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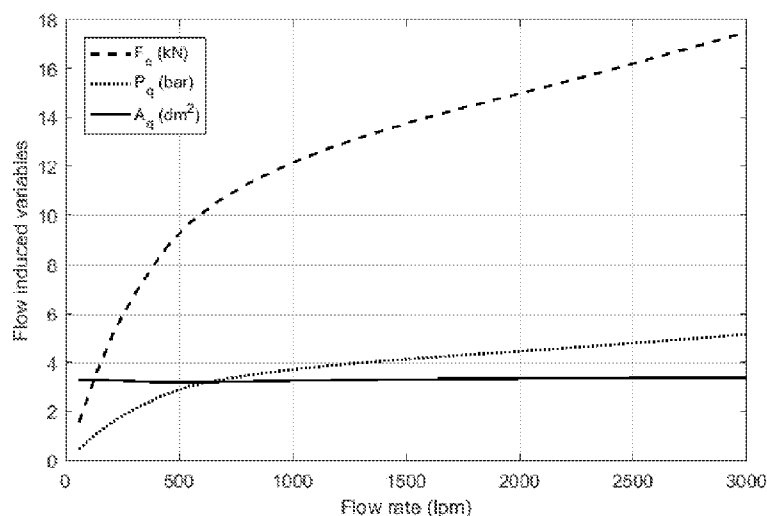


Fig. 1: Graph showing how the flow induced lift force F_q , pressure loss P_q and the ratio $A_q = F_q / P_q$ of a 3500m long string vary as a function of mud circulation flow rate.

(57) **Abstract:** There is disclosed a method for tuning a hydraulic model to be used for estimating down hole dynamic pressure as a function of flow rate, characterized in that the method comprises the steps of : a) selecting a non-tuned hydraulic model estimating the relative magnitude of the pressure losses in various annulus sections of the well bore; b) applying the non-tuned hydraulic model to give a first order estimate of the pressure gradients and the shear stresses at the drill string; c) applying the same non-tuned model to estimate the flow lift area for two different flow rates, where the first flow rate is zero or much lower than the second flow rate being substantially equal to a typical flow rate obtained during drilling; and d) performing a model tuning test where the string is rotated off bottom while said two different flow rates are used to obtain corresponding string weights. There is also disclosed a system for carrying out the method as well as computer-readable medium being provided with instructions for carrying out the method.



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SYSTEM AND METHOD FOR CALIBRATION OF HYDRAULIC MODELS BY SURFACE STRING WEIGHT

Background

Many of the wells being drilled today have small pressure margins, meaning that there is a relatively small difference between the fracture pressure and pore pressure. The fracture pressure is the threshold beyond which the formation is damaged, and the drilling mud tends to flow into cracks in the formation. The pore pressure is the lower pressure limit indicating when formation fluids or gas starts to flow into the well and mix with the drilling mud. Violation of these limits leads to situations commonly called loss and kick, respectively. Both situations are dangerous and can, if not handled quickly and properly, lead to disastrous blowouts. It is therefore important to know the downhole pressure and to have a control system that always maintains the pressure between the mentioned upper and lower limits. Downhole pressure in this context means the well bore pressure in an open hole zone where there is no casing to isolate the well bore from the formation.

The downhole pressure consists of two components, the hydrostatic pressure and the dynamic pressure. The former is the pressure when there is no circulation of the drilling mud and the string is not moving axially, *i.e.* upwards or downwards. The dynamic pressure is the extra pressure induced by fluid flow and/or axial string motion. The pressure increase resulting from a downwards motion is called surge pressure while the pressure reduction from moving the string upwards is called swab pressure.

The hydrostatic pressure can be calculated with a relatively high accuracy from the density of mud in the well bore trajectory and the true vertical depth. The dynamic pressure is far more difficult to estimate, and it must be calculated from very uncertain hydraulic models. The best option until now has been to measure the downhole pressure directly, either by a MWD tool communicating to the surface via slow mud pulse telemetry, or by wired pipe offering much higher data rates. Often none of these options are available for the driller, implying that he/she needs to rely solely on the hydraulic models when estimating the downhole pressure under different conditions.

The invention has for its object to remedy or to reduce at least one of the drawbacks of the prior art, or at least provide a useful alternative to prior art.

The object is achieved through features, which are specified in the description below and in the claims that follow.

