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Modeling And Simulation Of The Dynamic Behavior On Geothermal Drill Rod Train: Case Of Torsion Vibration

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Abstract*— The goal of this work is to understand the torsional vibration caused by the stick-slip or glue-slip phenomenon. In geothermal drilling operations, problems that hamper work efficiency and cause losses by lengthening the work often remain. Almost all of these problems come from unwanted vibrations which first affect the packing, causing them increased fatigue and causing them to fail prematurely. To better illustrate it, a tool-rock contact model is given. This model is made to observe the parameters that cause vibrations, giving a possibility to avoid them in reality. This model has been treated with a dry friction at the BHA (Bottom Hole Assembly) level. To show the simulation of the stick-slip phenomenon, parameters were given and simulated under MATLAB with the motorization system. In order to escape the dry friction; the combination of varying the three parameters: increasing the speed of the rotary table, reducing the weight on the tool and increasing the dynamic viscosity of the drilling mud allow the stick-slip phenomenon to be canceled. During the drilling operation, all the parameters which directly or indirectly affect the efficiency of the work will be taken into account and should not be excluded from a modification in order to reduce as much as possible the duration of the work. Operation while avoiding material wear, basically minimize the blow of labor.

Keywords— Influence of Vibration; Dry friction; Stick-slip Phenomenon; Tool-Rock Contact; Numerical Resolution

I. INTRODUCTION

Drilling is the set of operations that make it possible to dig holes to reach new underground areas likely to contain water vapor. Several are the techniques for drilling but for high depth Rotary drilling is the appropriate technique. This process represents the main and the bulk of the total cost of an installation.

1.1 Elements of a Drilling Set

The drill string is the most important part in a geothermal drilling operation. It is the part going down into the well. Also referred to as a drill shaft, because of the linkage mechanism that it establishes between the rotary motorization on the surface and the bit, it corresponds to the operative part in the well (Figure 1).

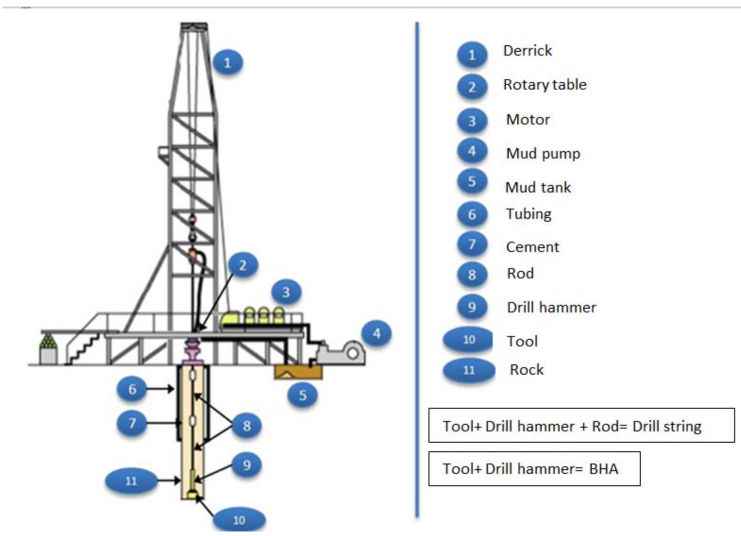

Fig. 01 Geothermal Drilling Structure

Several tasks are necessary in its field of application including the transmission of the energy necessary for the disintegration of the rock, the transmission of the thrust force, the guide and the control of the trajectory of the well, as well as the circulation of the fluid. drilling. Over its entire length, it consists mainly of drill collars (Drill Collars) and drill pipes (Drill pipes). To this are added accessories such as stabilizers for the drill bits, shock absorbers, measurement systems and all that may be essential during the operation. (Figure 2)

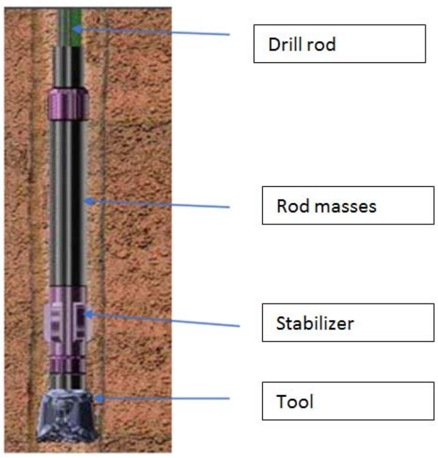

Fig. 02 the drill string [1]

1.2 Dynamics of Drill Rods (torsional vibrations)

The phenomenon of vibrations is recurrent during geothermal drilling operations, and is the major cause of fatigue in drilling systems. The vibrations of the lining are broken down into three modes: axial, torsional and lateral (Figure 3).

