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General conclusions, future works and publication

5.1
General conclusions

Stick-slip phenomenon is a quite frequent topic in recent published papers. The drill string models range from a simple one degree of freedom to approaches by finite elements, and it may include deterministic or stochastic modeling. Each model holds goals to understand phenomena involved and provide solutions for emerging problems. Assumptions in order to identify patterns and achieve those goals are always present to reach easier and faster solutions, but imposing limitation on the developed model of the system.

At first in this dissertation, a torsional drill string model in full scale dimensions aimed to identify vibration zones and the best way to mitigate, or eliminate, torsional vibrations encountered on the drilling system. Both models, two and fifteen degrees of freedom, presented similar qualitatively behavior under same conditions of $SRPM$ and WOB. Bifurcation points and nonlinear jumps have changed, however the stability of the equilibrium point (or periodic solution) has not changed, i.e the system continued presenting two stable solutions.

Therewith, the nonlinear jumps of the SSS provide an important visual tool to avoid (or eliminate) torsional vibrations. The Hopf bifurcation diagrams offer how severe (or not) are the torsional vibrations in terms of amplitudes at bottom end and, if they are acceptable or not in operation. For instance, since the system does not present torsional vibrations and it is necessary to change the set-points of [$SRPM$,WOB], check these graphics may prevent undesired motions. Now, suppose a drilling system presenting torsional vibrations and the mitigation (or elimination) of them is required, then the next set-points may be visualized in Figures 3.19, 3.21, 3.23, and 3.25 and a best choice can be taken. In general words, the relative fast computational acquirement (comparing with finite element models, for example) of these results provides tools for a best and fast decision about torsional vibration problems in field.

However, the nonlinear jump figures showed that the behavior of the stick-slip severity as function of surface RPM (or WOB) persists if the RPM (or WOB) starts from zero (blue line) or 160 RPM (red stars). It means that the torsional system holds only one attractor into each zone (with or without vibration) and does not identify the difference of increasing or decreasing of RPM (or WOB), typically encountered in nonlinearities. Thereby, the simulations showed that the system owns two stable solutions: vibration and no vibration. Nevertheless, there existed only one attractor depending of the zone which the point was. Other possible solution would be observed using basins of attraction. For instance, suppose that x_0, $\dot{x}_0 \in \Re^n$ are initial conditions of displacement and velocity, respectively, and $\mathbf{N}_{x_0}$, $\mathbf{N}_{\dot{x}_0} \in \Re^n$ are the number of set-points of initial conditions (IC), i.e. between -2π and 2π rad, it may discretized in $\mathbf{N}_{x_0}$ points, for example, and the same for initial velocity. Then, in order to construct the basins of attraction it is necessary a set of initial conditions $(x_0,\dot{x}_0) \in \Re^n$. Thus, the number of combinations of IC is $\mathbb{C} = (\mathbf{N}_{x_0} * \mathbf{N}_{\dot{x}_0})^{NDOF}$, resulting in time consuming calculations.

The experimental apparatus has been developed in order to represent a drilling system in reduced scale. The axial and lateral motion were constrained by bearings and only the torsional behavior is present. The representation of the system in reduced scale was achieved and stick-slip induced by dry friction was observed. The severity curve was performed, illustrating zones with and without torsional oscillations. The complete standstill of the rotor 1 was noticed and limit cycles of dimension one were depicted, as illustrated in Chapter 4.

Numerical and experimental results of the test rig presented similar behavior of the full scale model. For instance, the severity curve of the test rig presented the same pattern that the numerical test rig model and the same torsional behavior of the full scale system under dry friction model (see Chapter 3). The Hopf bifurcation diagrams of the test rig were presented. As in full scale analysis, the dry friction on the rotor $Frict$ and the angular velocity of the motor $MRPM$ were varied as control parameters. Also, the bifurcation diagrams from the measured data of the test rig were performed and the results illustrated a similar qualitatively behavior when compared with the numerical bifurcation diagrams. The experimental set-up presented the two stables solutions: equilibrium points and quasi-periodic solutions. These last solution appeared due to vibration of the brake device when the brake pads were in contact with the brake disc. This phenomenon led to the appearance of several frequencies in the torsional response, creating a quasi-periodic solution.

