

**Guilherme Rodrigues Sampaio de Paula**

**Dynamics and control of stick-slip and  
torsional vibrations of flexible shaft driven  
systems applied to drillstrings**

**Tese de Doutorado**

Thesis presented to the Programa de Pós-Graduação em Engenharia Mecânica of the Departamento de Engenharia Mecânica of PUC-Rio in partial fulfillment of the requirements for the degree of Doutor em Engenharia Mecânica.

Advisor: Prof. Hans Ingo Weber

Rio de Janeiro  
July 2017

**Guilherme Rodrigues Sampaio de Paula**

**Dynamics and control of stick-slip and  
torsional vibrations of flexible shaft driven  
systems applied to drillstrings**

Thesis presented to the Programa de Pós-Graduação em Engenharia Mecânica of PUC-Rio in partial fulfillment of the requirements for the degree of Doutor em Engenharia Mecânica. Approved by the undersigned Examination Committee.

**Prof. Hans Ingo Weber**

Advisor

Departamento de Engenharia Mecânica — PUC-Rio

**Prof. Marco Antonio Meggiolaro**

Departamento de Engenharia Mecânica — PUC-Rio

**Prof. Roberta de Queiroz Lima**

Departamento de Engenharia Mecânica — PUC-Rio

**Prof. Romulo Reis Aguiar**

Schlumberger

**Prof. Thiago Gamboa Ritto**

Universidade Federal do Rio de Janeiro — UFRJ

**Prof. Márcio da Silveira Carvalho**

Coordinator of the Centro Técnico Científico da PUC-Rio

Rio de Janeiro, July 20th, 2017

All rights reserved.

### Guilherme Rodrigues Sampaio de Paula

Guilherme Rodrigues graduated as control and automation engineer in 2010 from PUC-Rio (Rio de Janeiro, RJ), and got his master degree in mechanical engineering in 2012 from the same institution.

#### Bibliographic data

de Paula, Guilherme Rodrigues Sampaio

Dynamics and control of stick-slip and torsional vibrations of flexible shaft driven systems applied to drillstrings / Guilherme Rodrigues Sampaio de Paula; advisor: Hans Ingo Weber, 2017.

96 f. : il.; 30 cm

1. Tese (doutorado) - Pontifícia Universidade Católica do Rio de Janeiro, Departamento de Engenharia Mecânica.

Inclui referências bibliográficas.

1. Engenharia Mecânica – Teses. 2. Sistema embarcado. 3. Vibrações torcionais. 4. Controle adaptativo. 5. Perfuração. 6. Dinâmica não linear. I. Weber, Hans Ingo. II. Pontifícia Universidade Católica do Rio de Janeiro. Departamento de Engenharia Mecânica. IV. Título.

CDD: 621

## Acknowledgments

First I would like to thank my family, for all the support given.

To my advisor, professor Hans I. Weber, for the tutoring on this research and for providing the conditions for achieving the results presented

To the technician Wagner Epifanio for manufacturing several mechanical parts essential for the experimental setup

To professor Naira Hovakimyan and the Ph.D. candidates Thiago Marinho and Hamidreza Jafarnejadsani of the Intelligent robotics lab of the University of Illinois at Urbana-Champaign for the collaboration on the implementation of  $L_1$  adaptive control

To CAPES for the scholarship and financial support to the research

## Abstract

de Paula, Guilherme Rodrigues Sampaio; Weber, Hans Ingo. **Dynamics and control of stick-slip and torsional vibrations of flexible shaft driven systems applied to drillstrings**. Rio de Janeiro, 2017. 96p. Tese de Doutorado — Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro.

Systems actuated through a highly flexible shaft pose a big challenge to control strategies as the actuator is not connected directly to the end effector, causing propagation effects as well as an energy accumulation and dissipation in the shaft. This thesis focuses the study of one of the most investigated applications of this type, the top driven drilling system used in the oil and gas industry. Usually, the drilling system is composed of a top drive linked to the drill bit through hundreds or even thousands of meters of steel pipes. All kinds of vibrations will be found: longitudinal deformations will be associated with the bit bouncing, flexional with rubbing, and torsional with stick-slip effects. A better understanding is only possible when each of these situations is carefully investigated. This thesis focuses on the torsional deformation of the highly flexible string and presents two different models for the the drill string, the first is the most common 1 DOF single spring single damper model. The second one is a 20 DOF lumped parameter model that has the advantage of being able to consider the mass of the drill string and propagation of torsional waves in the shaft. The investigation includes the development of a test rig adequate for torsional vibrations under damping that may induce stick-slip in the system. Two control techniques are studied to reduce the torsional vibrations in drill strings with numerical and experimental results presented. The first is a behavior-based open loop control scheme that is very simple and effective to reduce stick-slip oscillations. The second one is the  $L_1$  adaptive control, which uses a reference model on its structure.

## Keywords

Stick-slip; Embedded system; Torsional vibrations; Adaptive control; Drilling; Nonlinear dynamics.