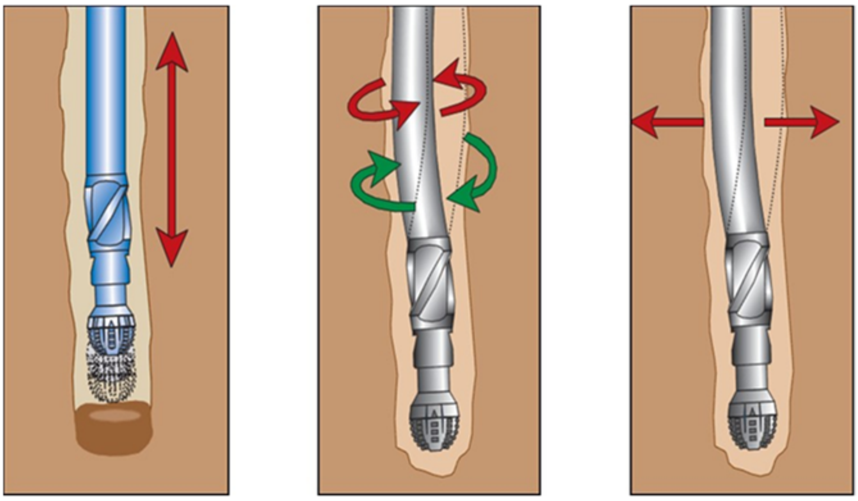

Fig. 03: Vibration Modes, (Left: Axial, Middle: Torsion, Right: Lateral)

Usually all three types of vibrations occur simultaneously during the drilling process and in some cases it is difficult to identify them separately. The most severe vibrations occur at the level of the BHA. They are responsible for reducing the speed of drilling and therefore increasing costs.

Variations in surface torque are often observed during drilling. Also, even if the rotational speed is kept constant at the surface, downhole measurements show that the rotational speed of the drill tool can fluctuate. These observations highlight the existence of torsional vibrations in the lining (Figure 4). The lining-forming interaction is the primary cause of these vibrations. Torsional vibrations are as harmful as axial vibrations in that they cause wear on rods, damage to rod fittings and the drilling tool.

The stick-slip phenomenon is the severe form of torsional vibration, it usually occurs at the tool level and is characterized by alternating stopping and acceleration phases of the tool. During the acceleration phase, the rotational speed of the tool can reach several multiples of the set surface speed (Figure 4).

This phenomenon is produced mainly by the different contact zones between the BHA and the well (these are well rod-wall and drill-rock interactions). This contact creates frictional forces, the most important of which are non-linear friction between the bit and the rock as a function of its speed.

In addition to its role of lubricating and cooling the tool, mud influences the coefficient of friction between the bit and the rock. Its influence is on the viscous coefficient of friction, which we will study in this work, looking for its influence on the Stick-Slip phenomenon.

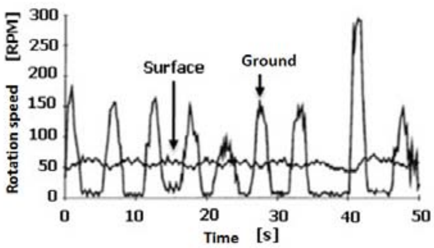

Fig. 04: The Stick-Slip Phenomenon (DYKSTRA, 2011)

II. MODELING THE STICK-SLIP PHENOMENON

1.3 Modeling of the dynamic system

1.3.1 Tool-rock contact model

Because of the diversity and inhomogeneity of the structure of the rocks to be drilled, modeling the contact between the latter and the tool is complex. As a result, several tool-ratchet interaction models have been developed and modeled. Among these models, the DETOURNAY model which is relatively easy to use will be developed in this work [3]. The interaction between the one-piece bit and the rock is actually a combination of two processes: the cutting of the rock and the friction of the tool against the rock.

