

Nonlinearity and Spectrum Analysis of Drill Strings with Component Mass Unbalance

F. Abdul Majeed, H. Karki, Y. Abdel Magid, M. Karkoub

Abstract—This paper analyses the non linear properties exhibited by a drill string system under various un balanced mass conditions. The drill string is affected by continuous friction in the form of drill bit and well bore hole interactions. This paper proves the origin of limit cycling and increase of non linearity with increase in speed of the drilling in the presence of friction. The spectrum of the frequency response is also studied to detect the presence of vibration abnormalities arising during the drilling process.

Keywords—Drill strings, Nonlinear, Spectrum analysis, Unbalanced mass

I. INTRODUCTION

THE performance of drill string and their effect on drilling performance has been investigated and analyzed by using the latest technologies of the time. The various vibrations affecting drill strings during drilling are mainly classified into three, axial, lateral and torsional. Axial vibrations are caused by sudden bit bouncing and cracks of the drill string. Lateral vibrations (bending) and torsional vibrations are caused by drill bit well bore friction. These vibrations require to be modeled carefully to analyze and understand the important and severe phenomena of stick slip, bit bounce and drill string rupture experienced in the drilling process. Many different models were set up to analyze drill string vibrations including lateral vibrations (whirl) and mode coupling [1-3]. Other researchers have focused on models which represent torsional vibration and have attempted to suggest methods to avoid stick slip behavior [4,5]. We have set up a model which works in the same principle as [4]. However taking into consideration recent researches in the field, [6] has modeled the drill string as an unbalanced rotor supported by two bearings. [7] explains that the source of vibration is the bit and hence the centrifugal forces developed when an unbalanced drill string is rotated can be one of the major sources of vibrations. [8] has modeled reduced order models for such a drill string system with a mass imbalance on the rotor and has analyzed the trajectory of the bit for various mass and angular velocities displaying bit whirl and stick slip characteristics.

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This paper intends to analyze the nonlinear properties displayed by the drill string system when a mass imbalance is added to the system. Further the paper also attempts to provide a discussion on the spectrum analysis of the system outputs in the no mass and mass imbalance cases. The discussion is based on the analysis done in [9] where vibration analysis of an electric motor with a mass imbalance is studied to detect abnormalities or cracks.

II. DESCRIPTION OF THE LABORATORY SET UP

To investigate the effects of nonlinear behavior exhibited by the drill string a laboratory set up (Fig. 1) is arranged. A DC motor is fixed to the upper platform of a cubical frame, and provides the torque necessary for simulating the drilling motion. A flexible string representing the drill string is connected to a rotary table fixed to the motor shaft by a universal joint (possess two degree of rotational freedom). A second rotor representing the BHA (drill bit and complementary components) is connected to the end of the string and hangs free. An unbalanced mass is added to study and analyse the nonlinear effects of bottom hole friction found in drilling wells. In the laboratory set up, when the motor is actuated, the shaft rotates the rotary table. This rotation forces the lower disc also to rotate. In the presence of unbalanced mass the lower disc is forced to move in elliptical and unexpected paths of rotation at lower speeds.



Fig. 1 Laboratory experimental drillstring set up and mass unbalance on lower rotor

A. Case 1: Ideal Zero Friction Condition

Initially the drill string system is allowed to rotate freely (0 unbalanced mass) condition. In this state the system can be compared to the state when the drill string rotates and there is no friction (ideal case) between the well bore hole and drill bit. It can be noted here that when the drill string is rotated in the ideal case with no friction at speeds of around 8 rpm, there exists some vibrations (Fig.2a). These can be termed as self

exited vibrations, which arise in the drilling at very low speeds. However it can be noted that when the speed is increased to around 36 rpm, the self excited vibrations disappear, and vibrations similar to limit cycling appear. At a speed of 51 rpm, the drillstring now rotates smoothly with lesser limit cycling and self excited vibrations.

