

Romulo Reis Aguiar

Experimental investigation and
numerical analysis of the
vibro-impact phenomenon

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Thesis presented to the Postgraduate Program in
Mechanical Engineering of the Departamento de
Engenharia Mecânica, Centro Técnico Científico, PUC–Rio
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Adviser: Prof. Hans Ingo Weber

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Resumo

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Existem aplicações técnicas onde o principal elemento de um sistema mecânico está sujeito a um padrão de vibração. Um exemplo se encontra na perfuração de poços de petróleo em rochas duras utilizando brocas tricônicas, uma vez que esse tipo de interação broca/ rocha impõe uma vibração longitudinal à estrutura. É possível utilizar parte desta energia para excitar um martelo, uma subestrutura do sistema principal capaz de gerar impactos. A onda de tensão gerada pelo impacto pode ser útil para remover o sistema de uma condição de *stick* (*stick-slip*) ou ajudar na propagação de trincas no material a ser perfurado. A perfuração de rochas duras ainda é um grande desafio para as empresas de perfuração e exploração de petróleo. Neste contexto, uma forma de conseguir maior eficiência da coluna de perfuração é combinando a perfuração rotativa convencional com um dispositivo de vibro-impacto. A tarefa de desenvolver um martelo embarcado na coluna de perfuração e que impacta sobre a broca ainda é uma sugestão a ser implementada. O propósito deste trabalho é a investigação experimental e a modelagem matemática do comportamento da força de impacto num sistema de vibro-impacto embarcado. Mudando a rigidez do martelo e a folga é possível investigar o comportamento do sistema sob diferentes frequências de excitação. É apresentada uma metodologia para a integração numérica de equações diferenciais descontínuas. Este trabalho também estuda a modelagem da força de impacto, investigando qual modelo matemático disponível na literatura melhor representa os dados experimentais. Os resultados experimentais serão usados para validar o modelo matemático, através do qual o sistema será estudado em maior detalhe. Uma análise não-linear é realizada (diagramas de bifurcação, mapas de Poincaré e mapas de Peterka). Finalmente, este trabalho mostra uma aplicação prática deste sistema de vibro-impacto, onde um sistema massa-mola é montado a uma bancada experimental de perfuração. Resultados experimentais mostram que a aplicação da força de impacto durante a perfuração aumenta a taxa de penetração.

Palavras-chave

coluna de perfuração, dinâmica não-linear, impacto, vibro-impacto.

Abstract

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There are technical applications when the main element of a mechanical system is subjected to a regular vibration pattern. An example of this is drilling with tricone bits on hard material, because under normal condition the contact surface becomes lobular, imposing a longitudinal vibration on the drilling structure. It is possible to use part of this energy to resonate a hammer, that is a substructure of the system and impacts on it. The stress wave created by the impact may be useful to release the system from the stick condition of stick-slip phenomenon or to help in the crack propagation of the material being cut. Hard rock drilling is still a great challenge for oil companies. Optimum productivity is made possible by combining the advantages of rotary and percussive drilling. The task of developing an internal hammer in the drillstring that impacts on the drill bit remains an idea to be implemented. The subject of this work is the experimental investigation and the mathematical modeling of the impact force behavior in a vibro-impact system, where a hammer is mounted on a cart that imposes a prescribed displacement. By changing the hammer stiffness and the impact gap it is possible to investigate the impact force behavior under different excitation frequencies. A methodology is presented to numerically integrate the ODEs with a discontinuous right-hand side. This work also compares different models of the impact force presented in prevailing scientific literature to determine which one best fits the experimental data. This information will be used to create a mathematical model of the test rig. The experimental data will be used to validate the mathematical model. The hammer behavior is studied in more detail using a nonlinear analysis (bifurcation diagrams, Poincaré maps and Peterka map). Nonlinear analysis shows the various responses of the hammer, such as dynamical jumps, bifurcations and chaos. Finally, this work shows the field application of this vibro-impact system. A mass-spring system is mounted to an experimental drilling rig. Experimental results shows that impact forces during drilling improve the rate of penetration.

Keywords

oilwell drillstring, nonlinear dynamics, impact, vibro-impact.

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Notation

BHA	Bottom Hole Assembly.
MWD	Measurement While Drilling.
LWD	Logging While Drilling.
$HWDP$	Heavyweight drill pipes.
TOB	Torque on bit.
WOB	Weight on bit.
RHD	Resonance Hammer Drilling.
FRF	Frequency response function.
DOF	Degree of freedom.
\sin	Sine.
\cos	Cosine.
z	Impact condition (number of impact per cycles of excitation).
F_i	Impact force, N .
F_{exc}	Excitation force, N .
m_{tot}	Total mass, kg .
m	Hammer mass, kg .
M	Cart mass, kg .
A_0	Excitation amplitude, m .
l	Length, m .
g	Acceleration of gravity, 9.81 m/s^2 .
t	Time, s .
c	Damping coefficient, Ns/m .
ζ	Damping ratio.
θ	Angle, rad .
$\dot{\theta}$	Angular velocity, rad/s .
$\ddot{\theta}$	Angular acceleration, rad/s^2 .
x	Displacement (hammer), m .
y	Displacement (excitation), m .
Ω	Excitation frequency, Hz or rad/s .
ω	System natural frequency, Hz or rad/s .
δ	Indentation during impact, m .
$\dot{\delta}$	Velocity of indentation during impact, m/s .
$\dot{\delta}^{(-)}$	Instant velocity before impact, m/s .
k_i	Stiffness of impact (modeling), N/m .
c_i	Damping of impact (modeling), Ns/m .
n	constant.
λ_i	Damping/ stiffness ratio (impact modeling), s .
e	Coefficient of restitution.
gap	Impact gap, m .
Γ	Subspace.
Σ	Hyper-surface.
$h(\mathbf{x})$	Scalar function.
η	Narrow band thickness.
\mathbf{x}	State-space vector.
\overline{co}	Convex set.

L'essentiel est invisible pour les yeux.

Antoine de Saint-Exupéry, Le Petit Prince.