]	small perturbations in tangent and normal direction
$\mathbf{d}$ [mm]	vector of displacements in normal and tangential direction
D_{eq} [mm]	equivalent diameter
D_r [mm]	roll diameter
D_w [mm]	wheel diameter
DoF	degree of freedom
FEM	Finite Element Method
F_n [N]	normal grinding force
F_t [N]	tangential grinding force
FRF	Frequency Response Function
$\mathbf{H}$ [mm/N]	overall compliance matrix of full system dynamics
$h_{BA_{CL}}$ [mm/N]	closed-loop FRF identified by measurements
$\mathbf{h}_{BP}^T$ [mm/N]	FRFs vector relating input forces at process DoFs to the displacement at the additional output DoF B
$\mathbf{h}_{PA}$ [mm/N]	FRFs vector relating a force at the additional input DoF A to the output displacements at the process DoFs
$h_{...}$ [mm/N]	dynamic compliance
k_t [N/mm^2]	grinding specific energy
k_n [N/mm^2]	normal force coefficient
$\mathbf{K}_g$ [N/mm], $\mathbf{K}_{gd}$ [N·s/mm]	grinding stiffness and grinding damping matrices
LS	Least Squares
LVDT	Linear Variable Differential Transformer
μ	ratio between normal and tangential force components
$\mathbf{M}$ [mm/N]	projected compliance matrix
$m_{...}$ [mm/N]	elements of projected compliance matrix $\mathbf{M}$
MIMO	Multi Input Multi Output
MRR_0 [mm^2/s]	material removal rate in the static case normalized with respect to grinding width
MRR [mm^2/s]	Material Removal Rate normalized with respect to grinding width
P	set of process DoFs
P_{s0} [W]	spindle power without material removal
P_s [W]	overall spindle motor output power
ω [2π/s]	pulsation
rn, rt, wn, wt	DoFs components for roll (r), wheel (w) in normal (n) and tangential direction (t)
σ	semi-interval of the identified parameters
sgn Ω	sign of wheel velocity
$\mathbf{t}(\omega_j)$ [mm/N]	known terms vector of the identification system
V_W, V_S [m/s]	wheel and roll velocities

A two DoFs (degrees of freedom) process model — that considers also the tangential force component and the corresponding displacement — has been proposed in [6] to deal with cutting instability generated by damping forces acting on vibration modes involving both radial and tangent displacements. Then, an additional coefficient is needed: the ratio between normal and tangential force components.

Relying on this 2D model, this paper characterizes the coupled machine-process behavior in the frequency domain and performs a reverse identification of grinding stiffness, grinding damping and normal/tangential ratio by a substructuring method. The adopted approach is the well known RCSA method (Receptance Coupling Substructure Analysis) that predicts frequency responses of a specific system, combining its substructures responses [7–12]. Schmitz and Donalson [7] were the first to propose RCSA for tool-tip FRF identification. Park et al. [8] presented an improved receptance coupling technique for the same purpose: the end mill was modeled numerically as a cylindrical beam, and spindle-tool-holder system FRF was identified by means of impact testing on two different blank cylinders — used as calibration tools — clamped on the tool-holder. Calibration tools were adopted to determine rotational responses using IRCSA (Inverse RCSA), by conducting additional experiments. In general, several authors adopt IRCSA to solve the reverse problem of joint identification between two substructures [13–15]. However, in all these works, the joint is modeled as a pure