6
Concluding remarks

Closing the thesis, this chapter contains a recalling of the addressed thematic, the main conclusions and contributions, and some suggestions for future works. Furthermore, the publications related to this thesis are listed.

6.1
Landscape of the thesis

One may note that drilling systems present a myriad of multidisciplinary problems with which the industry must deal in order to improve operational performance and reduce overall operating costs. In a scenario taking shape in the coming years, the drilling operations in Brazil will again be intense, as discussed in Section 1. Due to the rotational drilling process, the drill-string slenderness, the bit-rock interaction, the borehole-wall interaction, among other phenomena, the system may undergo axial, flexural and torsional vibrations, which may lead to increase of the operation time and costs. This latter vibration mode is present in almost all drilling processes (see Section 1.1).

As presented in Section 1.2, the thesis aims to propose a mitigation strategy in order to prevent stick-slip phenomenon. In order to address this problem in drilling system, the torsional vibration mode was isolated for the purpose to investigate the influence of a second dry friction source on the drill-string experimental set-up. The stick-slip phenomenon was observed numerically and experimentally. Latter for a given stick-slip situation, *i.e.*, for a (N_1,ω_{ref}) pair which induces this phenomenon, the second friction source was used aiming to prevent large vibration amplitudes.

6.2
Contributions and conclusions of the thesis

In relation to the drill-string experimental set-up, the test bench and the experiments of the thesis consisted primarily of an improving the understanding of dry friction-induced stick-slip phenomenon [83]. It is important to point out this experimental evolution (second device) which led to the results for this thesis and a better control of the applied normal force on the discs. Although the experimental apparatus presents limitations such as no lateral and axial motions, it is worth mentioning that the drill-string experimental set-up presents similar torsional behavior compared to a full-scale system. It is fully instrumented consequently it is possible to observe torsional vibrations and the stick-slip phenomenon. The parameter characterizations of the experimental apparatus were performed for the purpose of later use in the mathematical model. Moreover, the dry friction device presented a better control of the applied normal force on the discs: the contact force is measured directly via a load cell attached to the pins. The modifications may yield several analysis and works on friction-induced vibrations with different contact materials.

Regarding the modeling of the experimental apparatus, the lumped parameters technique was used to achieved this mathematical model. Thereafter, comparisons between experimental and numerical models in order to observe and verify whether the mathematical model was representing the experimental apparatus were performed. Nevertheless, some non-modeled phenomena may influence the response of the system such as temperature between the disc and pin. Furthermore, manufacturing limitations imposed a slight rotation out of plane of the disc R_1 and therewith variation in the normal force N_1 is observed. Moreover, an initial electro-mechanical analysis was performed: once the DC-motor is not strong enough, its angular velocity oscillates due to the transient state and the stick-slip phenomenon. The numerical model did not depict the oscillation amplitudes but it oscillates nearly in the same frequency. In addition the DC-motor velocity presents fluctuations around an angular speed slightly lower than the reference speed during stick-slip phenomenon. This fact proves the influence of one subsystem on the other, and then both must be considered.

In the stability analysis, the friction model slope presented substantial influence to the local stability of the equilibrium solutions. Further, the system experienced a Hopf bifurcation: the bifurcation diagrams were numerically obtained with the reference angular velocity as bifurcation parameter and the normal force N_1 was considered constant. One verified that there is an angular velocity range in which stable periodic and equilibrium solutions coexist and from this fact the mitigation strategy may be applied in this range. Basins of attraction had shown this bi-stability behavior: into the velocity range, the solution depends on the perturbation on the system. Therewith, from a stick-slip situation on Disc 1 (R_1), perturbations were imposed numerically on the mathematical model via torques on Disc 2 (R_2) in order to verify the efficiency of the strategy and prevent damage on the drill-string experimental set-up.

Numerically the mitigation strategy presented effectiveness such that the system rapidly passes from a limit cycle to an equilibrium solution. However, experimentally, the mitigation strategy was limited to the first proposal so far: by using the pin and the servo controller, it was only possible to impose a torque against the rotation. The T_{r_2} may control the energy transfer to the Disc 1 (R_1) presenting a reduction of the stick time, but not a complete mitigation of torsional oscillations. The total efficiency of the mitigation strategy on the experimental apparatus may also be influenced by the delay and the frequency of the servo controller actuation which were not considered in numerical simulations. Later analysis using an embedded DC-motor on R_2 combined with the active pin may lead to the second studied strategy and better experimental results in terms of torsional vibration prevention. This embedded motor is already installed as one may see in [42].

At present in field operations, there is no tool capable to induce torsional oscillations as studied here. However, this work aims to provide theoretical basis for improvement of future operations and better understanding about stick-slip phenomenon.