## Resumo

de Paula, Guilherme Rodrigues Sampaio; Weber, Hans Ingo. **Dinâmica e controle de stick-slip e vibrações torcionais em sistemas acionados por eixos flexíveis aplicados a colunas de perfuração**. Rio de Janeiro, 2017. 96p. Tese de Doutorado — Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro.

Sistemas rotativos atuados através de um eixo flexível apresentam um grande desafio para estratégias de controle, uma vez que o atuador não está conectado diretamente ao sistema principal, causando efeitos de propagação de ondas e acúmulos e dissipações de energia no eixo. Este trabalho apresenta um estudo sobre uma das mais notórias aplicações deste problema, sistemas de perfuração de petróleo. Habitualmente, o sistema de perfuração é composto por um motor de topo conectado à broca através de milhares de metros de tubos de aço que transmitem o torque. Diversos tipos de vibrações podem ser observadas: Axiais, de flexão e torcionais, estas últimas ligadas ao fenômeno stick-slip. Para um completo conhecimento do problema, é necessário conhecer cada uma delas. Esta tese trata especificamente das vibrações torcionais através de uma análise com dois diferentes modelos, um primeiro mais simples de dois graus de liberdade (inércia, mola torcional, amortecedor), e um segundo mais completo discretizado em 20 graus de liberdade capaz de considerar a massa do eixo e efeitos de propagação de ondas mecânicas no eixo. Este trabalho inclui ainda a construção de uma bancada em escala reduzida para observar os fenômenos associados às vibrações torcionais. São apresentados ainda estudos numéricos e experimentais de técnicas de controle para minimizar os efeitos do atrito na dinâmica torcional do sistema. Duas estruturas de controle são estudadas nesta tese a fim de reduzir vibrações torcionais em colunas de perfuração. A primeira é um controle simples, de malha aberta, baseado no comportamento do sistema. A segunda é o controle adaptativo  $L_1$ , que faz uso de um modelo de referência do sistema em sua estrutura.

## Palavras-chave

Stick-slip; Sistema embarcado; Vibrações torcionais; Controle adaptativo; Perfuração; Dinâmica não linear.

# Contents

1	Introduction	<b>12</b>
1.1	Motivation of the Thesis	12
1.2	Objectives	15
1.3	Literature review	16
1.4	Organization of the Thesis	19
2	Mathematical formulations	<b>21</b>
2.1	Torque on bit formulation	24
2.2	Stick-Slip	25
	One cart mass-spring-damper system stick-slip	26
2.3	Rotational stick-slip system	28
3	Control strategies	<b>33</b>
3.1	PID control	33
3.2	Adaptive control	34
3.3	MRAC control	37
3.4	$L_1$ adaptive control	39
3.5	$L_1$ control formulation	41
	$L_1$ Control simulation results	42
3.6	$L_1$ augmented PID control	49
3.7	Multi-Objective Filter Optimization for Output Feedback $L_1$ Adaptive Controller	57
4	Experimental results	<b>64</b>
4.1	Mechanical properties of the experimental setup	67
4.2	Sensors analysis	71
4.3	Dynamical behavior based control	77
4.4	Influence of top drive speed on stick-slip	82
5	Conclusions	<b>86</b>
6	Future works	<b>88</b>
	Bibliography	<b>89</b>
A	$L_1$ adaptive controller implementation in Simulink	<b>94</b>

## List of Figures

1.1	Drilling rig - <i>Image from Fox Oil Drilling Company</i>	13
1.2	Drill bit types - <i>Image from Petroleum online</i>	14
2.1	2DOF mechanical system	21
2.2	DC Motor scheme - <i>Image from The MathWorks, Inc.</i>	23
2.3	Lumped parameters flexible shaft	23
2.4	Friction torque by angular speed	25
2.5	1 DOF linear stick-slip	26
2.6	Simulation results for the 1 DOF linear system: (a) Displacement in m and (b) Velocity in m/s	27
2.7	Phase plot of the 1 DOF linear system	28
2.8	Rotational stick-slip model	28
2.9	Simulation with parameters from Table 2.2	29
2.10	Simulation with Coulomb friction coefficient $\mu = 0.48$	30
2.11	Simulation with Coulomb friction coefficient $\mu = 0.6$	30
2.12	Simulation with viscous friction coefficient $b = 0.001$	31
2.13	Simulation with viscous friction coefficient $b = 0.005$	31
3.1	PID Control closed loop structure	34
3.2	MRAC Controller scheme	37
3.3	$L_1$ Control closed loop structure	41
3.4	Closed loop $L_1$ architecture	42
3.5	Two cart mass spring damper system	43
3.6	Two cart mass spring damper system with friction on $m_2$	44
3.7	Displacement of the cart $m_2$ of the mass spring damper system with dry friction on $m_2$	44
3.8	$C(s)$ filter bode plot	45
3.9	Displacement of the cart $m_2$ without control	46
3.10	Displacement of the cart $m_2$ with $L_1$ control	46
3.11	Control effort of the $L_1$ controller	46
3.12	Simulation results for the 2 DOF linear system: Displacement of the cart $m_2$ without control	47
3.13	Simulation results for the 2 DOF linear system: Displacement of the cart $m_2$ with $L_1$ control	48
3.14	Control effort of the $L_1$ controller	48
3.15	Displacement of $m_2$ (blue) and reference signal $r(t)$ (orange)	48
3.16	Control effort of the $L_1$ controller	49
3.17	$L_1$ augmented PID control structure	49
3.18	$L_1$ augmented PID control structure with time delay	50
3.19	Mechanical model with second dry friction point	50
3.20	Reference system response to a step at $T = 1s$ with amplitude of 20	52
3.21	Magnitude and phase plot of the $C(s)$ filter	52
3.22	Angular velocity response of PID control	53
3.23	$L_1$ control system response	53