- Cutting process

Fixed cutting element tools (PDC or TSP) work much like a machine tool tool, shearing rock. But to achieve this effect, a crushing force necessary to counter any resistance in the system and a cutting force causing the tool to rotate will be applied. The resulting cutting torque on the tool is given by:

$$T_c = \frac{1}{2} R^2_{bit}\, \varepsilon\, d \qquad (1)$$

With

R_{bit} : Tool radius (m)

ε : Intrinsic specific energy of the rock (J/m^3)

d : cutting depth (m/rev)

- Dry rubbing process

Torque input that opposes the friction torque of the tool against the rock is imperative in a drilling process. The friction model taken into account in this study is that of KARNOPP. This model was designed to make it possible to define a zero speed interval in which friction is no longer a function of speed, but depends only on the external force. This model is able to simulate Stick-Slip type movement. The dry friction at the level of BHA under the model of KARNOPP [4] are given by:

$$T_f = \begin{cases} T_e & \text{if } |\Omega_b| < D_v \text{ et } |T_e| < T_s \\ T_s \,\mathrm{sign}(T_e) & \text{if } |\Omega_b| < D_v \text{ et } |T_e| \geq T_s \\ T_d \,\mathrm{sign}(\Omega_b) & \text{if } |\Omega_b| \geq D_v \end{cases} \qquad (2)$$

With

Ω_b : tool rotation speed (rd/s)

T_e : torque of the resulting external forces (N.m)

T_s : static friction torque (N.m)

T_d : dynamic friction torque (N.m)

D_v : zero speed interval.

The frictional forces are present mainly at the level of the blades of the drilling tool, an elementary calculation of the forces of dry friction guides us to a formula of the torques of dry friction on the tool. The resulting static (dynamic) friction torque on the tool:

$T_{s(d)} = \frac{1}{2} N_b\, \mu_{s(d)} R_{bit}$ *(3)*

With

$\mu_{s(d)}$: coefficient of static friction (dynamic)

N_b : the normal force on the tool (N) such that: $N_b = g$ Wob

g : gravitational constant,

Wob : Wob: weight on the tool (Kg)

The total torque that manifests at the tool (Tob: Torque on the Bit) and the sum of the two torques, cutting and friction.

$Tob = T_c + T_f$ *(4)*

$$Tob = \begin{cases} T_e & \text{if } |\Omega_b| < D_v \text{ et } |T_e| < (T_s + T_c) \\ \frac{1}{2} R^2_{bit}\, \varepsilon\, d + \frac{1}{2} \mu_s\, g\, Wob\, R_{bit} \operatorname{sign}(T_e) & \text{if } |\Omega_b| < D_v \text{ et } |T_e| \geq (T_s + T_c) \\ \frac{1}{2} \mu_d\, g\, Wob\, R_{bit} \operatorname{sign}(\Omega_b) & \text{if } |\Omega_b| \geq D_v \end{cases}$$

1.3.2 Dynamics of the BHA (Bottom Hole Assembly)

By applying the fundamental principle of Dynamics (PFD) on BHA we find:

$$J_b \ddot{\varphi} = k(\varphi_t - \varphi_b) - C_b \dot{\varphi}_b - Tob(\dot{\varphi}_b, Wob) \qquad (5)$$

By asking: $\Phi = \varphi_t - \varphi_b$ et $\dot{\varphi}_b = \Omega_b$

This equation is written:

$$J_b \dot{\Omega}_b = k\Phi - C_b \Omega_b - Tob(\dot{\varphi}_b, Wob)$$

With

$\varphi_{t(b)}$: angular position at the top (bottom) of the drill rod (rad)

Φ : Difference between angular positions at the top and bottom of the drill pipe (rad)

Ω_b : tool rotation speed (rd/s)

Tob : Torque on Bit (N.m)

C_b : Viscous coefficient of friction equivalent to the level of BHA. (N.m.s)

J_b : Moment of inertia equivalent to the level of BHA (kg.m²)

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The Top Drive (TD) is a multi-functional unit that rotates the drill string, without the need for a rod (Kelly), and performs other operations at the wellhead. It offers parameters (torque, speed) greater than those provided by the rotation table