With the aim to investigate the quasi-periodic solution, a sinusoidal function was implemented in the resistive torque (Eq. 4-11). Three frequency peaks were used in this investigation. These frequencies were extracted from the frequency-response function of the resistive torque on rotor $RTor$ illustrated in Figure 4.26. It was concluded that these harmonic function included in Eq. 4-10 did not create a quasi-periodic solution in the numerical model of the test rig. Furthermore, the increasing of sinus frequency (Figure 4.29) provided a decreasing of the vibration amplitudes when compared to lower frequency peaks (Figure 4.27).

Moreover, the experimental and numerical models did not presented chaotic behavior.

5.2 Future works

The approached nonlinear analysis in this dissertation has relevance to describe the torsional dynamics of a drilling system in full and reduced scales. Based on the results, it is possible to define few procedures to avoid/mitigate stick-slip. Nevertheless, further studies on the dynamics of the drilling system are necessary. Herein, a few suggestions of future works are listed.

Numerically, a lumped parameter model of the torsional dynamics of the drill string was performed. Assumptions about uncoupling vibration behaviors of the system were considered as axial and lateral motions were neglected. However, it is necessary to increase complexity into the numerical model.

- Several works considered that torsional vibrations occur coupled with axial vibrations - bit-bounce motions ([3, 21, 31]). In order to achieve a best description of the drilling system, the axial vibration may be included in the numerical model and a further nonlinear investigation could be performed.
- A constant concern in oil field is the rate of penetration (ROP). Vibrations normally decrease this important parameter while drilling. In order to include this concern and understand the evolution of the ROP during vibrations, friction torque models encompassing ROP must be implemented.
- A transient analysis of the nonlinear torsional dynamics of the drilling system could investigate the transition between the zones with and without torsional vibrations. This study could provide properly set-points changes of the $SRPM$ and WOB with no excitation of the torsional mode shapes of the drill string.
- Not so fast as lumped parameter model but still interesting, a model using finite element method (FEM) may be implemented. Order reduction methods of FEM models may be applied and the second order tensor of deformation (Piola-Kirchoff) may be adopted to large deformations, depending of the torsional vibration severity, as in [31].
- In order to describe the drilling system while drilling, the lithological parameter could be changed. Parameter estimation methods would be applied to estimate the lithology and change the friction characteristics. The recursive estimators extended Kalman and extended second order filters would be approached for this purpose.

Experimental analysis is essential to validate the numerical models comparing results. The experimental set-up has been developed for this goal. The stick-slip was induced by a brake device with a dry friction. However, a few adjustments would be interesting to obtain an experimental test rig closer to the dynamics of a drilling system.

- A dry friction in the rotor 2 of the test rig could simulate the rubbing effect of the drill string with the wall of the bore hole. This experience may provide a better understanding on rubbing influence in the nonlinear dynamics of the system.

– Since torsional oscillations have been identified, a close loop control must be implemented in order to eliminate these vibrations of the test rig. Different control methods may be tested for this purpose and the best controller performance should be identified.
– In order to investigate, an impact device may be developed and placed at rotor 1 position. This device should impose small impacts in the longitudinal direction of the experimental set-up and its influence on torsional dynamics could be verified. Also, the contact material of the brake device could be changed and the system response could observed.
– Aiming to understand these unexpected quasi-periodic solutions, the identification of the other frequencies in the system response could be performed.

5.3 Publication

This dissertation provided one conference paper submitted and accepted in ICoVP (Lisbon, Portugal), so far. The paper title and the authors are described below [7].

– ”Experimental and Numerical Drill String Modeling Friction Induced Stick-Slip”; B. C. Cayres, C. A. L. L. Fonseca and H. I. Weber. 11^{th} International Conference on Vibration Problems. 2013. *Published.*