3.24	PID augmented $L_1$ controller response	54
3.25	PID augmented $L_1$ controller control effort	54
3.26	PID controlled system response	55
3.27	$L_1$ controlled system response	55
3.28	PID augmented $L_1$ controller response	55
3.29	PID augmented $L_1$ controller control effort	56
3.30	PID augmented $L_1$ controller response with 40ms time delay	56
3.31	PID augmented $L_1$ controller response with 40ms time delay	57
3.32	Simplified output feedback system	58
3.33	Step response of the reference system	60
3.34	Bode plot of the optimized low pass filter	60
3.35	$L_1$ control system after optimization	61
3.36	PID controlled system	61
3.37	Control effort of the optimized $L_1$ controller	62
3.38	$L_1$ control system after optimization starting at $T=0s$	62
3.39	PID controlled system starting at $T=0s$	63
4.1	Mechanical model with an extra motor on $J_1$	64
4.2	Experimental setup	64
4.3	Top drive DC motor	65
4.4	Inertia chuck	65
4.5	Incremental encoder (left of inertia) and tachometer (belt driven on right of inertia)	66
4.6	DC motor on $J_1$	66
4.7	Electronic diagram of the $J_1$ motor	67
4.8	Experimental torque measurement	69
4.9	Time response of the system with initial displacement	70
4.10	Angle displacement between $J_1$ and top drive over time	71
4.11	Force as a function of the angle between $J_1$ and top drive	71
4.12	Encoders and tachometers in $J_1$ (left) and Top drive motor (right)	72
4.13	Quadrature encoder	72
4.14	Tachometer measurement of angular velocity (RPM)	73
4.15	Optical encoder measurement of angular velocity (RPM)	73
4.16	Percentual difference between encoder and tachometer measurements.	74
4.17	Histogram of motor encoder measurements	74
4.18	Histogram of motor tachometer measurements	75
4.19	Tachometer measurement of angular velocity (RPM)	75
4.20	Optical encoder measurement of angular velocity (RPM)	76
4.21	Histogram of motor encoder measurements	76
4.22	Histogram of motor tachometer measurements	77
4.23	Mechanical model with motor on $J_1$	77
4.24	Angular speed on top drive (green) and $J_1$ (blue)	78
4.25	Torque on top drive (green) and $J_1$ (blue)	78
4.26	Angular speed on top drive (green) and $J_1$ (blue)	79
4.27	Torque on top drive (green) and $J_1$ (blue)	79
4.28	Angular speed on top drive (green) and $J_1$ (blue)	80
4.29	Torque on top drive (green) and $J_1$ (blue)	80

4.30	Angular speed on top drive (green) and $J_1$ (blue)	81
4.31	Torque on top drive (green) and $J_1$ (blue)	81
4.32	Experimental results for torque applied on $J_1$ in green and speed at $J_1$ in orange	82
4.33	Influence of top drive speed on stick-slip	83
4.34	Influence of top drive speed on stick-slip from 35s to 100s	84
4.35	Influence of top drive speed on stick-slip from 100s to 114s	84
4.36	Influence of top drive speed on stick-slip from 115s to 150s	85
4.37	Influence of top drive speed on stick-slip from 140s to 170s	85
A.1	Block diagram of $L_1$ controller and PID	95
A.2	Block diagram of $L_1$ controller	96
A.3	Subsystems block diagram of $L_1$ controller	96

## List of Tables

2.1	1DOF model parameters	27
2.2	Friction parameters	29
2.3	Simulation parameters	29
2.4	Friction parameters	30
2.5	Friction parameters	31
3.1	Model parameters	51
3.2	PID gain	53
4.1	Mechanical parameters of drillstring	68
4.2	Mechanical parameters of $J_1$	68
4.3	Inertias of $J_1$	68
4.4	Experimental stiffness of drillstring	69
4.5	DC motor parameters	69
4.6	Frequencies and damping of the system	70
4.7	Statistical analysis of angular velocity sensors	74
4.8	Statistical analysis of angular velocity sensors	76