Bruno Cesar Cayres Andrade

Nonlinear dynamic analysis of dry friction-induced torsional vibration in a drill-string experimental set-up

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The author was born in June 14th, 1988 in Belém - Pa, Brazil. In 2006, he started to study Mechanical Engineering at Universidade Federal do Pará (UFPA), Brazil, and graduated in 2011. For his performance, the author won the Kawaguchi Awards - which is an awards to the best student. Meanwhile, in 2009-2010, he partially studied at *Institut Polytechnique de Grenoble* (INP-G) - France. His master's dissertation was entitled "Numerical and experimental analysis of nonlinear torsional dynamics of a drilling system" and was conducted under supervision of Prof. Dr.-Ing. Hans I. Weber and Dr. Romulo R. Aguiar at PUC-Rio. In the same university, in September 2013, he started his doctoral research in Applied Mechanics under supervision of Prof. Dr.-Ing. Hans I. Weber. The results and contributions are presented in this thesis which focused in nonlinear dynamics of the drill-string experimental set-up. Since 2013, the author is lecturer at CEFET/RJ.

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Abstract

Andrade, Bruno Cesar Cayres; Weber, Hans Ingo (Advisor). **Nonlinear dynamic analysis of dry friction-induced torsional vibration in a drill-string experimental set-up**. Rio de Janeiro, 2018. 101p. Tese de Doutorado - Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro.

The latter round bids of the pre-salt for exploration and production of oil and natural gas in Brazil indicate the drilling operations will become more intense in coming years. The rotational drilling process is largely used to reach the oil reservoirs and because of diameter-to-length ratio of the drilling system, torsional vibration mode is present in most all drilling processes and may reach an undesired severe stage: the stick-slip phenomenon. In order to address this problem, the torsional vibration mode is isolated and the stick-slip is observed in a fully instrumented drill-string experimental set-up in this work. During this phenomenon, another torque may be applied on an intermediate position of the test bench. The lumped parameter mathematical model is obtained and it is compared to experimental data to validate whether the mathematical model represents the experimental apparatus. A stability analysis is performed using the validated mathematical model in order to identify stable solutions of the system. Therewith, one observed that there is a range of the bifurcation parameter in which stable equilibrium and periodic solutions may coexist. For a given stick-slip situation in bi-stability range, two mitigation strategies of torsional vibration were considered which consisted of imposing perturbations in the system via torques on the intermediate position of the test bench: (i) torques applied only against the direction of motion of the system, and (ii) torques applied in both directions. The strategies were tested numerically and presented efficiency so that the stick-slip was completely mitigated: the energies of the system and the work created by the intermediate torque were compared in order evaluate the feasibility and reasonableness of the strategy. Experimentally, the system continued to oscillate, however it presented a significant reduction of stick phase even with limitations of torque applications.

Keywords

Drill-string dynamics; Stick-slip phenomenon; Nonlinear dynamics; Stability analysis; Mitigation strategy.

Resumo

Andrade, Bruno Cesar Cayres; Weber, Hans Ingo (Orientador). **Análise da dinâmica não linear de uma bancada experimental de uma coluna de perfuração com vibração torcional induzida por atrito**. Rio de Janeiro, 2018. 101p. Tese de Doutorado - Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro.

