Aspects of non-smooth dynamics in models of percussion drilling

Alexandre Depouhon[*,**], Emmanuel Detournay[**] and Vincent Denoël[*]
[*] *Structural Engineering, ArGEnCo, Department of Applied Sciences, Université de Liège, Belgium*
[**]*Geomechanics, Department of Civil Engineering, University of Minnesota, MN, USA*

Summary. Percussion drilling is a technology used across the earth resources industries to drill holes in medium to hard rock formations. By design, the process spans several timescales, with the percussive activation lasting for about 1 ms, the percussive frequency of the order of 30 Hz, and the duration of a drilling cycle lying between zero and the latter scale. Under the cover of various assumptions and on account of a bilinear bit/rock interaction law, dynamical models of the process require the handling of non-smooth dynamical features such as discontinuities at the velocity (impulsive excitation), acceleration (contact interaction) or jerk (bit/rock interaction) levels. This paper reviews two families of hybrid models of percussion drilling that neglect (rigid body dynamics) or include (elastodynamics) wave propagation in the modeling of the tool response to external excitations. Modeling and analysis (numerical and analytical) perspectives related to non-smooth aspects are covered.

Introduction

Figure 1 provides a simplified representation of a down-the-hole hammer such as the ones used in percussive drilling. It mainly consists of three bodies: the bit, the piston, and the hammer casing that establishes the connection with the surface through the drill pipes. The hammer system is subject to continuous rotation at an assumed constant velocity. Vertical motion is achieved through the application of a vertical force F_s on the drill pipes, at the surface, and the percussive activation of the piston that repetitively impacts the bit under the action of compressed air F_{air} injected through the drill pipes. Penetration principally results from the fracturing process led to by the percussive activation F_c; vertical movement can duly be assumed independent of the system angular motion. Interactions take place at three levels. At the bit/rock interface, a non-smooth bilinear law is used to represent the force/penetration relation $F_R(p)$. At the piston/bit and casing/bit interfaces, contact interactions respectively enable the transfer of momentum and the repositioning of the drill bit with respect to the rock fragmented surface for the next blow.

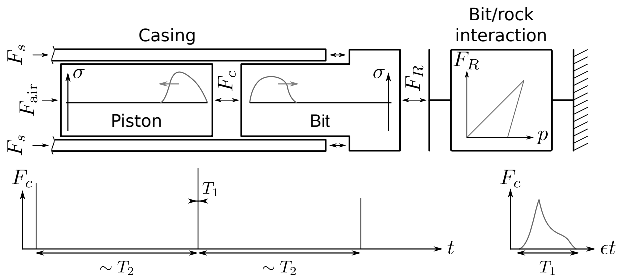

Figure 1: Simplified representation of a down-the-hole percussive hammer.

In light of experimental results [1], the scaling analysis of the process highlights three principal timescales: $T_1 = \mathcal{O}(1 \text{ ms})$ the duration of the percussive activation, $T_2 = \mathcal{O}(50 \text{ ms})$ the period of the percussive activation, and $T_3 \in [0, T_2]$ the duration of the drilling cycle. The duration of the percussive activation T_1 is the result of the interactions of the waves propagating in the system and is dictated by the system geometry and the boundary conditions at the bit and at the piston over the impact duration. These also play a significant role on the rebound velocity of the piston after completion of the percussive activation, a parameter critical to the good performance of the hammer.

Rigid body dynamics

Under the assumption of timescale separation $T_1 \ll T_2$, percussive activation becomes instantaneous and wave propagation can be neglected on timescale T_2 at which the bit motion is observed. Further assuming that the activation is independent of the bit engagement conditions in the rock, percussive activation can be modeled as a periodic impulsive force. Considering a permanent closed contact at the casing/bit interface and a rigid casing, two single degree of freedom hybrid models can be set up to represent the process, based on the assumptions that $T_1, T_3 \ll T_2$ or $T_1 \ll T_2, T_3$. Figure 2 presents the hybrid model obtained for the latter assumptions, in dimensionless coordinates. The analysis of its periodic motion [2] has been conducted using semi-analytical event-driven integration. Stability of the limit cycles was assessed via a numerical Floquet analysis that has been validated using analytical arguments. The latter have required the extension of the saltation matrix definition to problems including state-dependent or history variables [3].

