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CFD Simulation of the Hydrodynamic Vibrator for Stuck - Pipe Liquidation

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Abstract**—**Stuck-pipe in drilling operations is one of the most pressing and expensive problems in the oil industry. This paper describes a computational simulation and an experimental study of the hydrodynamic vibrator, which may be used for liquidation of stuck-pipe problems during well drilling. The work principle of the vibrator is based upon the known phenomena of Vortex Street of Karman and the resulting generation of vibrations. We will discuss the computational simulation and experimental investigations of vibrations in this device. The frequency of the vibration parameters has been measured as a function of the wide range Reynolds Number. The validity of the computational simulation and of the assumptions on which it is based has been proved experimentally. The computational simulation of the vibrator work and its effectiveness was carried out using FLUENT software. The research showed high degree of congruence with the results of the laboratory tests and allowed to determine the effect of the granular material features upon the pipe vibration in the well. This study demonstrates the potential of using the hydrodynamic vibrator in a well drilling system.

Keywords**—**Drilling, stuck-pipe, vibration, vortex shedding.

I. Introduction

DRILLING wells for the procurement of natural resources such as oil and gas holds prime importance in today's world. Drilling procedure requires a drill string to transmit the torque provided at the surface to rotate the bit, and to transmit the weight necessary to drill the formation. The driller and the directional driller steer the well by adjusting the torque, pulling and rotating the drill string. When the drill string is no longer free to move up, down, or rotate as desired, the drill pipe is stuck. Stuck drill pipe leads to vast time and money losses. Sticking can occur while drilling, making a connection, logging, testing, or during any kind of operation which involves leaving the equipment in the hole.

According to Bowes and Procter [1], position of hydrostatic head can also cause a stuck-pipe. If it is lower than normal, stuck pipe problem may arise. There are many causes of pipe sticking; yet the most common one is differential sticking. It occurs when there is less pressure in the formation fluid and high pressure in the mud. In other words, when the drill collar which is resting at the borehole wall sinks into the mud cake, differential sticking occurs.

In this case, the portion of a drill collar which does not sink into the mud cake has a different pressure than the area embedded in the mud cake. Fig. 1 illustrates this point.

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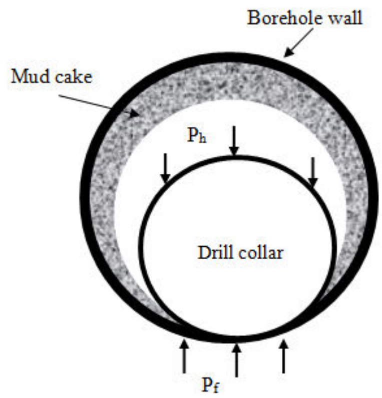

Fig. 1 Differential sticking, Ph hydrostatic pressure and Pf is formation pressure

As illustrated in the figure, the pressure on the area which does not sink is equal to the hydrostatic pressure in the mud, whereas the pressure on the embedded area is equal to the formation pressure. Now when Ph > Pf, the drill collar will be pushed towards the borehole wall due to the force acting on it. There are various methods to eliminate sticking and one of them is to balance the pressures. We can create vibration perpendicular to the axis of the drill collar. These vibrations are generated by a hydrodynamic vibrator, which can be connected to the drill collar near the area where the stuck member is located. The hydrodynamic vibrator generates sinusoidal vibrations perpendicular to the pipe axis and at the same time transmits large percussive forces to the pipe. The vibrating transverse pipe condenses surrounding granular material to reduce the well bore friction, and thus allows to balance the pressures. The work principle of the vibrator is based upon the known phenomena of Vortex Street of Karman and the resulting generation of vibrations. It is known [2]-[4] that the process of fluid flow around a sphere is accompanied by a periodic vortex trail (vortex street of Karman), which induces vibrations and that the resulting forces act on the sphere in a direction perpendicular to that of the flow.

The growth and movement of these vortices creates a fluctuating lift and drag force on the sphere [4], [5]. It is known that the flow in a hydraulic device is turbulent and it causes chaotic vibration [3]-[5]. A growing body of evidence shows benefits of exploitation of vibration for the operation of hydro-mechanical systems.

