Design of a Sub-Surface Drilling Mechanism through Solid Modelling and Analysis

Kaustubh Mohta¹, Samarth Yelvande², S Venkatesan³

¹UG Student, School of Mechanical Engineering, Vellore Institute of Technology, TN, India.
²UG Student, School of Mechanical Engineering, Vellore Institute of Technology, TN, India.
³Professor, School of Mechanical Engineering, Vellore Institute of Technology, TN, India.

Abstract. Current mechanisms for drilling and milling fall short in creating holes beneath the surface without disrupting bulk portion of the material. Presently, the only way to drill underground is through tunnel boring machines - each of them weighing hundreds of tons and costing millions of dollars. Clearly, they can’t be used to drill small diameter holes. This paper produces a novel idea for making U-shaped holes and for drilling beneath the surface without any digging. This has wide range applications in fields of road and transport, wires and pipe installation, component manufacturing etc. and can be used for all the sub-surface drilling operations. The materials used for this purpose are HSS Steel, Carbide Steel, and Cobalt-alloy Steel. These materials are assigned to the body of the drill and FEM analysis is conducted to find the total deformation and the Von-Mises stresses induced in the drill body.

1. Introduction
Drilling is the most common type of metal cutting operation in the current industry. About 75% of the machining operations are different type of drilling. There are various methods to make a hole in a metal or other material. Depending on the requirement, the types include vertical drilling, step drilling, countersink drilling, centre drilling, etc. Among these methods, horizontal drilling is also an operation. Horizontal drilling includes extruding a horizontal hole in the workpiece by piercing the side walls of the metal by a sharp cutting edge of the cutting tool and then making the required hole. The process of making a horizontal hole in a workpiece without disturbing the side walls is very uncommon and difficult. To address this issue, a new method has been presented. In this paper, the procedure of designing the tool, working and simulation of the cutting tool (using ANSYS Workbench) is done along with the possible applications of this method. Since concepts of horizontal drilling are employed, an apparatus containing a flux sensitive coil and directional drilling control apparatus can be used as a guidance system [6]. Alternatively, manual supervision may be possible for small distances.

During drilling operation, axial thrust and cutting torque are generated. These two parameters greatly affect the viability of the drilling and the materials used for drilling operation. Relations between cutting parameters and the corresponding forces have been modelled through Artificial neural networks (ANNs) by Gurumukh Das and Padam Das [1]. Similar analyses have been performed based on ANOVA (analysis of variance) and Response Surface Methodology in the paper “Prediction of Thrust Force and Cutting Torque in Drilling Based on the Response Surface Methodology” [2]. Both these papers have been considered during design stages. Drilling requires rotational as well as translational motion. In order to transmit power for sub-surface drilling an incompressible fluid have been chosen.

The is justified by the fact that fluids do not have a definite shape, making power transfer practical even over varying geometry. To facilitate analysis of fluid dynamics, moment of momentum equation has been used as described in the book “Fundamentals of Fluid Mechanics” [3]. In this paper, a horizontal, sub-surface drilling system has been designed and modelled using SolidWorks and Ansys. A load of 5KN compressive load is applied on the tool. The corresponding deformations and von-mises stresses are calculated for three different materials. Material properties are varied in order to perform structural and modal analysis on cutting tool. The different materials taken in analysis in this study are high carbon steel, cobalt-steel alloys and high speed steels (HSS).
2. Materials and Methods

As shown in Figure 1 two tubes are wound around two cylinders namely cylinder A and cylinder B. These two tubes are connected through a circular or helical pathway embedded in the drilling tool. The ends of the tubes are connected to an oil chamber. Oil flows towards the drilling cone through tube 1 and flows back to oil chamber through tube 2. A third tube is wound around another cylinder, namely cylinder C.