The average speed of the drilling is at 50 – 60 rpm. Analyzing the graphs for case 1 angular velocity data, it is also worthy to note that the drill string system lags behind the command speed required to be followed at lower speeds of 8 rpm and almost reaches up to the command speed at 51 rpm. This deficiency at low speeds can be attributed to power dissipation in the elements. It is seen that the drill string upper and lower velocities are follow the command speed more closely at higher speeds due to the fact that the power received by the system is much higher than the power dissipated in the system.

B. Case 2: Small Unbalanced Mass Condition Representing Low Drill Bit - Well Bore Hole Friction

Utilizing the arguments from [6] and [7], we add a mass of 28gm on the lower rotor which represents the drill bit. Note the casing around the lower rotor in fig. 1, which represents the borehole, so as to study the effects of stick slip and whirling. It is seen that the drill string upper and lower velocities follow the command speed better than in the ideal condition(Fig.2). It is also noted that the self excited vibrations appear similar to case 1 when rotated at low speeds, but they are less prominent due to the higher mass of the bit. The increased mass forces the system to keep closer to the center and vibrations of the self excited type are minimized. This can also provide an explanation for the use of drill collars in the drilling rig to provide increased weight for the bit. As the speed is increased to 50 rpm, the system now rotates at a speed slightly higher than the command speed, this could be attributed to the increase in nonlinear properties of the drill string with an unbalanced mass addition.

C. Case 3: Large Unbalanced Mass Representing Higher Drill Bit – Well Bore Hole Friction

The unbalanced mass added to the lower rotor is further increased and now a 56 gm mass rests on the bit. The drill string follows the command speed closer at a speed of 39 rpm, but higher at speeds of 50 rpm, this may also be due to increased centripetal force and increased nonlinearity. Limit cycling vibrations are also more prominent, and a type of whirling can be noticed for the lower bit at higher speeds (Fig.2). This whirling will be changed to stick slip when there is increased friction between the well bore and lower bit. It is note worthy to mention here that the unbalanced mass can only represent the effect of constant friction on the lower drill bit. It cannot represent sudden friction or jerks effected on the drill bit due to unseen hard rocks or obstacles in the path of drilling.

Displayed in the figure 2a, 2b and 2c are the command speed applied to the system to be followed, the angular velocity data of the upper rotary and lower bit for the three cases. The angular velocities are displayed and analyzed in contrast to angular positions, because the vibration information is clearer and the behavior of the drill string at the lower bit in the x-y plane can be better analyzed in this manner.

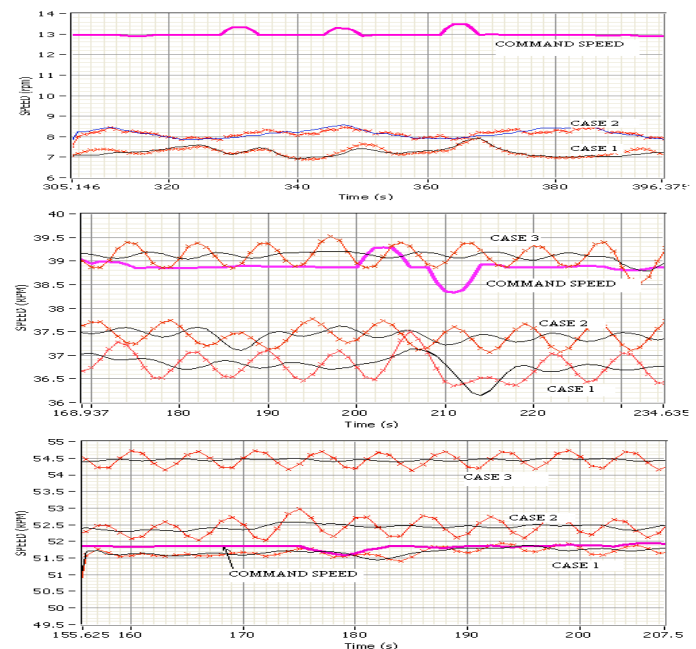
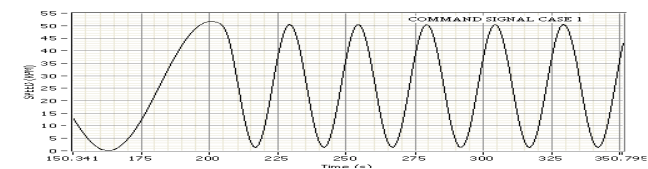