- Mechanical equation

The motor shaft is coupled to a gearbox coupled directly to the drill pipes

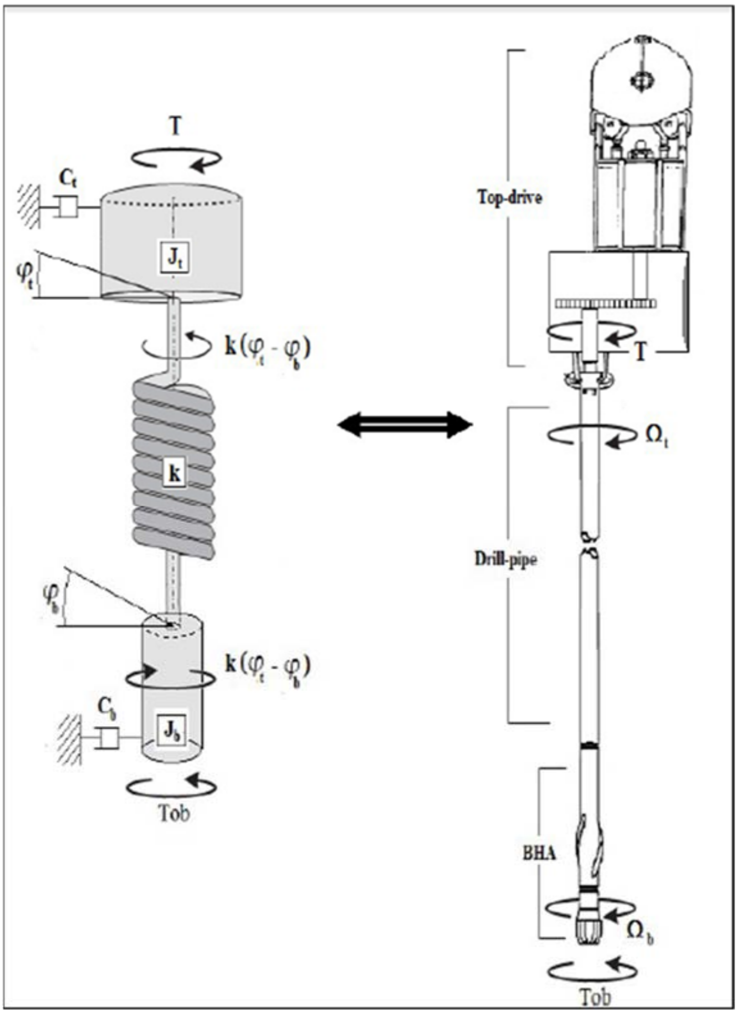

Fig. 05 Torsion pattern of the packing

The drill string is modeled as a simple torsion pendulum with a spring of stiffness k equivalent to drill rods. (Figure 05)

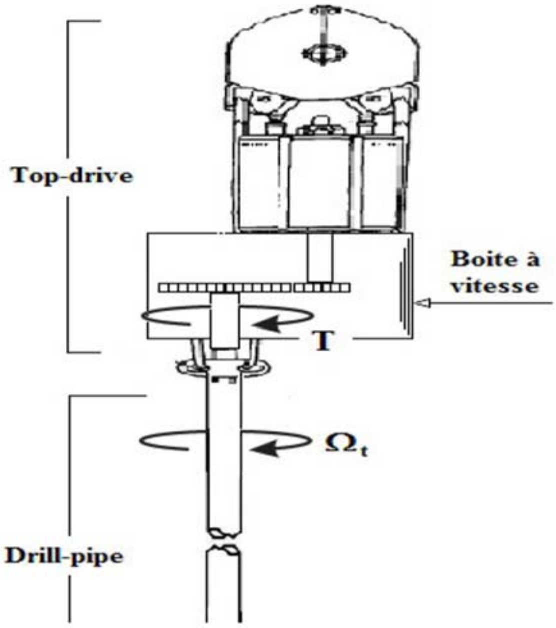

Fig. 06 Attaching the Drill Rod to the Reducer

By applying the principle of PFD on the drive shaft of the drill pipes, we find the mechanical equation of the motor (figure 06):

$J_t\ddot{\varphi}_t = T - C_t\dot{\varphi}_t - k(\varphi_t - \varphi_b)$ ***(6)***