We reveal the phenomenon of the ball vibration of the sphere in direction perpendicular to that of the flow. This phenomenon was investigated by an experimental device and by computational simulation.

Applications of computational fluid dynamics (CFD) to the industry continue to grow as this advanced technology takes advantage of the increasing speed of computers. In the last two decades, different areas of flow modeling including grid generation techniques, solution algorithms, turbulence modeling, and computer hardware capabilities have witnessed tremendous development. In view of these developments, computational fluid dynamics can offer a cost-effective solution to many engineering problems. Various researchers used turbulence modeling to simulate flow around axisymmetric bodies.

In this study we use FLUENT (fluid dynamics computer simulation software) to model the flow around a sphere in a pipe, when the flow is turbulent. Prediction of flows that exhibit massive separation remains one of the principal challenges of CFD. The main interest of the present study is to calculate the turbulent flow over a sphere at high Reynolds numbers.

The aims of this study were: the experimental investigation of the stability and instability of the vibration of the sphere in fluid flow inside a hydrodynamic vibrator; validation of the computational simulation versus experimental results; illustration of the possibility to exploit this phenomenon.

The nature of the flow around a sphere in a pipe changes as the Reynolds number of the flow increases, according to Constantinescu [6], [7].

II. Experimental Apparatus

A schematic description of the experimental setup is presented in Fig. 2. The system consists of the following components: storage tank (1), centrifugal pump (2), throttle valve (3), flow meter (4), manometers (5) and (8), hydrodynamic vibrator (6), spectrum analyzer vibration meter (7). The fluid (in our case water) is circulated from tank (1) through hydrodynamic vibrator (6) by centrifugal pump (2). The flow rate was controlled by throttle valve (3) and measured by flow meter (4).

The fluid passes through the gap between the ball surface, which is replaced, and the wall of the vibrator's body. The frequency of the vibration was measured by FFT spectrum analyzer vibration meter (type SR 760) and using acceleration sensor (Bruel & Kjaer type 4375V). The size of the ball in combination with the inner vibrator's diameter was examined for certain value of the flow rate (in the following ranges: ball diameter 0.035 m; inner diameter of the vibrator 0.039m, and flow rate up to 1 x 10^{-3} m^3/s).

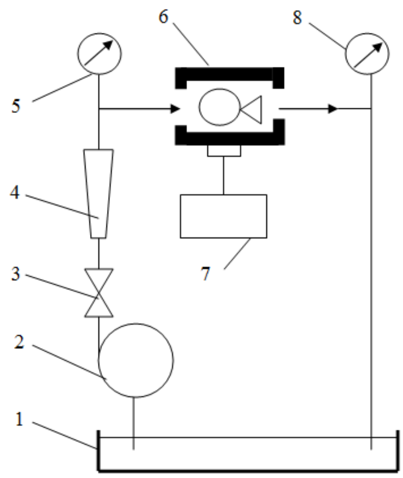

Fig. 2 Experimental setup

The distinctive features of the vibration device are: the module- based construction providing significant force for the pipe; easy and convenient adjustment of the vibration parameters by changing the liquid flow; simplicity and reliability of the design; time-efficient installation of the vibration module directly in the location of the stuck member.

III. Experimental Results

The experimental apparatus allows us to explore the ball and the vibrator wall interactions for different conditions. The results of the measurement dimensionless vibration and rotation of the ball vs. Reynolds number are presented in Fig. 3. It's evident that the frequency of the vibration depends on the flow rate. The experiments showed that the frequency of the ball vibration is directly proportional to the angular velocity of its rotation.

The regimes of the stable and unstable vibrations of the ball for other conditions of the device were also found.

Fig. 3 represents the results of the measurements and numerical calculations. It can be seen that the frequency of the vortex shedding is directly proportional to the flow rate (the graph shows the rotation of the ball dependence on Reynolds number) in the hydrodynamic vibrator.

The experiment results (empty diamond points) showed that the frequency of the ball rotation is also directly proportional to the flow rate. The linear relationship between ball rotation and the Reynolds number was highly congruent with the result of the computational simulation (full triangle point).