Fig. 2 The command speeds and the responses of the drill string angular velocity for different un balanced mass conditions and various speeds.

III. NONLINEARITY ANALYSIS: MINOR CHANGE IN INITIAL CONDITION

Case 1: Minor Change In Initial Condition: Frequency

Analysis of the system behavior for a minor change in input frequency signal for ideal and unbalanced mass conditions. Fig.3a displays the system response to a change in the frequency of applied input signal for the system under no mass or ideal condition. The residual signal from the system is plotted. It can be noticed that there is no major or erratic behavior displayed by the system in this case. The pattern of vibration is the same and there is only a slight change in the magnitude of the residual.



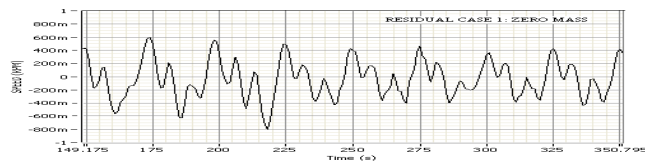


Fig. 3a Command signal (upper) and residual signal (lower) for zero mass condition

Fig.3b displays the command signal and the residual plots for the system when the input signal frequency is changed under un balanced mass condition. It can e noted here , that now the pattern of the residual signal has changed with a sight change in magnitude also. This implies that the vibration pattern of the lower bit when compared to the upper rotary has changed. It is interesting to note here that the implication is the increase of nonlinear properties of the drill string in the presence of continuous friction, represented by the unbalanced mass.

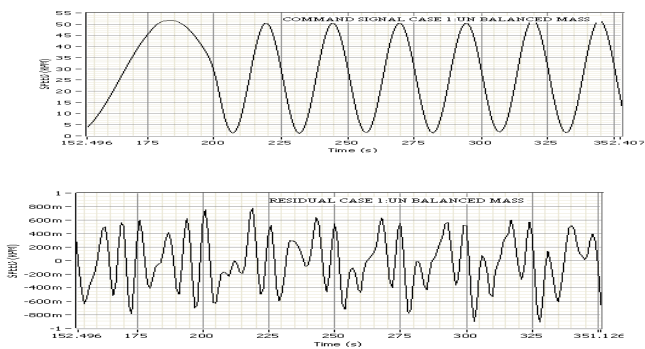


Fig. 3b Command signal (upper) and residual signal (lower) for un balanced mass condition

Case 2: Minor Change In Initial Condition: Magnitude

Here, we present an analysis of the drill string system behavior under ideal and unbalanced mass conditions, when a slight change in magnitude is made to the input command signal. Fig.4a displays the response of the system to a magnitude shift of the applied input signal under no mass or ideal condition. A command speed of 50 rpm is applied to the drill string system, and shift to 52 rpm is made at a time of approximately 150s. The residual signal from the system is potted. It can be noticed that the residual initially decreases in magnitude slightly, but returns to the original magnitude soon and there is no evident change in vibration pattern.