The drilling tool consists of two parts, a stationary cylinder and other a rotating cone. One end of the cylinder has 3 ports, two of which carry the oil used to drive the drill while the third port is connected to a tube that maintains pressure during cutting action and drives the tool forward. The interior portion of the cylinder contains a cavity which houses the rotor. The rotor arms attached to the drilling cone making the cone rotate when oil flows through the rotor. The main advantage of having a split design is that, since the cylinder doesn’t rotate, the pipes attached to it won’t wind up. Further design modifications to the tool are possible in case certain amount of lubrication is required during cutting. This can be done by channelling a small portion of oil to the drill cone.

The drilling tool consists of a pathway which allows flow of oil into the rotor at the base. The fluid moves through the rotor and exits into the cavity in the tool cylinder. The spent oil then moves into tube 2 from an exit port. Flute angle, cutting age, rake angle etc can be made on the conical part of the drill. Oil chamber contains the oil which is used to cool as well as drive the drilling zone. The chamber is sealed with a plunger that is driven downwards by rotating the screw using a drilling machine.

3. Results and Discussion

The tool requires rotational as well as translation motion in order to have cutting action. Translation is provided by connecting the pipe from cylinder ‘C’ to port 3. The other end of the pipe can be connected to a reservoir containing a pressurised fluid. The pressure force will cause the drill to move forward. However, this will also pull the pipe forward. Thus, sufficient length of pipe must be provided (At least 1.2 times the drilling length).

For rotational motion, tubes from cylinder ‘A’ and cylinder ‘B’ are connected to ports 1 and 2 respectively. As the piston moves down in the oil chamber oil enters into the drill tool through port 1. Oil then enters into the base of the rotor (as shown in Figure 2) and moves through the neck. Finally, oil exits through the rotor arms. As the exit directions of the two arms are opposite to one another, there is no net force acting on the system. Thus, application of momentum equation to the rotor arm is of no
significance. However, the moment of momentum equation predicts that the rotor arms will experience a couple which will cause rotation. Therefore, when oil moves out of the rotor arm, it will impart rotational motion.

Figure 2. Rotor mechanism.

4. Design Calculations

Moment of momentum equation [3]:

$$\frac{\partial}{\partial t} \int (r \times V) \rho dV + \int (r \times V) \rho V \cdot n \wedge dA = \sum (r \times F)$$  \hspace{1cm} (1)

Here, $r$ is the radius of rotor arm; $V$ is the linear velocity of fluid leaving rotor arm; $CV$ represents the control volume; $CS$ corresponds to the control surface and $F$ is force applied (refer Figure 3.).

1. The flow is assumed to be one-dimensional with an uniform distribution of average velocity at each and every section.
2. Analysis is performed for “steady in the mean” or steady cyclical flows. Therefore, at any given point of time the flow is assumed to be steady on a time-average basis (for cyclical unsteady flows).
3. Calculations are performed considering the component of equation (1) resolved along the axis of rotation.
Considering the rotor, as the magnitude and direction of the flow changes from rotor inlet to outlet of the rotor arm, the liquid exerts a torque on the rotor head. The causes a rotational motion or an impending rotational motion in the direction shown (similar to a turbine rotor). Applying the moment of momentum equation [3]:

\[
-T_{shaft} = \omega U V m \theta 
\]

(2)

No load speed is [3]:

\[
\omega = \frac{W}{r}
\]

(4)

In the equation (4),
1. \(W_2\) is the velocity of fluid relative to the exit nozzle
2. \(T_{shaft}\) is the external torque on shaft during cutting
3. \(W_{shaft}\) is shaft power
4. \(U\) is linear velocity of rotor arm nozzle
5. \(v_{\theta 2}\) is linear velocity of fluid leaving rotor arm
6. \(\dot{m}\) is mass flow rate
7. \(\omega\) is angular momentum

5. Modelling of the horizontal drilling tool

SolidWorks is a computer aided design software with analytical tools and an easy to learn windows graphical user interface. It facilitates construction of 3-Dimensional solid models through automatic or user-defined relations. The 3D model (as shown in Figure 4.) of the drilling system is designed using SolidWorks.[8]
Figure 4. New Drill bit model.