5 This specification describes a system and a method that, under certain conditions, can measure the downhole pressure indirectly from the string weight and use these measurements to tune or calibrate the used hydraulic model. The system and method may include an accurate load cell measuring the string tension (weight) at the top of the string. The system and method may also include a basic hydraulic model describing how the pressure loss gradient varies with the annulus geometry. The system and method described
10 herein are quite robust against model errors, meaning that the system and method have the potential of providing far more accurate estimates than the pure hydraulic model itself. There is also described a computer-readable medium including instructions for carrying out the method described herein.

15 The method and system described herein have as their goal to provide indirect measurements of the downhole pressure when direct pressure measurements are not available.

In a first aspect the invention relates to a method for tuning a hydraulic model to be used for estimating down hole dynamic pressure as a function of flow rate, wherein the method comprises the steps of :

- 20 a) selecting a non-tuned hydraulic model estimating the relative magnitude of the pressure losses in various annulus sections of the well bore;
b) applying the non-tuned hydraulic model to give a first order estimate of the pressure gradients and the axial shear stresses at the drill string ;
c) applying the same non-tuned model to estimate the flow lift area for two different flow
25 rates, where the first flow rate is zero or much lower than the second flow rate being substantially equal to a typical flow rate obtained during drilling; and
d) performing a model tuning test where the string is rotated off bottom while said two different flow rates are used to obtain corresponding string weights.

In a second aspect the invention relates to a system for tuning a hydraulic model to be
30 used for estimating down hole dynamic pressure as a function of flow rate, wherein said system comprises a weighing means and a control unit, where said control unit is adapted to:

- a) select a non-tuned hydraulic model estimating the relative magnitude of the pressure

losses in various annulus sections of the well bore;

b) apply the non-tuned hydraulic model to give a first order estimate of the pressure gradients and the axial shear stresses at the drill string ;

c) apply the same non-tuned model to estimate the flow lift area for two different flow

5 rates, where the first flow rate is zero or much lower than the second flow rate being substantially equal to a typical flow rate obtained during drilling; and

d) perform a model tuning test where the string is rotated off bottom while said two different flow rates are used to obtain corresponding string weights by means of said weighing means.

10 In a third aspect the invention relates to a computer- readable medium provided with instructions to carry out a method according to the first aspect of the invention.

Basic theory

The annulus pressure can be formally written as the following integral.

$$p(x) = p(0) + \int_0^x (\rho_o g \cos \theta + p'_q) dx \quad (1)$$

15 Here ρ_o is the fluid density, g is the acceleration of gravity, θ is well inclination (deviation from vertical) and p'_q is the dynamic pressure gradient (the prime symbol ' here denotes derivation with respect to the depth variable x). We have also included an optional pressure at the top of the string $p(0)$ in case there is a sealing device (for instance a rotary seal and a choke) that creates an exit pressure. Throughout, for simplicity, we shall assume that the pressure is gauge pressure so that $p(0) = 0$ if the return flow is without
20 restriction to the ambient atmospheric pressure.

The first term of the integrand is the axial component of the hydrostatic pressure gradient. It is to be noted that the mud density is often treated as a constant, but it is generally a function of both pressure and temperature. Compressibility tends to increase the density
25 as the vertical depth increases while thermal expansion has the opposite effect: it makes the density decrease with temperature and depth. Very often, if the mud temperature follows the natural geothermal temperature profile of the earth crust, the thermal effect is the dominating one, thus making the density decreasing slightly with vertical depth.

The dynamic pressure gradient p'_q is a function of many variables. The most important

30 ones are the annulus geometry (well bore diameter d_w outer string diameter d_o and

string eccentricity), pump rate and string speed. However, the mud rheology (viscosity) also plays an important role. The rotation speed of the string has a minor effect on the dynamic pressure gradient, and is often neglected. A complicating factor is that the rheology is often strongly non-Newtonian, meaning that the shear stress is far from a linear function of the shear rate, as it is for Newtonian fluids. Often the rheology also varies with time. The dynamic pressure gradient is therefore extremely difficult to predict accurately. While the hydrostatic pressure can be determined within a few percent's accuracy, the dynamic pressure estimate will often be off either ways by a factor 2 or more.