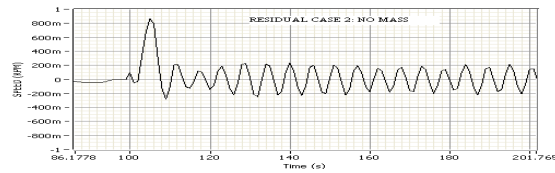
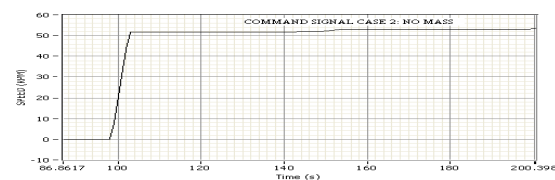


Fig. 4a Command signal (upper) and residual signal (lower) for no mass condition

The command signal and the residual plots for the system when the input signal magnitude is changed slightly under un balanced mass condition is plotted in figure 4b. The shift takes place at approximately 265 s and the magnitude of the command signal is varied from 50rpm to 52 rpm. Analyzing the residual plot, it is seen that following a delay of around 30 s to follow the command, the residual signal displays a slight decrease in magnitude and does not return to the previous magnitude or pattern of vibration. These experiments prove the increase of nonlinear properties of the drill string in the presence of continuous friction, represented by the unbalanced mass.

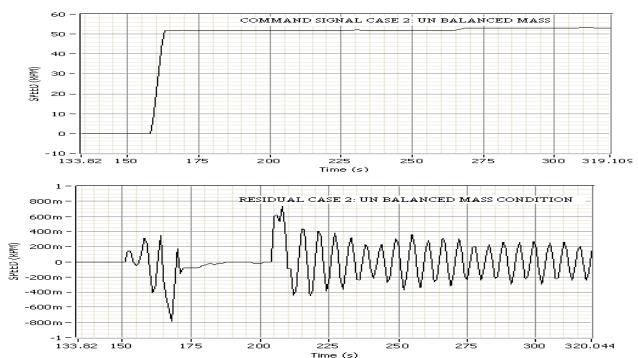


Fig. 4b Command signal (upper) and residual signal (lower) for un balanced mass condition

IV. SPECTRUM ANALYSIS

Spectrum analysis of the drill string system in the presence of small mass unbalance and high mass unbalance is discussed below. Referring to [9], where they have identified vibration abnormalities from spectrum analysis, we can see the same pattern in the drill string analysis. Fig.5 (upper) shows the frequency response spectrum of the drill string system in the presence of a small un balanced mass on the rotor. Fig.5 (lower) plots the frequency response spectrum of the drill string system for a large un balanced mass on the rotor. The 'high peaks' in the magnitude of the spectrum for large mass implies the presence of larger vibration in the system. The spectrum analysis of fig 4a also shows that the system initially experienced vibration, but it is trying to overcome it during the rotation. Both the spectrum is taken from readings when a sweeping sine signal is applied to the system under the respective mass unbalance conditions.

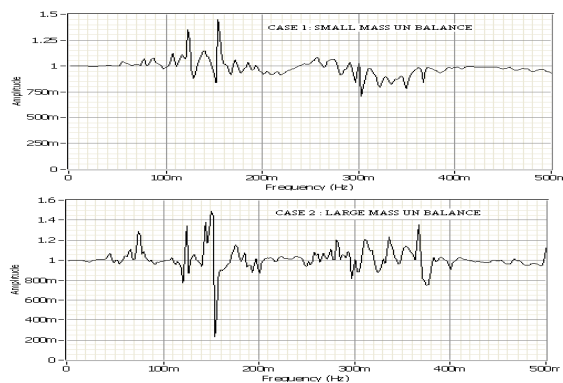


Fig. 5 Drill string vibration frequency response spectrum under small mass (upper) and large mass (lower) unbalance.

V.CONCLUSION

This paper analyses the study on the underlying causes for the non linear properties exhibited by drill string when affected by continuous friction. The study proves that the nonlinear properties exhibited by the drill strings increase with increase in the friction between the drill bit and well bore hole interactions. The nonlinearity and the increase in limit cycling tendencies are also proven. Further recommendations are for study of the dynamics under various other friction conditions affecting the drill string.

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