Os últimos leilões do pré-sal para exploração e produção de petróleo e gás no Brasil indicam que as operações de perfuração se tornarão mais intensas nos próximos anos. O processo de perfuração rotativo é amplamente utilizado para alcançar os reservatórios de petróleo e devido à relação diâmetro/comprimento do sistema de perfuração, o modo de vibração torcional está presente em quase todos os processos de perfuração, podendo chegar a um estado crítico indesejável: o fenômeno de *stick-slip*. Com o intuito de abordar este problema, o modo torcional é isolado e o *stick-slip* é observado em uma coluna de perfuração em escala reduzida completamente instrumentada. Durante o *stick-slip*, outro torque pode ser aplicado em uma posição intermediária da bancada de teste. O modelo matemático de parâmetros concentrados é obtido e o modelo é comparado com dados experimentais com o propósito de verificar se o modelo matemático representa o aparato experimental. Uma análise de estabilidade é feita usando o modelo validado com o objetivo de identificar soluções estáveis do sistema. Com isso, observou-se que existe uma faixa do parâmetro de bifurcação na qual soluções de equilíbrio e periódicas estáveis coexistem. Para uma dada situação de *stick-slip* na faixa de biestabilidade, duas estratégias de mitigação de vibração torcional foram consideradas e consistiram em impor perturbações no sistema por meio do torque na posição intermediária da bancada de teste: (i) torques aplicados apenas contra a direção de movimento do sistema, e (ii) torques aplicados em ambas as direções. As estratégias foram testadas numericamente e apresentaram eficiência de tal modo que o *stick-slip* foi completamente mitigado: as energias do sistema e o trabalho gerado pelo torque intermediário aplicado foram comparados com o propósito de avaliar a factibilidade e razoabilidade da estratégia. Experimentalmente, o sistema continuou a oscilar, porém apresentou uma significante redução na fase de *stick* mesmo com limitações de aplicações de torque.

Palavras–chave

Dinâmica de coluna de perfuração; Fenômeno de stick-slip; Dinâmica não linear; Análise de estabilidade; Estratégia de mitigação.

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Nomenclature

List of abbreviations

APL amplitude pulse level

BHA bottom hole assembly

SRPM surface rotation per minute

WOB weight on bit

List of symbols

δ_{12} angular phase between R_1 - R_2

δ_{23} angular phase between R_2 - R_3

$\dot{\theta}_1$ angular velocity of R_1

$\dot{\theta}_2$ angular speed of R_2

$\dot{\theta}_3$ angular speed of R_3

$\dot{\theta}_m$ angular velocity of the J_m

η transmission factor

$\mathbb{H}^*$ Hurwitiz matrix

$\mathbb{J}^*$ Jacobian matrix

μ_k kinetic coefficient of friction

μ_s static coefficient of friction

ω_{ref} reference angular velocity

τ_m motor ouput torque

τ_s torque provided by the DC-motor

θ_1 angular displaciment of R_1

θ_2 angular displaciment of R_2

θ_3 angular displaciment of R_3

ξ_i damping ratio (1,2)

C_m speed regulation constant of the DC-motor

D_1 diamater of Disc 1

D_2 diamater of Disc 2

d_1 damping between R_1 - R_2

d_2	damping between R_2 - R_3
E_{k_i}	relative kinetic energy of Disc i (1,2)
E_{p_i}	relative kinetic energy of spring k_i (1, 2)
g	gravitational acceleration
i	electric current of the DC-motor
J_1	inertia of the Disc 1
J_2	inertia of the Disc 2
J_3	inertia of the motor including the transmission factor
J_m	inertia of the motor
K_E	voltage constant of the DC-motor
k_i	integral constant of the DC-motor
k_p	proportial constant of the DC-motor
K_T	torque constant of the DC-motor
k_1	stiffness of the shaft between R_1 - R_2
k_2	stiffness of the shaft between R_2 - R_3
L	armature inductance of the DC-motor
m_1	mass of Disc 1
m_2	mass of Disc 2
N_1	normal force at Disc 1
N_2	normal force at Disc 2
P_C	Pearson correlation coefficient
R	armature resistance of the DC-motor
R_1	Disc 1
r_1	distance between the contact point of the pin and the geometric center of rotation of disc R_1
R_2	Disc 2
r_2	distance between the contact point of the pin and the geometric center of rotation of disc R_2
R_3	Disc 3 (DC-motor)
T_f	internal friction torque of the DC-motor
T_{r_1}	torque on Disc 1
T_{r_2}	torque on Disc 2

A vaidade cega a sabedoria.

Matias Aires.