Such as

$T = nT_m$

T_m : engine couple (N.m)

n : gear ratio of reducer

The motor torque is the current in the armature to a constant such that

$T_m = K\, i$ ***(7)***

By asking: $\Phi = \varphi_t - \varphi_b$ et $\dot{\varphi}_b = \Omega_b$

Finally the equation is written

$$J_t\dot{\Omega}_t = nKi - C_t\Omega t - k\,\Phi$$

With

Ωt : : surface rotation speed (rd/s)

J_t: Equivalent moment of inertia at the upper part of the rods (kg.m²)

C_t: Equivalent viscous coefficient of friction at surface level (N.m.s)

K : torque constant (~ speed constant) (N.m/A)

i : current in the armature (A)

- Electric equation

The motor in question is a direct current motor, the armature diagram is shown in the figure below (figure 07):

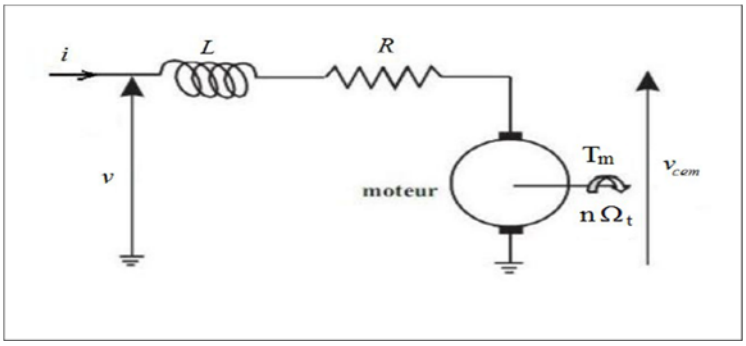

Fig. 07 DC motor armature circuit diagram

The application of the Mesh laws leads us to the result

$$v = L\frac{di}{dt} + Ri + v_{cem} \qquad \textbf{(8)}$$

Such as

$$v_{cem} = nK\,\Omega_t \qquad \textbf{(9)}$$

v_{cem} : voltage against electromotive (V)

Therefore

$$v = L\frac{di}{dt} + Ri + nK\,\Omega_t$$

With

v : armature voltage (V)

i : current in the armature (A)

R : armature resistance (Ω)

L : armature inductance (H)

1.4 State representation and main parameters of the model

State representation allows you to model a dynamic system using state variables. This representation makes it possible to determine the state of the system at any future moment if we know the state at the initial moment and the exogenous variables which influence the system.

The state formatting of the previous equations is shown below. The system is nonlinear because of the presence of the discontinuous function

$Tob\ (\Omega_b, Wob)$. The system has four state variables. The system is put in the following form:

$$\begin{cases} \dot{x}(t) = Ax(t) + g(x(t),u) \\ y(t) = Cx(t) \end{cases} \qquad \textbf{(10)}$$

Où : $x(t) \in R^4$ is state vector,

$u(t) \in R^2$ is the entered vector,

$y(t) \in R^2$ is the output vector,

such as

$x = (\Phi\ \Omega_t\ \Omega_b\ i)^t$, $u = (v\ Wob)^t$, $y = (\ \Omega_t\ i\ )^t$

With

Φ : $\Phi = \varphi_t - \varphi_b$

Ω_t : $J_t \dot{\Omega}_t = nKi - C_t \Omega t - k\ \Phi$

Ω_b : $J_b \dot{\Omega}_b = k\Phi - C_b \Omega b - Tob(\dot{\varphi}_b, Wob)$

i : $v = L\dfrac{di}{dt} + Ri + v_{cem}$

What gives us the shape

$$A=\begin{pmatrix} 0 & 1 & -1 & 0 \\ \dfrac{-k}{J_t} & \dfrac{-C_t}{J_t} & 0 & n\dfrac{K}{J_t} \\ \dfrac{k}{J_b} & 0 & \dfrac{-C_b}{J_b} & 0 \\ 0 & -n\dfrac{K}{L} & 0 & \dfrac{-R}{L} \end{pmatrix} \quad g(x,u,t)=\begin{pmatrix} 0 \\ 0 \\ \dfrac{-1}{J_b} Tob(\Omega_b, Wob) \\ \dfrac{1}{L} v \end{pmatrix} \quad C=\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