There exist different hydraulic models that predict how the dynamic pressure gradient p'_q vary with the mentioned variables. American Petroleum Institute (API) provides one relatively advanced model in their API Recommended practice 13D called *Rheology and Hydraulics of Oil-well Fluids*, to which reference is made for an in-depth disclosure of the mentioned model. It is beyond the scope of this disclosure to repeat the details of this model, but the model provides relatively advanced analytical expressions for the pressure gradient as a function of flow, and annulus geometry for non-Newtonian fluids. The model is adapted to handle both laminar and turbulent flow in addition to the eccentricity effect. This API model and even more advanced hydraulic models may be used subsequently to estimate the coupling between the downhole pressure and string weight in a system and method according to the invention.

The tension in the string can be described by the following integral

$$F(x) = F_b + \int_x^L (w \cos \theta + \mu_a f_c - A_o p'_q - \pi d_o \tau_o) dx \quad (2)$$

Here F_b represents the tension, minus weight on bit (WOB) at the lower end of the string, w is the buoyant weight per unit length, θ is the inclination, μ_a is the axial friction coefficient, f_c is the normal contact force per unit length, $A_o = (\pi/4)d_o^2$ is the outer string cross-sectional area and τ_o is the flow-induced axial shear stress at the outer string surface (averaged over all directions if eccentricity is included). The specific buoyant weight can be expressed by the sum of pipe weight and inner mud weight minus the buoyancy weight. That is

$$w = (\rho_s A_s + \rho_i A_i - \rho_o A_o) g \quad (3)$$

where ρ_s , ρ_i and ρ_o are the densities of the string (steel), inner mud and annular mud, respectively and $A_s = A_o - A_i$, A_i and A_o represent the corresponding cross-sectional areas. Finally, g is the acceleration of gravity. The first and second terms of the integrand of equation 2 therefore represent gravitation force and well bore friction force, respectively. The two last terms represent two different components of what is conveniently called hydraulic lift force. The first is a kind of dynamic buoyancy resembling to the classical Archimedes buoyancy (being a part of the first term) but instead of being vertical and thereby proportional to $\cos \theta$, it is acting in the axial direction and is therefore independent of the inclination.

The various terms in equation 2 are not novel as such, and have been discussed previously in the scientific literature. See for instance section 3.2 in: E. Cayeux and H.J. Skadsem: *Estimation of Weight and Torque on Bit: Assessment of Uncertainties, Correction and Calibration Methods* Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, June 8-13, 2014, San Francisco, California, USA, to which reference is made for an in-depth discussion of the constituents of equation 2. What is believed to be novel over the prior art is the discovery that the dynamic, flow-induced downhole pressure is so closely related to the hydraulic lifting force on the string. The two effects are nearly proportional and can be represented by a flow lift area that can be estimated as justified below.

In the following we shall simplify to cases where the string is rotating off bottom without any axial motion. Then the bit force and axial friction vanish, $F_b = 0$ and $\mu_a = 0$ so that the tension at the top of the string can be written

$$F(0) = \int_0^L (w \cos \theta - A_o p'_q - \pi d_o \tau_o) dx = W_0 - F_q \quad (4)$$

where W_0 denotes the buoyant, rotating off bottom weight at no flow, and

$$F_q = \int_0^L (A_o p'_q + \pi d_o \tau_o) dx \quad (5)$$

is the flow-induced lift force. It should be mentioned that reference weight W_0 has a tiny component of the dynamic pressure because the dynamic pressure affects the mud density and thereby also the buoyant weight of the string. However, this effect is negligibly small compared with the other dynamic lift effects.

It can be shown, from force balance of a differential fluid element, that the flow-induced pressure gradient can be written as

$$p'_q = \frac{\pi d_o \tau_o - \pi d_w \tau_w}{A_a} = \frac{\pi d_o \tau_o}{\beta A_a} \quad (6)$$

where A_a is the annular cross section area. In the last expression we have used the fact

- 5 that the axial shear stress, τ_w , at the well bore surface is normally negative (because the radial shear rate is negative). It means that

$$\beta = \frac{d_o \tau_o}{d_o \tau_o - d_w \tau_w} \quad (7)$$

is a positive factor less than unity. It approaches $d_o/(d_o + d_w)$ or 0.5 for narrow annuli, that is when $d_w - d_o \ll d_w$.