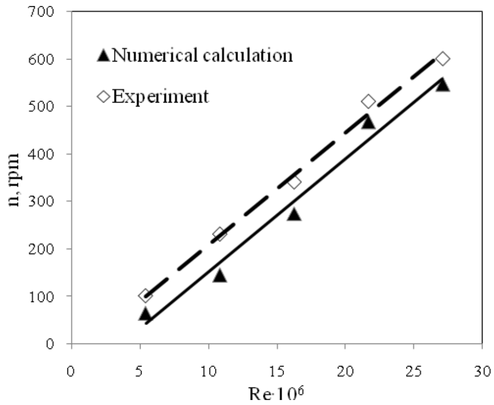

Fig. 3 Rotation of the ball in the experiment (empty diamond points, dashed line) and drag coefficient frequency (C_D) from numerical calculation (full triangle points, solid line) vs. Reynolds number

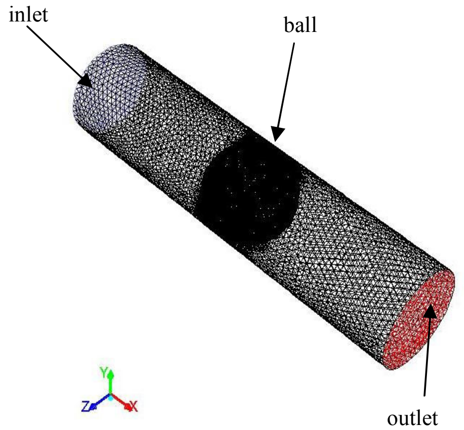

Fig. 4 Numerical calculations mesh

IV. Simulation Overview

A computational model of unsteady, periodically separated, high Reynolds number flow in the hydraulic vibrator is developed using FLUENT computational fluid dynamic software (14). The code solves time-dependent equations for conservation of mass, momentum using second-order accurate, cell-centered finite volume method on the unstructured grids. The computation domain (Fig. 4) is divided into 128960 grid elements of edge size ~1 mm with the strong smoothing region around the ball and with the medium smoothing region in the vibrator the ball (i.e. in the ball-wake region).

The simulations include large-eddy simulation turbulence modeling based on a wall-adapted local eddy-viscosity sub-grid-scale model. Due to the high Reynolds number simulations, wall shear stress of the ball is modeled by using the instantaneous logarithmic law of the wall. Since the simulated flow is assumed to be fully turbulent, the turbulence model is active over the entire surface of the ball using the Switch P-V Coupling Scheme, Bounded Central Differencing for spatial discretization of the momentum equation and Switch Spatial Discretization scheme for pressure. The calculations were running for 10000 time steps with 1e-3 seconds time step size yielding 50 iterations per time step.

The periodicity nature of the flow over the ball is considered to be due to periodical shedding of vortexes. To determine the major vortex-shedding frequency we have used Fast Fourier Transform (Fig. 5) of time-history of the drag coefficient on the ball recorded during simulations. To observe the shedding of vortexes we presented the iso-contours of vortices magnitude (Fig. 7).

The numerical simulations carried out here show stability of the changes the drag coefficient of the ball in the hydrodynamic vibrator. This proves that the process is not random. Another proof of the above-mentioned is shown in Fig. 6, which presents measurements of acceleration of the drag coefficient (curve 1, numerical simulation) and changes in amplitude vibration of ball in the hydrodynamic vibrator (curve 2, experiment) as a function of time. These measurements confirmed the stability of the process of ball vibration, and also confirmed the identity of the frequency oscillations.

