Drill string nonlinear vibrations: experimental studies and finite-element analysis

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Abstract. In the present work, nonlinear vibrations of drill strings are studied. A laboratory scale arrangement consisting of a flexible rod with rotor-stator system is used to study the system dynamics. A finite-element model has been developed to study the system dynamics. Qualitative changes in the system dynamics are examined with respect to variation in the rotation speed, with a focus on whirling and stick-slip motions. The finite-element model results are compared with experimental results. It is believed that the developed finite-element model can be important for the design analysis of drill strings as well as understanding the system dynamics.

1. Introduction
Drill strings are assemblies of slender structured pipe segments, which are used especially in drilling operations to transfer power from the rotating motor, at the surface, to the drill bit at the bottom. Due to interactions with the accumulation of cuttings in a wellbore as well as the wellbore, a drill string can experience several problems during operations\cite{1}. One of them is nonlinear vibrations, which can affect the different system components and lead to drilling operation failures. In general, capturing nonlinear effects is not an easy task, and in the current context, this makes the prediction of drill-string dynamics difficult.

Over the last decade, challenging research studies involving experimental and numerical methods have been undertaken to explore drilling operations and understand associated stick-slip whirl interactions. For instance, several finite-element-models (FEM) have been developed and used to predict system response. Klocke \textit{et al.} \cite{2} predicted the cutting forces by using a three-dimensional thermomechanical coupled FE method for carbide gun drills. Su \textit{et al.}\cite{3} used commercial FE analysis software to carry out finite volume simulations of titanium alloy drilling for different feed rates and drilling speeds. Fu \textit{et al.}\cite{4} modelled the transient response of string performances during gas drilling. Gardner and Dornfeld \cite{5} showed that it is possible to capture needed drilling parameters on a FEM based software called DEFORM. Experimental validation of FEM studies has been discussed by Kheireddine \textit{et al.}\cite{6}. Overall, from a review of previous studies, the authors have formed the opinion that FEM based modelling efforts to explain the phenomenon of stick-slip motions and whirling involving torsional and lateral motions have not received much attention. Furthermore, experimental
efforts in conjunction with FEM studies have been rather limited. This gap is addressed in the present work.

In the present study, an experimentally validated three-dimensional FEM model for a rotor enclosed within a stator and subjected to dry friction is presented. Predictions of lateral vibrations are made and compared to experimental observations. Different operating conditions are examined.

2. System Description
One of the main components of the bottom hole part of a drilling system is the drill string that is comprised of three parts, namely, drill pipes, bottom hole assembly, and drill bit, as presented Figure 1.

![Figure 1. Schematic of vertical drilling system.](image)

The drill string can be said to be the most critical part of a drilling system since it is used to transmit torque and drilling mud to the bit, exert weight on bit, and control trajectory of the bit deep below the Earth’s surface. The drill bit is used to cut through rock and other formations to create holes. The top drive is principally composed of rotary table, which is used to provide the drilling torque to the drill string and through it to the drill bit. The drill string system is surrounded by soil and rock. Structurally, a drill string can be considered as a long, flexible and rotating core embedded into an outer shell or simplistically as a rotor enclosed within a stator subjected to dry friction. This structure is the subject of the author’s investigation, which is presented next.

3. Finite Element Analysis and Experimental Validation

3.1 Experimental design and arrangement
During operations, a drill string may undergo forward whirling without any contact with the surroundings, forward whirling with contact and stick-slip motions, or backward whirling with contact. For furthering the understanding of drill string dynamics and exploring schemes for controlling them, a 24:1 laboratory scale version of a drill string section has been constructed. As presented Figure 2 and 3, a rotor-stator system is considered: The drill string is represented by a long aluminium rod with an unbalanced aluminium disc at the bottom.

The system is driven at the top by a servomotor with controlled rotation speed. The borehole is simulated by an outer shell. The experimental system parameter values and operating conditions are shown in Table 1.
Figure 2. Three-dimensional design of experimental apparatus.

Figure 3. Experimental realization of rotary drilling system at Qatar University.