Multibody elastodynamics

A major drawback of the rigid body dynamics models is that they do not properly account for the contact interaction between the bit and the piston in modeling the percussive activation. In particular, even if two bodies were used in com-

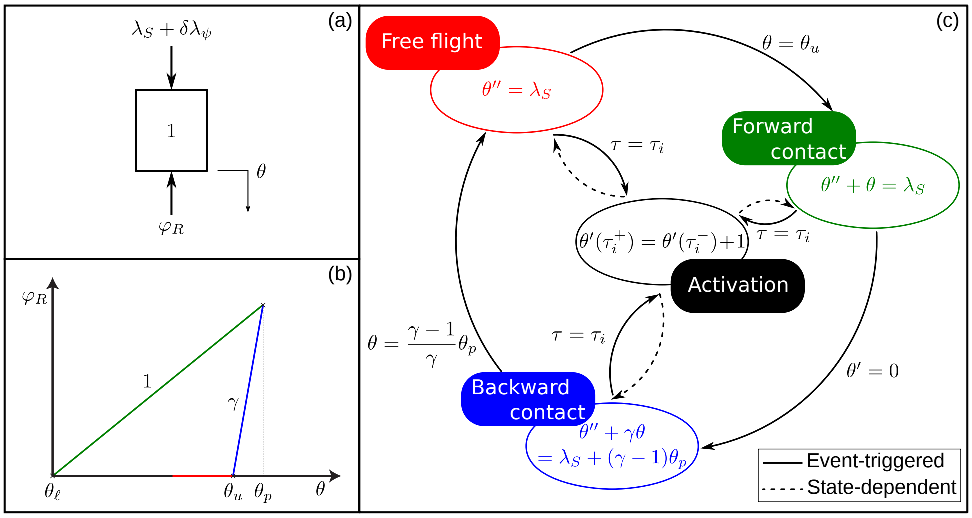

Figure 2: Single degree of freedom model for the representation of the percussive drilling process, $T_1 \ll T_2, T_3$. (a) Free body diagram – (b) Bit/rock interaction law – (c) Hybrid model.

bination with a restitution coefficient, the models would be unable to capture behaviors consequent to wave propagation phenomena such as double piston/bit impact. Relaxation of the assumption of timescale separation and multibody elastodynamics (FEA) are thus required for a proper handling of the piston/bit interaction ruled by the wave propagation in the system. Given the non-smooth nature of the problem (bit/rock interaction and persistent contact), the authors have developed an event-driven integration procedure for use with one-step structural dynamics time integration schemes [4]. This numerical procedure enables an accurate treatment of the non-smooth elastodynamics problem and, in combination with a finite element discretization in space, yields accurate post-activation piston velocities, even if double impact occurs; Figure 3 presents the time evolution of average bit and piston velocities for three different impact configurations and the idealization of the bit and the piston using steel cylinders.

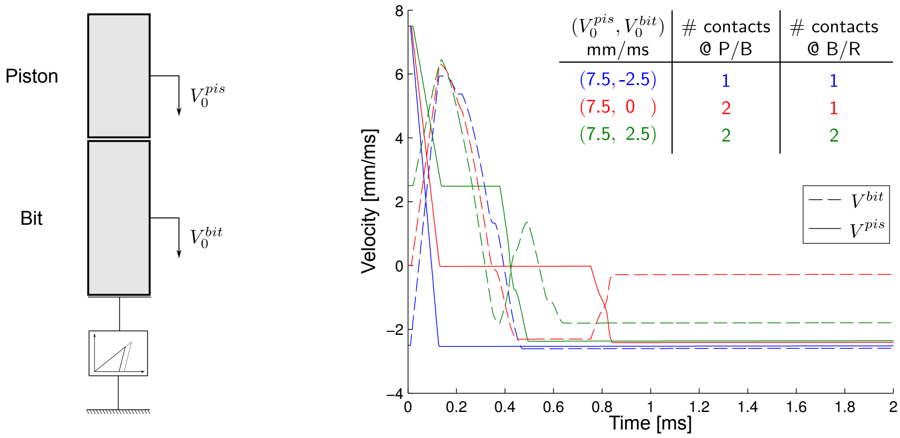

Figure 3: Elastodynamics simulation using spatial finite elements and event-driven time integration. Such simulations enable the capture of peculiar behaviors such as double piston/bit impact (see inset table that counts the number of impact at a given interface).

Concluding remarks

Hybrid dynamical models and non-smooth dynamics enable the modeling of complex processes, such as percussion drilling. For instance, they enable the reduction of multiple timescale problems to simpler representations. However, this has a price, as non-smoothness brings its lot of difficulties in regards to simulation and analysis. Specific tools have to be developed for the application under scrutiny, given the current absence of a unified theory and analysis framework.

References

[1] Hustrulid W. A., Fairhurst C. E. (1971) Theoretical and Experimental Study of Percussive Drilling of Rock - Part II - Force-Penetration and Specific Energy Determinations. *Int. J. Rock Mech. Sci.*, **8**(4):335-356.

[2] Depouhon A., Denoël V., Detournay E. (2013) A drifting impact oscillator with periodic impulsive loading: Application to percussive drilling. *Physica D*, **258**:1-10.

[3] Depouhon A., Detournay E., Denoël V. (2013) Limit Cycling Behavior of a Hybrid System: Application to Percussive Drilling. *Proceedings of the 2nd International Colloquium on Non-Linear Dynamics and Control of Deep Drilling Systems*, May 15-16 2012, Eindhoven.

[4] Depouhon A., Detournay E., Denoël V. (In preparation) Event-driven integration of linear structural dynamics models under unilateral elastic constraints.