- 10 The flow-induced lift force can now be written as

$$F_q = \int_0^L (A_o + \beta A_a) p'_q dx \quad (8)$$

The downhole pressure can finally be written as

$$p_q = \int_0^L p'_q dx = A_q F_q \quad (9)$$

where the flow lift area is

$$15 \quad A_q = \frac{\int_0^L (A_o + \beta A_a) p'_q dx}{\int_0^L p'_q dx} \quad (10)$$

- This parameter cannot be calculated without having a starting model predicting how the pressure gradient varies along the string. The great advantage of this approach (the last expression of equation 9) over direct application of the hydraulic model (the first expression of the same equation) is that the flow lift area is much more robust against model errors than the gradient and pressure itself. Because both integrands of equation 10 are proportional to the pressure gradient p'_q , a multiplicative error has no impact on neither the lift area estimate nor the weight-based estimate of the pressure. What is needed is that the model gives a correct ratio of the pressure drop for the various annulus sections.
- 20

This is a far less restrictive requirement than having a good model predicting the down-hole pressure directly. Moreover, if the downhole pressure is measured indirectly from the string weight, this can be used for improving the model accuracy by the following

$$p'_{q,corr} = cp'_q \quad (11)$$

- 5 where the correction factor equals the ratio of measured and calculated downhole pressure, that is

$$c = \frac{A_q F_q}{\int_0^L p'_q dx} \quad (12)$$

Before discussing practical sides of how to implement the invention it is useful to calculate the order of magnitudes of the flow lift force, the dynamic pressure loss and the flow lift
10 area. As an example, we use the data from a real, horizontal well which is 3500 m long with a true vertical depth of approximately 1800 m. The string comprises a 3300 m long 5 inch drill pipe section and a 200 m long 5.5 inch heavy weight drill pipe section. The well bore is, for simplicity, assumed to have a constant bore diameter of 12.25 inches

Reference is made to figure 1 showing how the flow induced lift force F_q , the pressure loss
15 P_q and the ratio $A_q = F_q/P_q$ of the above string vary as a function of mud circulation flow rate. The hydraulic model used for calculating these curves is resembles but is slightly more advanced than the mentioned API model. The curves are calculated for a typical non-Newtonian mud commonly used in the drilling industry and the gradients include the effect of reduced cross section at the tool joints. In contrast to the API model the applied
20 model also includes the relatively weak effect of drill string rotation and the plotted curves are calculated with a string rotation speed of 60 rpm. Further comments to the theoretic results in the reference figure are the following.

The non-linearity causing the variable slope of both the force and pressure curves comes from the non-linear rheology characteristics of the mud, which follows the well-known Her-
25 schel-Bulkley rheology model tightly. The flow is laminar for most of the included flow rate span but the slight increase of the slopes at the highest flow rates indicate that the highest flow rates are close to the transition where the flow goes from laminar to turbulent. The most interesting observation is that ratio between the two curves, which has the dimension of a flow lift area, is surprisingly constant over the entire flow range. It has a minimum
30 of 3.2dm² (=0.032 m²) at a flow rate of 500 liters per minute. Then increases slowly to about 3.4dm² at the maximum flow rate.

Both the calculated flow induced pressure and the lift force are relatively small compared with their static values. The rotating of bottom weight is $W_0 \approx 480$ kN while the static downhole pressure at the bit is 179 bar = 17.9e6 Pa. At a maximum flow rate of 3000 lpm the dynamic effects therefore a weight reduction of 3.6% weight reduction and a pressure increase of 2.9%. Practical considerations

As the numerical example indicates, the hydraulic flow lift effect is relatively small compared with the buoyant string weight itself. This fact implies that the weighing means/load cell measuring the flow lift must be rather accurate, preferably more accurate than the traditional deadline anchor hook load. Therefore, it is recommended to use an inline and highly accurate load cell, either as an integrated part of the top drive output shaft or as a standalone sub installed just below the top drive shaft. The accuracy goal for this load cell may be 0.1% or better. If the load cell is based on strain gauges applied on the outer surface of the shaft it is important to measure also the inside pressure and correct the raw force signal (proportional to the axial strain) for the pressure cross-talk effect. The effect of temperature variations should also be considered because radial temperature gradients will cause internal thermal stresses and offset drift of the sensor signal. However, if the calibration test has a short duration, the variation of the inside mud temperature will probably have a minor or negligible effect on the calibration results below.

