Couplings and nonlinearities modelling in drillstring dynamics

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Summary. The drillstring dynamics is a complicated nonlinear rotordynamics problem. The slender drillstring is immersed in a 3D well in the presence of mud, drillstring-well contacts, fluid-structure interactions, bending-torsion-axial vibrations. The induced vibration problems increase the energy loss and cause failures. In order to understand and predict better the vibrations phenomena a Finite Element model is proposed. The simulation results are compared to field data.
Keywords: Nonlinear rotordynamics, drillstring, fluid-structure interaction, rotor-stator contact, contact models

Drillstring description

In rotary drilling which addresses today more and more geothermal application, drillstring is a very slender rotor immersed in a well with a 3D trajectory, Fig. 1. The drillstring, driven by an electrical motor within a 0-180 rpm range, is an assembly of pipes 9 to 10 m long confined in tension in a 3D curvilinear well of several kilometers. Towards the drill bit, over 100 to 200 meters long, the drill collars have a larger outer diameter to ensure the Weight On Bit (WOB) on the rock and then constitute the Bottom Hole Assembly (BHA). Stabilizers act as bearings to maintain the drill collar concentric with the well and permit directional drilling. The drill collar is kept in compression with, at its upper end, the tension-compression neutral point. The mud, i.e. the drilling fluid, circulates downward inside the drill-pipes and upward in the pipe-well annular space. The role of the mud is to clean out rock debris and calories, to lubricate the numerous drillstring – bore hole contacts.

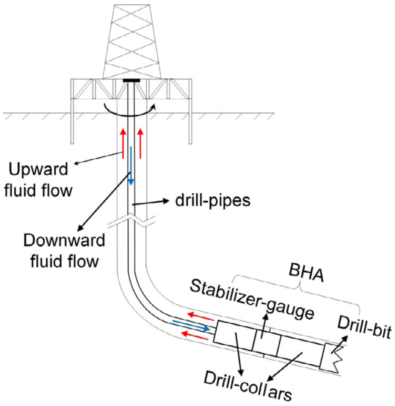

Fig. 1. Sketch of the drillstring immersed in the well

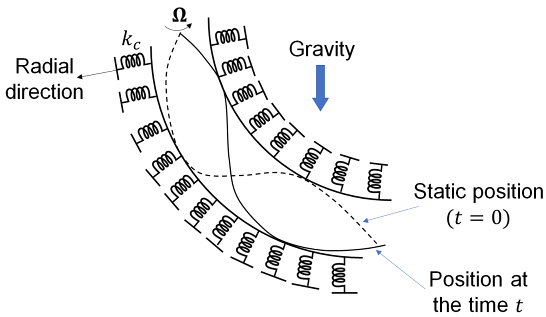

Fig. 2. Configuration of nonlinear response computation

Nonlinear phenomena

Solicited by mud pulses, mass unbalances, pipe-well interactions and friction, motor and resistant torques as well as the axial forces of the various drill-bit shapes, the drill string has a dynamic behavior governed by equations of motion involving in particular the fluid-structure coupling, the nonlinearities of contact, and the axial-bending-torsion couplings. The drillstring is therefore a complex dynamic system because it is non conservative, gyroscopic, with parametric excitations, and necessarily non-linear. Thus, it is expected in the different portions of the drill string, nonstationary behaviors, stick-slip motion, tool-bit bouncing, forward and backward, periodic, quasi-periodic, and chaotic whirls. This set of phenomena induces, in particular, energy loss, failures. Consequently, the Rate of Penetration (ROP) decreases while the Non-Productive Time (NPT) increases.

Coupled and nonlinear proposed model

Facing these technical issues requires to understand as well as possible the drillstring behavior with the implementation of a specific nonlinear rotordynamics model in order to predict in fine the forced dynamics response, the total amount of friction torques, and the drill pipe stresses. The proposed model is based on the Finite Element method using Timoshenko beam elements with 6 degrees of freedom per node. At the beginning of the computational process, the FE mesh of the drillstring is vertical and its positioning on the 3D-well neutral line is computed without any external load, combining the Newton-Raphson technique with a co-rotational formulation. The obtained path serves for starting the Newton-Raphson iterative method for calculating the drillstring quasi-static equilibrium position inside the well by considering: the drillstring pre-loading induced by the 3D-well, the gravity, the buoyancy, the nonlinear well end-stops, the inner and annular fluids, the static stress-stiffening due to the Weight-on-Bit (WOB), and the torque on-Bit (TOB). The drillstring-well contacts are modeled with contact stiffness and damping which are smoothed by using the arctan function. From this quasi-static equilibrium, assuming that the contacts remain permanent and linear, a classical modal analysis is carried out and a Campbell diagram is plotted by employing specific criteria that tracks the mode shapes and classifies them. In the case of the nonlinear response, the contacts are free to become unilateral, see Fig. 2. Finally, the dynamic response of the complete FE model in the time domain is governed by the following set of nonlinear equations:

$$\boldsymbol{M}\ddot{\boldsymbol{\delta}} + \boldsymbol{C}\dot{\boldsymbol{\delta}} + \boldsymbol{K}\boldsymbol{\delta} = \boldsymbol{F}(t, \boldsymbol{\delta}, \dot{\boldsymbol{\delta}})$$

$$\boldsymbol{M} = \boldsymbol{M}_{\mathrm{a}} + \boldsymbol{M}_{\mathrm{fe}} + \boldsymbol{M}_{\mathrm{fi}}$$

