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Conclusions and future works

This work had the purpose of an experimental investigation and mathematical modeling of the impact force behavior in a vibro-impact system, where the hammer is mounted on a cart that imposes a prescribed displacement. By changing the hammer stiffness and the impact gap it was possible to investigate the impact force behavior under different excitation frequencies. The first task was to have a full understanding of the hammer when it is free to move in a longitudinally vibrating structure. This impact mass should have very low damping in order to generate considerable displacement amplitudes, which were reduced through a gap, developing impacts. Previous prototypes were studied at the Dynamics and Vibration Laboratory at PUC-Rio, where in all test rig arrangements the hammer was always impacting against a rigid support. These previous experiments were important to characterize the impact force generated by the hammer under different stiffness/gap combinations and under different excitation frequencies. However, the hammer concept was designed as part of a device to be mounted on a vibrating structure. In other words, it was necessary to take into account that the impact surface was vibrating with the entire structure (in the field, this would occur inside the Bottom Hole Assembly).

The thesis contains an introductory chapter which surveys oil well drilling, presenting the two existing drilling techniques used in the field and proposing a new hybrid drilling technique. The first chapter also discussed the different types of drillstring vibration and the bit/rock interaction. This established a basis for building an experimental test rig that would better reproduce the relevant field characteristics for the new drilling technique.

In both experiments, while studying the impact force characteristic, covering the range of excitation frequency, it was noted that, in all stiffness/ gap combinations, there was a certain pattern of the impact force behavior. This behavior could be divided into frequency bands, presenting similar characteristics in each frequency band for all stiffness/ gap combinations. In each frequency band, impact force behavior had a regular pattern, while in frequency band transitions the hammer showed nonlinear behavior, as basins of attraction, and even chaotic behavior. The presence of the gap significantly changed the impact resonance. This impact resonance differed from the hammer's natural frequency. A smoothing effect during impact was noticed in the phase plane charts, caused by the differentiation of a low-pass filtered signal, and it does not reflect the reality of the impact. When comparing the magnitudes of the impact force for the case of the hammer supported by wires with the hammer supported by beam springs, it was noted that the second test rig generated significantly higher impact forces, due to the capacity of the beam springs to store potential energy into bending deformation.

Chapter 3 presented a general view of the state of the art of impact mechanics, as well as some methodologies to model impact and the numerical integration of discontinuous ordinary differential equations using the Filippov theory. In both test rigs, the comparison between the numerical simulation and the experimental data was satisfactory, showing the capability of the mathematical model to predict the maximum impact force and the impact resonance for all stiffness/ gap combinations. Nonlinear tools were used to understand the hammer behavior, such as bifurcation diagrams, basins of attraction, Poincaré maps and Peterka maps.

Also, a new methodology was proposed to better visualize each impact force behavior in the Peterka map, plotting one impact force characteristic at a time, adding colors to the third coordinate F_i. This methodology provided important information regarding the hammer behavior and confirmed some aspects observed during the experiment analysis. By observing the experimental data and the nonlinear tools, the recommendation was made to optimize result one should operate with a 0.0 mm gap, because the magnitude of the impact forces were in the same range as the impact force in higher gap values. However, in higher gap values, nonlinear jump was observed, which did not occur in the case of 0.0 mm gap.

For the second test rig, i.e., hammer supported by beam springs, the mathematical model was capable of qualitatively determining the frequency bands, and predicting the impact force magnitude in the frequency domain for all stiffness/ gap combinations. However, the mathematical model did not predict well the hammer displacement, due to the energy distribution in the bending vibration modes of the beam springs following each impact. Since the mathematical model only considers the first bending vibration mode, the amplitude of the mathematical model was always higher than the experimental data, even when the impact force presented equivalent values. This difference appeared to be higher as the beam springs stiffness increased.

One last aspect that was observed in the case of the hammer supported by beam springs was the similarity in the shape pattern of the Peterka maps regardless of the hammer stiffness imposed, except for the chaotic region between frequency bands $z = 1/1$ and $z = 1/2$. This was an indication that the impact force behavior was somehow not dependent on the hammer stiffness.

In the application of this new drilling technique in an actual system (Frank Jr.), the addition of the impulsive load to the drilling process brought an increase of the rate of penetration (ROP) in tests under weight-control-mode as well as a reduction in the drilling parameters (weight-on-bit and torque-on-bit) in tests under kinematical-control-mode. Indeed, the percussive action provided an extra energy to the bit during tests under weight-control-mode. Consequently this created an improvement in the ROP. For tests conducted under kinematical-control-mode, the energy supplied to the bit was constant, and thus less weight and torque-on-bit were observed, in view of the fact that part of the energy was provided by percussive action. These results support this new drilling method as a alternative technique to improve drilling performance.

5.1 Topics for Further Research

Many problems are still open for further research. This section gives recommendations and starting points for further research.

- The first topic concerns the improvement of the mathematical model of the hammer supported by beam springs. The presented model is capable of predicting the impact force magnitude and qualitatively describe the impact force behavior under different gap/ stiffness combinations. However, the model is not capable of predicting the hammer displacements, because it does not model the energy transfer of the impact energy to the elastic support dynamics.
- Because the hammer should be mounted inside the bottom hole assembly (BHA), which is a rotating device, it would be interesting to investigate the impact force behavior when the hammer is rotating along its central axis. This topic could describe the effect of drillstring rotation over the hammer.

– Tests on Frank under kinematical-control-mode have shown an advantage of this new technique, in which the magnitude of the drilling parameters can be minimized when impulsive loading or percussive action is added to the drilling process. Based on this result, we can consider that the RHD has potential application as an alternative technique for drilling highly deviated or horizontal and deep wells, where the torque and weight on bit are limited. However, this should be investigated in detail, so the advantage of such technique under directional drilling could be quantified.

– Another topic is the application of stochastic mechanics into the present research [66]. By considering each parameter of the impact model (k_i and c_i) a probability density function, instead of a deterministic parameter, it is possible to evaluate how the variation of the impact model parameters affects the overall system response.

– A recent article presented in the CILAMCE 2009 proposes harmonic solutions of nonlinear systems using Taylor and Fourier series [39]. It would be interesting to investigate if this theory is applicable to non-smooth dynamical systems, like the one presented in this thesis.

– In this work the impact force magnitude was used as the parameter that maximizes the hammer behavior. There are other parameters available, such as the impulse transmitted in each impact or the impulse transmitted per second. Other parameters should be investigated and compared in order to verify which parameter better describes the hammer behavior.

– Another topic is to observe the drilling progression (rate of penetration) using this hammer configuration, since the test rig studied does not consider rate of penetration.

– The last topic proposed is the application of this hammer configuration inside a BHA (bottom hole assembly) prototype. In this case the test rig would be mounted in the vertical position, more realistic with the field application. Other interesting effect to be observed is the influence of drillstring rotation over the hammer.