If an accurate, inline load cell is not available, the method is still applicable with a traditional dead line based hook load signal. Usually the accuracy of a dead line tension sensor is poor because of the sheave friction causing the dead line tension to deviate from the average tension of the lines strung between the crown block and the travelling block. However, these friction errors are much smaller under the test conditions with no axial motion of the string.

The following procedure may be used for tuning the hydraulic model by surface measurements.

1. Select a basic hydraulic model to be tuned, for instance the model recommended by API, or a more advanced one, if available.
2. Use the non-tuned hydraulic model to calculate a first order approximation for the steady state dynamic downhole pressures p_0 and p_1 for two different flow rates q_0 and q_1 , where q_0 is either zero or much lower than q_1 , while q_1 is approximately equal to flow rate to be used in drilling.
3. Use the same, non-tuned model to calculate also the flow lift area, A_q for the highest flow rate. (A slightly more accurate alternative is to calculate the flow lift area for a series of different flow rates in the range $[q_0 \quad q_1]$ and use a flow rate weighted average of areas.)

4. Perform a two-step calibration test where the string is rotated off bottom while the pump rate is kept constant at the selected rates, q_0 and q_1 . Measure (the time averages of) the corresponding string weights F_0 and F_1 when the string weight is fully stabilized.
5. Estimate the real downhole pressure increase by $\Delta p = (F_0 - F_1) / A_q$
- 5 6. Update the hydraulic model by multiplying the non-tuned pressure gradients by the correction factor $c = \Delta p / (p_1 - p_0)$

The tuned or calibrated model can now be used to provide more accurate values for the dynamic and total pressure also for conditions like drilling with the bit on bottom.

10 It is recommended to repeat the suggested tuning procedure at regular intervals, for instance at every connection when new drill pipes are added to the string and the pump must stop anyway. It is important that the standpipe pressure and return flow rate are stabilized before the weight readings are carried out. The readings themselves can be averages over short time intervals, *e.g.* in the order of 10 seconds. However, due to the mud compressibility and the big cushion effect of the inner pipe volume, there will be a significant time from a new value of pump rate is reached until the annular flow rate and therefore the flow lift force stabilizes. The entire tuning test can therefore take a few minutes in long and deep wells.

20 It should be noted that the above-mentioned embodiments illustrate rather than limit the invention, and that those skilled in the art will be able to design many alternative embodiments without departing from the scope of the appended claims. In the claims, any reference signs placed between parentheses shall not be construed as limiting the claim. Use of the verb "comprise" and its conjugations does not exclude the presence of elements or steps other than those stated in a claim. The article "a" or "an" preceding an element does not exclude the presence of a plurality of such elements.

25 The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage.

C l a i m s

1. A method for tuning a hydraulic model to be used for estimating down hole dynamic pressure as a function of flow rate, c h a r a c t e r i z e d i n
that the method comprises the steps of :
 - 5 a) selecting a non-tuned hydraulic model estimating the relative magnitude of the pressure losses in various annulus sections of the well bore;
 - b) applying the non-tuned hydraulic model to give a first order estimate of the pressure gradients and the axial shear stresses at the drill string;
 - 10 c) applying the same non-tuned model to estimate the flow lift area for two different flow rates, where the first flow rate is zero or much lower than the second flow rate being substantially equal to a typical flow rate obtained during drilling; and
 - d) performing a model tuning test where the string is rotated off bottom while said two different flow rates are used to obtain corresponding string weights.
2. Method according to claim 1, wherein the method further comprises the step of:
 - 15 e) using the observed weight difference and said estimated flow lift area to calculate the real dynamic downhole pressure.
3. Method according to claim 2, wherein the method further includes the step of updating the non-tuned hydraulic model using the observed weight difference and said estimated flow lift area.
- 20 4. Method according to claim 2 or 3, wherein the method further comprises of using said down hole dynamic pressure to calculate a total down hole pressure.
5. Method according claim 3 or 4, wherein the method further comprises the step of drilling a well bore while utilizing said calculated down hole dynamic pressure.
- 25 6. System for tuning a hydraulic model to be used for estimating down hole dynamic pressure as a function of flow rate; , c h a r a c t e r i z e d i n that said system comprises a weighing means and a control unit, where said control unit is adapted to:
 - a) select a non-tuned hydraulic model giving estimation of the relative magnitude of the pressure losses in various annulus sections of the well bore;
 - 30 b) apply the non-tuned hydraulic model to give a first order estimate of the pressure gradients and the axial shear stresses at the drill string;
 - c) apply the same non-tuned model to estimate the flow lift area for two different

flow rates, where the first flow rate is zero or much lower than the second flow rate being substantially equal to a typical flow rate obtained during drilling; and
d) perform a model tuning test where the string is rotated off bottom while said
two different flow rates are used to obtain corresponding string weights by means
of said weighing means.