TABLE I: PARAMETER OF THE DRILLING SYSTEM

Settings	**Description**	**Value**	**Unit**
Jt	Equivalent moment of inertia at the upper part of the rods	1030.45	kgm²
J_b	Moment of inertia equivalent to the level of BHA	223.44	kgm²
C_t	Equivalent viscous coefficient of friction at surface level	51.38	$Nms.rad^{-1}$
C_b	Viscous coefficient of friction equivalent to the level of BHA	39.79	$Nm.rad^{-1}$
k	Drill pipe stiffness constant	481.29	$Nm.rad^{-1}$
R	Armature resistance	0.01	Ω

K	Motor torque constant	6	$Nm.A^{-1}$
N	Reducer transmission ratio	7.20	-

TABLE II: PARAMETERS OF THE TOOL-ROCK CONTACT MODEL

Settings	**Description**	**Value**	**Unit**
E	Energie spécific	130	$MJ.m^{-3}$
D	Cutting depth	4	$mm.rev^{-1}$
μ_s	Static coefficient of friction	0.6	-
μ_d	Dynamic coefficient of friction	0.4	-
R_{bit}	Tool radius	0.10	M

The step-by-step temporal calculations and the eigen mode calculations can be very cumbersome if the model has many degrees of freedom. In certain fields such as that of vibrations, the engineer may be particularly interested in the steady state of the response of a structure subjected to a loading of very long duration.

1.4.1 Time calculations.

Time calculations aim to reproduce what would happen in reality and are therefore the most general. Temporal calculations can be carried out on a physical basis or on a modal basis, with linear or non-linear models

The choice of the time step has a major importance

- When an algorithm of implicit temporal integration is used, the choice of the time step is dictated by the physical phenomenon which one wants to describe (generally related to the period of the eigen modes being able to be excited and to the frequential contents of the loading) ,
- When an explicit algorithm is used, the choice of the time step is dictated by the stability conditions of the algorithm ($\omega\Delta t < 2$ for the centered differences). In the presence of non-linearities, it is advisable to adopt margins compared to the criteria given for elastic systems

When a direct temporal integration method is used, the loading can be

- the initial conditions imposed (initial speed of a projectile for example)
- point and distributed forces varying over time
- imposed displacements varying over time

Thus the loading associated with an earthquake can be described either like distributed forces proportional to the mass if the computation is carried out in the reference attached to the base (non-Galilean relative reference), or like an imposed displacement when computation is carried out in the absolute benchmark

The loadings of the type force and imposed displacement varying according to time are defined in [5]. Note that the mobile loads are equivalent to distributed forces varying as a function of time. The operator makes it possible to define the loadings for the temporal calculation procedures on a physical basis or on a basis. In some cases, full knowledge of the load is not necessary for sizing. This is the case with spectral calculations and calculations in frequency domains.

1.4.2 Taking into account of the initial loading.

The initial loading can have a major importance on the dynamic response of the system. Its taking into account, in particular in the computations of clean modes, is less obvious than in the incremental computations in which the static and dynamic loadings can be cumulated. Indeed, the eigen modes correspond to vibrations around a state of equilibrium for which the stresses can be high: vibrations of a taut guitar string, of the membrane of an inflated balloon, of a structure comprising bolted connections… The linearization around this state is complete only by taking into account the stiffness of prestressing [6].

III. Results And Interpretation

1.5 Appearance of the stick-slip phenomenon

The introduction of a weight on the tool Wob = 20 tonnes, constant and with the motor voltage v = 225V also gives rise to the stick-slip phenomenon early on. (Figure 08). From this figure, we see that the curve shape of the tool rotation speed shows periodic movement, ranging from 0 to 53 RPM. From fifth second, the rotation speed of the table remains constant (20 RPM)

The result clearly shows that for low table rotation speeds, the speed of the tool is unstable which can vary from 0 to 3 times more than that provided by the Top drive.