Table 1. Parameter values for experimental studies.

| System Variables & Parameters | Notation | Value | Units |
|-------------------------------|----------|-------|-------|
| Rotor diameter                | Dr       | 0.15  | m     |
| Stator diameter               | Ds       | 0.18  | m     |
| Drill string length           | L        | 1.92  | m     |
| Mass of rotor                 | mr       | 1.1   | Kg    |
| Unbalanced mass on rotor      | mm       | 0.06  | Kg    |
| Initial rotor position        | ρ        | $10^{-3}$ | m |
| Rotation speed                | Ω        | 60-120 | RPM  |

Strain gauges were used at different spatial locations along the drill string and accelerometers were fixed to the rotor to measure accelerations in the lateral direction. Experimental data of rotor lateral vibrations and torsional strain were recorded for different rotor drive speeds. The studied motions included whirling. By integration of the obtained acceleration time histories, velocity of the rotor is obtained.
3.2 Finite element analysis: Result and comparisons

Rotor motions were examined for driving speeds in the range of 60 to 200 RPM. A finite-element model of the drill string was first constructed by using LS DYNA software. Adaptive explicit meshing is performed. The assembly is composed of four FEM parts, including the servomotor, the drill string, the rotor and the outer shell, as presented in Figure 4.

The drill string, rotor, and stator are described with 2.5, 4.6, and 6.321 millions of nodes, respectively. The resulting model is used to study the non-linear response for different rotation speeds. The nonlinear response of the structure has been analyzed with finite element method. Qualitative comparisons are made between experimental results and FEM based results.

Figure 4. FEM representation of system components.

Figure 5. Rotor response velocity variation with drive speed. (a) FE analysis at $\Omega=60$ RPM. (b) FE analysis at $\Omega=100$ RPM. (c) Experimentally observed rotor velocity response at $\Omega=60$ RPM. (d) Experimentally observed rotor velocity response at $\Omega=100$ RPM.

At low driving speeds, the simulation results suggest that the lateral vibrations have irregular characteristics. Rolling and bouncing phases of motion dominate, leading to the irregular characteristics observed. When the vibrations have regular characteristics, the rotor motion is found to be stable and
the drill-string motions are closer to the radial center of the system. As the driving speed is increased, the lateral vibrations are found to be excited further and sliding motion phases are also observed, as found in previous work[7]. The FEM based simulation results are found in to be good qualitative agreement with the experimental results. When the driving velocity is enhanced, these vibrations are converted to regular lateral oscillations over time. Rotor is more stable and drillstring motions are closer to the radial centre. For both cases, the FE analysis results compared well with the experimental studies (see Figure 6). For high driving speed, lateral vibrations are excited, sliding motion with rotor-stator contact results on dry friction permanent whirl[7]. Torsional and lateral motions are strongly coupled and backward whirl also occurs for certain rotation speeds. When only the first torsion mode of vibration is excited, the strain measurements are directly proportional to the torsion displacement[8]. Strain measurements made on the drill string close to the rotor-stator system are presented in Figure 7.

At low driving speeds, the drill-string motion is dominated by torsion motion, with associated impacts of the rotor with the stator, as shown in Figure 8a. For intermediate rotation speed values, the drill-string lateral vibrations are excited, which result in bending of the system. For high driving speeds, lateral and torsional motions are coupled and the rotor undergoes whirling motions, as seen in Figure 7b and confirmed by the EM based results of Figure 8d.

![Figure 6](image1.png)

(a) (b)

**Figure 6.** Rotor motions illustrating sticking and sliding phase at $\Omega=200$ RPM. (a) Experimental observation. (b) FEM results.

![Figure 7](image2.png)

Figure 7. Experimental observed torsion strain. (a) $\Omega=60$ RPM. (b) $\Omega=200$ RPM.
Figure 8. System lateral displacement. (a) $\Omega= 60$ RPM, (b) $\Omega= 100$ RPM, (c) $\Omega= 140$ RPM, and (d) $\Omega=200$ RPM.

4. Concluding Remarks
Dynamic of a section of a drill-string within a wellbore has been studied as a rotor-stator system through experiments and finite-element model-based simulations. The experimental results and simulation results are in good qualitative agreement. The results suggest that intermediate driving speeds may be preferable comparable to low or high driving speeds.

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