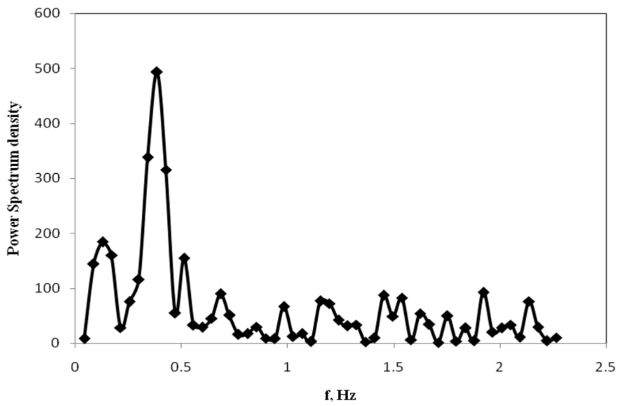

Fig. 5 Power spectrum of C_D for mass rate flow of 0.4 kg/sec

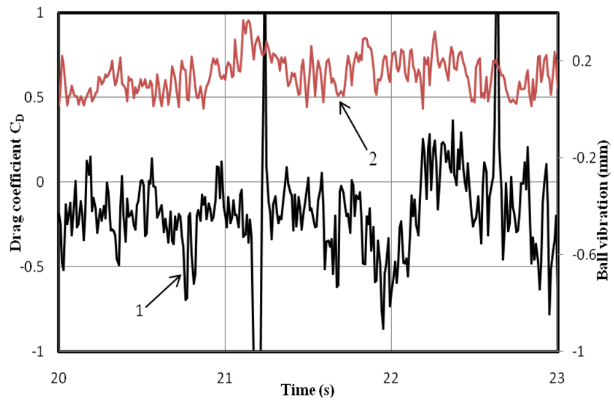

Fig. 6 Oscillations drag coefficient (curve 1) and ball vibration (curve 2) vs. time

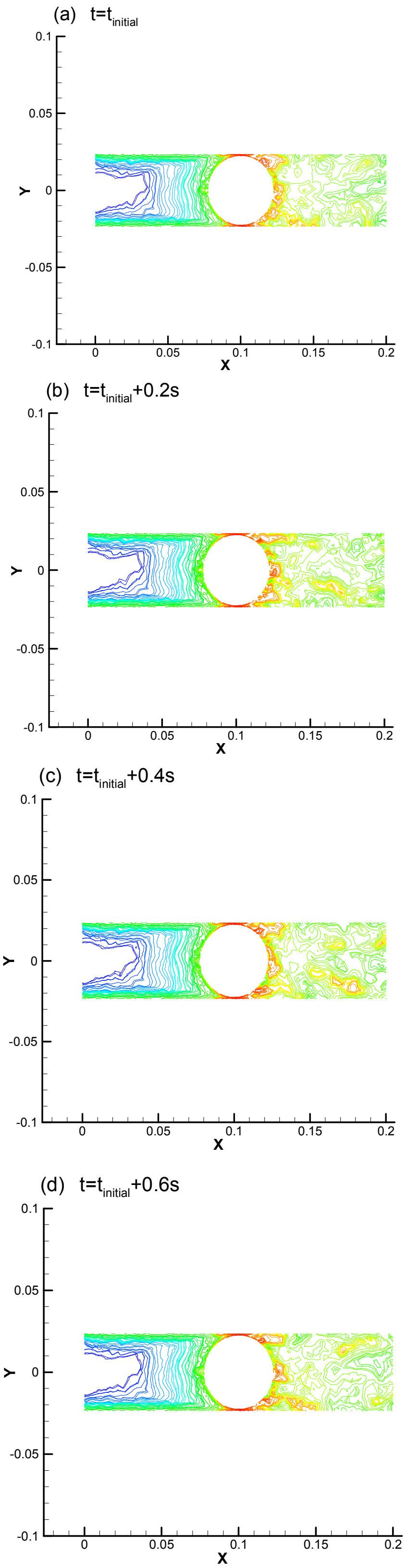

Fig. 7 Mid-section (X-Z plane) iso-contours of vortices magnitude during one period of oscillation

III. Conclusions

The following results were obtained in this study. The stability and instability of the ball vibration in a valve were studied by an experimental method and CFD simulation. A FLUENT model is used to predict the flow over a sphere in the valve for a range of Reynolds number up to 10^5. Comparison of the present results with experimental data showed that the predictions obtained by CFD software successfully reproduced most of the flow features associated with the vortex shedding. This study demonstrates the possibility to control the vibration in a hydraulic system.

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