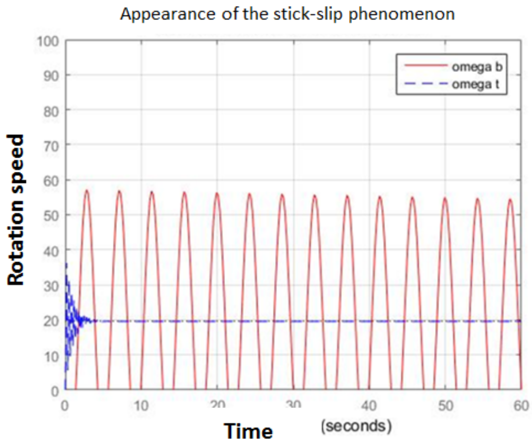

Fig. 08 Appearance of the stick-slip phenomenon

1.6 Influence of the Top drive speed change

When increasing the table rotation speed by the voltage (v = 275V), the vibration phenomenon is gradually eliminated until it disappears from 53RPM under the weight of 20 tons (Figure 09).

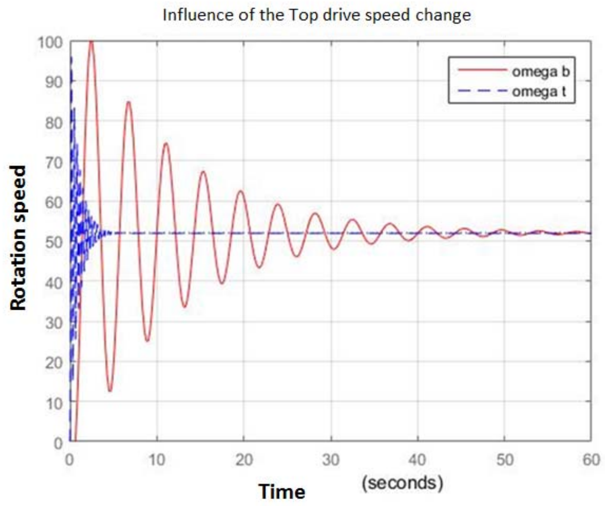

Fig. 9 Influence of the Top drive speed change

The table rotational speed reaches up to 98 RPM. Their rise is at the level of the motor voltage. With this speed, the risk of premature breakage of the tool is too high in the event of contact with rocks having a high intrinsic specific energy. The stick-slip phenomenon reappears again if the weight is increased on the tool.

1.7 Influence of weight variation on the tool

The weight on the tool is the primary factor in torsional vibration. The more you increase it, the amplitude of vibration follows it too. To reduce this nuisance, we proceed to reduce its intensity (Wob = 15tonnes). Then the new problem arises and that is the speed of advance of the wells. The decrease in weight affects it greatly and that will cause a loss of time (Figure 10).

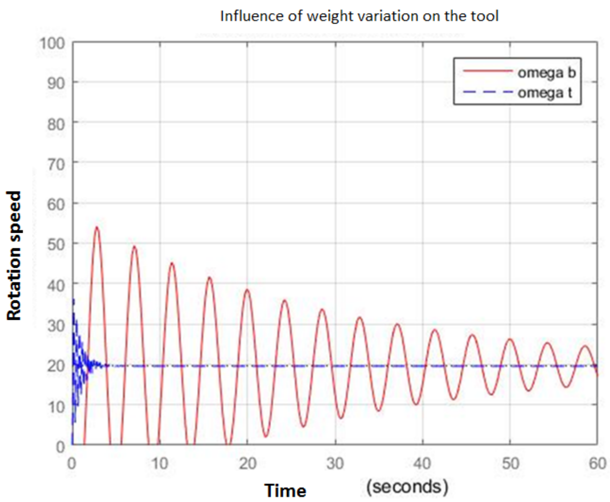

Fig. 10 Influence of weight variation on the tool

The shape of the curve shows that the table rotation speed varies from 0 to 32 RPM before 5s and then remains constant thereafter. The other gait shows the convergence little by little along the horizontal asymptote y = 20 up to certain times. It varies from 0 to 54 RPM on the rotational speed axis.