6.3 Directions for future works

In view of the partially experimental nature of this thesis, there are some limitations that must be overcome. One may list the necessary improvements of the test bench that have be made as follows:

- a proper characterization of the DC-motor would provide a better dynamical description: the motor is old, then the internal properties may not be same as described in the manual;
- armature current measurements: this procedure will provide comparisons between numerical and experimental data. Therewith, the nonlinear behavior would be observed also at the electrical subsystem. This measurement is being arranged;
- a better rotation centering of the Disc 1: the weight of the disc is supported by ball bearings. Over time, the disc is losing its orthogonality to the shaft, which creates a rotation out of the plane. This leads to a variation of normal force N_1 as a function of the R_1 rotation. This procedure is being arranged;
- the device development that may allow an impact at the Disc 1: currently, the normal force N1 is manually driven by a worm screw which generates a smooth torque application on the R_1.

In terms of mathematical model, the system was described via lumped parameters technique: the numerical results presented good match with experimental data of the mechanical subsystem. However, the DC-motor dynamics still must be improved. With the armature current measurements and the validated mathematical model, it is possible to:

- analyze the nonlinear electro-mechanical system [120]: the nonlinear phenomena rising from torsional vibration may occur faster on the electrical dynamics. This fact may yield knowledge of an early identification of the stick-slip phenomenon;
- identify an electrical parameter which may hold great influence on the mechanical subsystem: numerically, one may use this as a bifurcation parameter for a given stick-slip situation. For example, the internal PI constants of the DC-motor may be used in this numerical analysis.

Bearing in mind that the on board DC-motor may be a control actuator, the analysis done before, along with the stability investigation performed in this thesis may furnish grounds for the development of a robust controller.

Throughout the work herein presented, other research possibilities emerged:

- The possibility of studying dry friction-induced vibrations for different friction coefficients, since the contact material may be modified;
- The friction model may include hysteresis [121]: due to the out-of-plane rotation of the Disc 1, the friction model may be addressed as a hysteric curve. This approach is already being performed;
- The investigation of the N_2 in order to guarantee the minimum sufficient value: depending on the ω_{ref} value in bi-stability range, the N_2 magnitude may be bigger or smaller. Thereby, a proper investigation of this magnitude must be accomplished. This approach is already being performed;
- One-parameter bifurcation analysis was herein performed: the normal force N_1 was kept constant and the system was analyzed varying the reference angular velocity ω_{ref}. However, the normal force N_1 may also be a control parameter, and therefore a two-parameter bifurcation analysis is needed, *i.e.*, N_1 and ω_{ref} should vary simultaneously;
- Novel mathematical model in which an embedded motor on Disc 2 (R_2) may provide torque: combining the active pin with the actuation of the embedded motor, the needed perturbation to pass from stable limit cycle to stable equilibrium solution may be experimentally achieved, as studied in Section 5.1.2. This approach is already being performed;

– Instead of Ordinary Differential Equations, one may model the test bench using Delay Differential Equations: the infinite dimension system may provide a better description of the system and may make easier a controller development. Also, the stability analysis should be performed again.

6.4 Publications

During the doctoral period, some publications related to this thesis were generated such as:

[P1] Cayres, B. C.; Fonseca, C. A.; Santos, A.; Weber, H. I. (2015). Analysis of dry friction-induced stick-slip in an experimental test rig modeling a drill string. In *Proceedings of the 9th IFToMM International Conference on Rotor Dynamics* (pp. 195–204). Springer, Cham.

[P2] Pereira, L. D.; Cayres, B. C.; Weber, H. I. (2018). Numerical application of a stick-slip control and experimental analysis using a test rig. In *MATEC Web of Conferences* (Vol. 148). EDP Sciences.

[P3] Pereira, L. D.; Cayres, B. C.; Weber, H. I. (2018). Numerical application of torsional vibration controllers at surface. Rio Oil & Gas Conference. ACCEPTED.

[P4] Cayres, B. C.; Fonseca, C. A.; Sampaio, G.; Weber, H. I. (2018). Analysis of a drill-string experimental set-up with dry friction-induced torsional vibration. IFToMM International Conference on Rotor Dynamics. ACCEPTED.

[P5] Cayres, B. C.; Weber, H. I. (2019). Nonlinear analysis of a drill-string experimental set-up with dry friction-induced stick-slip. In XVIII International Symposium on Dynamic Problems of Mechanics (DINAME). SUBMITTED.

[P6] Pires, I.; Cayres, B. C.; Weber, H. I. (2019). Friction-induced vibrations in a drill-string experimental set-up. In XVIII International Symposium on Dynamic Problems of Mechanics (DINAME). SUBMITTED.