$$\boldsymbol{C} = \Omega(\boldsymbol{C}_{\mathrm{ac}}^{\boldsymbol{T}} - \boldsymbol{C}_{\mathrm{ac}}) + \boldsymbol{C}_{\mathrm{ad}} + \boldsymbol{C}_{\mathrm{fe}}(\Omega) \qquad \boldsymbol{C}_{\boldsymbol{ad}} = c_M \boldsymbol{M}_{\boldsymbol{a}} + c_K(\boldsymbol{K}_a + \boldsymbol{K}_{\mathrm{gpa}} + \boldsymbol{K}_{\mathrm{gpo}}(\boldsymbol{\delta}_{\mathrm{s}}))$$

$$\boldsymbol{K} = \boldsymbol{K}_{\mathrm{pa}} + \boldsymbol{K}_{\mathrm{gpo}}(\boldsymbol{\delta}_s) + \boldsymbol{C}_{\mathrm{ac}}^{\boldsymbol{T}}\dot{\Omega} \qquad \boldsymbol{K}_{\mathrm{pa}} = \boldsymbol{K}_{\mathrm{a}} + \boldsymbol{K}_{\mathrm{gpa}} + \boldsymbol{K}_{\mathrm{fe}}$$

$$\boldsymbol{F} = \boldsymbol{F}_{\mathrm{s}} + \boldsymbol{F}_{\mathrm{u}}(t) + \boldsymbol{F}_{\mathrm{c}}\big(\boldsymbol{\delta}, \dot{\boldsymbol{\delta}}, \boldsymbol{\Omega}, \mathrm{ROP}\big) - \boldsymbol{F}_{\boldsymbol{\theta_z}}\dot{\Omega} + \boldsymbol{R}_{\mathrm{ipa}}$$

$\boldsymbol{M_a}$, $\boldsymbol{M_{fi}}$,	Mass matrices of the drillstring and of the inner mud
$\boldsymbol{M_{fe}}$, $\boldsymbol{C_{fe}}$, $\boldsymbol{K_{fe}}$,	Mass matrices of the annular mud
$\boldsymbol{C_{ac}}$, $\boldsymbol{C_{ad}}$,	Matrices of gyroscopic effect and of Rayleigh damping (coeff c_M, c_K)
$\boldsymbol{F_{\theta_z}}\dot{\boldsymbol{\Omega}}$,	Torque vector
$\boldsymbol{F_c}$, $\boldsymbol{F_u}$,	Contact load and mass unbalance force vectors
$\boldsymbol{R_{ipa}}$,	Vector of the static pre-loading

The dynamic response is computed using a RK4 scheme with an adaptative time step. A reduced model based on the Craig and Bampton technique is also available. The simulations are carried out on a field unconventional well with downhole measurements. Figure 3 presents the full-spectral analysis of the orbits all along the drillstring abscissa while Fig. 4 compares predicted and measured lateral accelerations.

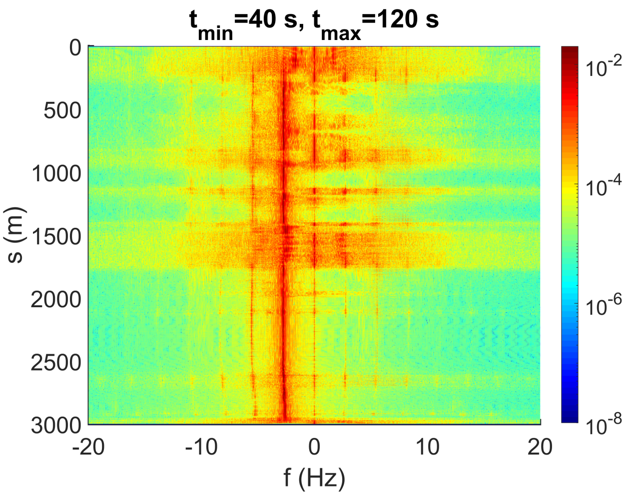

Fig. 3. Full spectrum analysis all along the drillstring.

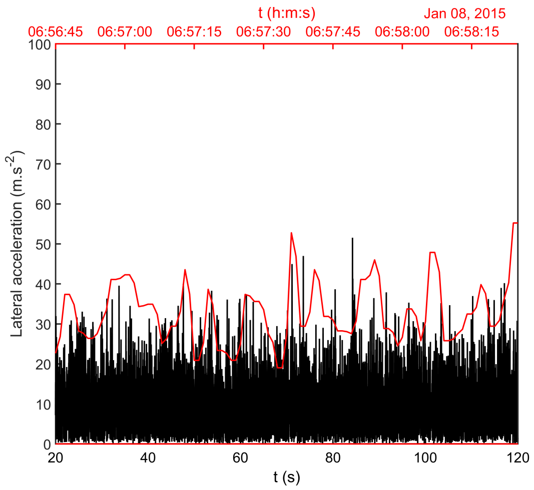

Fig. 4. Measured (red) and predicted (black) radial acceleration at a downhole sensor

Acknowledgment

The authors are indebted to the *Agence Nationale de la Recherche* for its financial support given to this research. In the framework of the LaBCoM-SME program of ANR 15-LCV4-0010-01, this research is conducted by DrilLab, a joint laboratory founded by DrillScan and INSA Lyon – LaMCoS.

† Our friend and colleague Lionel Manin passed away in May 2021. May his memory be honored and his dynamic management of DrilLab acknowledged.

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