1.8 Influence of dynamic viscosity of drilling mud

To see the influence of the viscosity of the drilling fluid on the dynamics of the lining, a simulation is made by changing the viscous friction constants in the model by a change of the dynamic viscosity of the drilling mud Cb = 63.15 Nms. rad^{-1}, and that under an input Wob = 20 tonnes and a motor voltage v = 225V (figure 11)

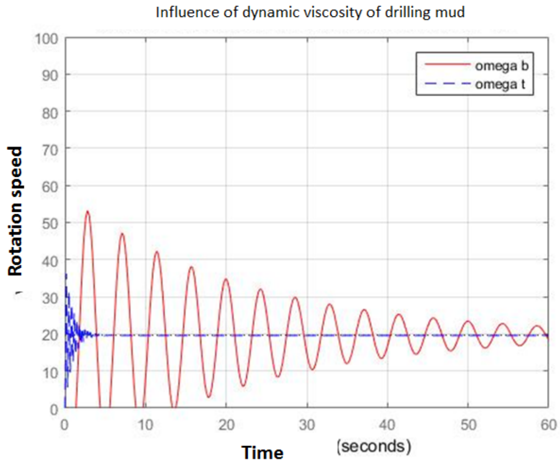

Fig. 11 Influence of dynamic viscosity of drilling mud

Figure 11 shows the variation in the speed of rotation of the tool by tending along the horizontal asymptote y = 20. But the speed of rotation of the top drive remains constant from 5 seconds. The 2 curves could be superimposed from certain times. This explains the elimination of the stick-slip phenomenon. This method requires changing the viscosity of the whole mud, the more viscous it is, the higher the tool energy will be which accelerates the fatigue of the drill pipe.

E. **Elimination of the stick-slip phenomenon**

The rotational speed of the table, the weight on the tool, and the viscosity of the drilling mud are the main variables to dampen torsional vibration. According to the results obtained previously, these parameters can be operated separately but each has major drawbacks. Preserving the lining is vital during the operation, so all risk factors must be eliminated. For the suppression of the phenomenon to be done well (figure 12), the best way is to combine these 3 parameters at the same time

v = 250V ; Wob = 17 tonnes ; C_b = 51.23 Nms.rad^{-1}

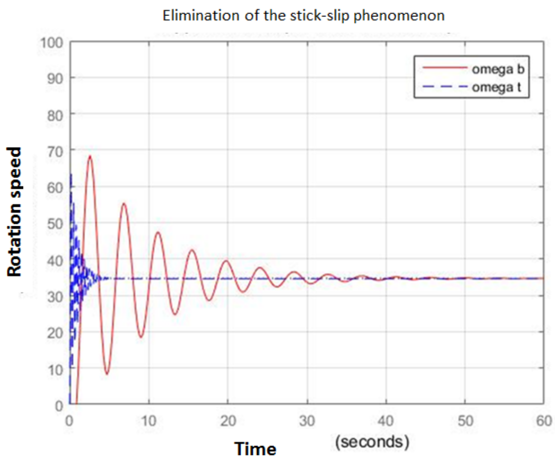

Fig. 12 Removal of the stick-slip phenomenon

The curves converge, follow the horizontal asymptote y = 20. From the 30th second, they overlap. This superposition shows the disappearance of the stick-slip phenomenon.

IV. Discussion

The combination of variation of the three parameters: increase in the speed of the rotating table, decrease in the weight on the tool and the multiplication of the dynamic viscosity of the drilling mud in order to escape the dry friction makes it possible to cancel the stick phenomenon. -slip. The control of materials and parameters during geothermal drilling takes a lot into account in order to avoid the risk of loss in production. During the drilling operation, all the parameters which directly or indirectly affect the efficiency of the work will be taken into account and should not be excluded from a modification in order to reduce as much as possible the duration of the work. operation while avoiding material wear, basically to minimize as much as possible the blow of the work. Dependent on each other but each having its own specific domains, these parameters make the modeling and simulation of the dynamic movement of drilling very complex.

V. Conclusion

The breakage of the drill string and the loss of the bit are caused by cyclical stops of the tool. this is the phenomenon called stick-slip. in geothermal drilling operations, problems that hamper work efficiency and cause losses by lengthening the work often remain. almost all of these problems come from unwanted vibrations which first affect the packing, causing them increased fatigue and causing them to fail prematurely. faced with geothermal drilling, which is becoming increasingly complex, controlling these vibrations is more than ever a major stake in the economic success of the project. there are three modes of vibration according to their plane of evolution: axial vibrations, lateral vibrations, and torsional vibrations. the goal of this work was to understand one of those pests which is the torsional vibration caused by the stick-slip phenomenon. to better illustrate, a tool-rock contact model was given. this model is made to observe the parameters that cause vibrations, giving a possibility to avoid them in reality.

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