7. System according to claim 6, wherein the control unit further is adapted to utilize the observed weight difference and said estimated flow lift area to determine the real dynamic downhole pressure.

8. System according to claim 7, wherein the control unit further is adapted to update the non-tuned hydraulic model by using the observed weight difference and said estimated flow lift area.

9. System according to claim 7 or 8, wherein the control unit is adapted to utilize said down hole dynamic pressure to find a total down hole pressure.

10. System according claim 8 or 9, wherein the system further comprises a drilling means to which said control unit is connected, wherein said control unit is adapted to control said drilling means in order to drill a well bore while utilizing said down hole dynamic pressure.

11. System according to any of the claims 6-10, wherein said weighing means includes a load cell.

12. System according to claim 11, wherein said load cell has an accuracy of around 0.1% or better.

13. System according to claim 11 or 12, wherein said load cell is an integrated part of a top drive output shaft of said drilling means.

14. System according to claim 11 or 12, wherein said load cell is included in a standalone sub provided below a top drive shaft of said drilling means. .

15. A computer-readable medium provided with instructions to carry out the method of any of the claims 1-5.

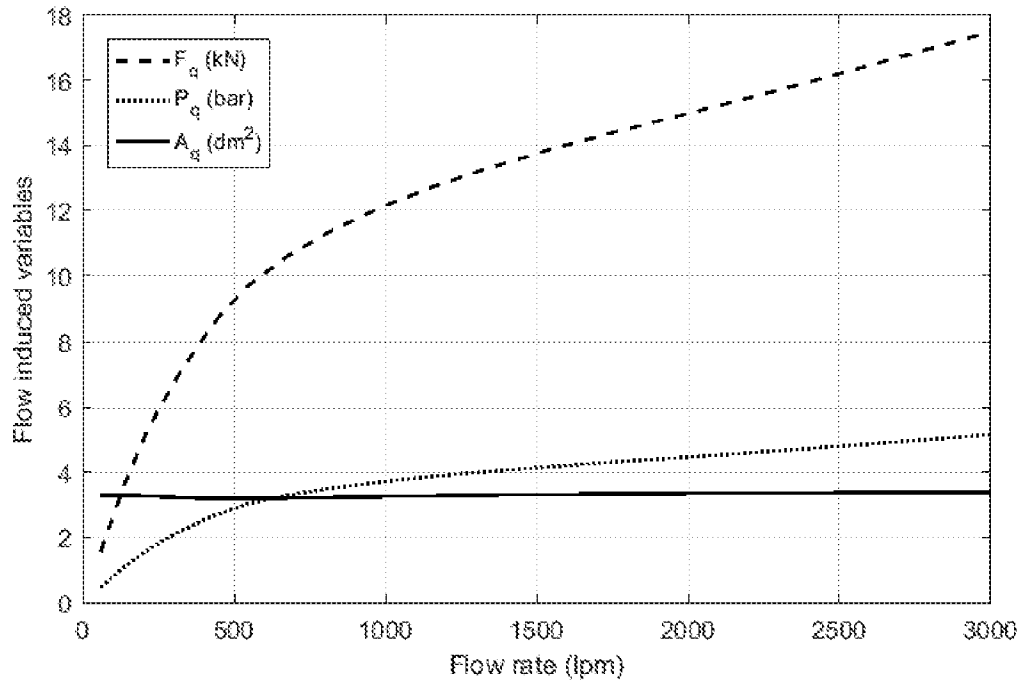


Fig. 1: Graph showing how the flow induced lift force F_q , pressure loss P_q and the ratio $A_q = F_q / P_q$ of a 3500m long string vary as a function of mud circulation flow rate.

INTERNATIONAL SEARCH REPORT

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B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) E21B Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched DK, NO, SE, FI: Classes as above. Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPODOC, WPI, FULL TEXT: ENGLISH, ELSEVIER (XPESP), NPL, COMPENDEX, ONEPETRO		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
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