**a. Material Properties**

The design file is imported into ANSYS workbench by converting it into IGES/STEP format. Structural analysis is performed for the drilling system. Static structural analysis is chosen and 3 different materials are used, namely Carbide steel, HSS steel and Cobalt steel alloy. The following table (Table 1.) gives the material property for the materials mentioned above.[8]

| Parameter                  | Carbide steel | HSS steel | Cobalt-steel alloy |
|----------------------------|---------------|-----------|--------------------|
| Density (kg/m³)            | 15630         | 7972      | 8500               |
| Modulus of Elasticity (GPa)| 700           | 215       | 210                |
| Poisson’s Ratio            | 0.31          | 0.29      | 0.3                |

**b. Analysis using ANSYS Workbench**
Figure 5. Load applied and Boundary conditions applied.

Once the IGES file is imported into Ansys a mesh generated. The boundary conditions and the loads are applied on the body as shown in Figure 5. and then static structural analysis is performed. The results are then simulated.

i. Carbide Steel

A mesh is generated to perform static structural analysis. A 5000N load is applied in compression, normal to the head of the drill bit. The lower end of the drilling system is defined as fixed. Material chosen is Carbide steel and the solutions for deformation and Von-Mises stress are obtained. The Figures. 6-7 show the output solutions simulated on ANSYS workbench 18.1[8].

Figure 6. Total deformation of Carbide steel.
ii. HSS Steel

A mesh is generated to perform static structural analysis. A 5000N load is applied in compression, normal to the head of the drill bit. The lower end of the drilling system is defined as fixed. Material chosen is HSS steel and the solutions for deformation and Von-Mises stress are obtained. The Figure. 8-9 show the output solutions simulated on ANSYS workbench 18.1.[8].

Figure 7. Von-Mises stress of Carbide steel.

Figure 8. Total deformation of HSS steel.
iii. Cobalt-Steel alloy

A mesh is generated to perform static structural analysis. A 5000N load is applied in compression, normal to the head of the drill bit. The lower end of the drilling system is defined as fixed. Material chosen is Cobalt-steel alloy and the solutions for deformation and Von-mises stress are obtained. The Figure. 8-9 show the output solutions simulated on ANSYS workbench 18.1[8].

![Figure 9. Von-Mises stress of HSS steel.](image-url)
6. Conclusion

U-shaped/sub-surface drilling is a very crucial method to save material and drill in places where reaching end walls is difficult. For instance, drilling an underground hole across a road without disturbing the overall structure of the road. A practical application would be pipe laying and wire laying. Further, the concept of using fluids for power transfer can be utilised for drilling in various geometries and for making internal holes. Therefore, geometrical constraints to drilling have been addressed in this paper. From design point of view, the tool has a rotating as well as a stationary part. This prevents entanglement of tubes carrying the working fluid.

The analysis of the horizontal drilling system is done using ANSYS Workbench 18.1. The material used for the drilling system is changed for each analysis and the corresponding values are obtained. From this analysis it is inferred that the stress values of the materials used are within the acceptable range. Hence the method developed is feasible. The design can also be optimized and modified to suit the required environment. Sensors and flux sensitive coils can be integrated to serve as a guidance system for complex or large-scale applications [6]. Design modifications to the tool are possible for lubrication that might be required during cutting. This can be easily done by channelling a small portion of oil (or working fluid) to the drill cone. The method developed can serve as a basis for future developments and outcomes.

7. References

[1] Gurumukh Das and Padam Das, 2015. Cutting Forces in Drilling Operation: Measurement and Modeling for Medium-scale Manufacturing Firms. International Journal of Computer Applications 121 8 0975-8887

[2] Kyrratis P, Markopoulos AP, Efikolidis N, Maliagkas Vand Kakoulis K. 2018 Prediction of thrust force and cutting torque in drilling based on the response surface methodology. Machines 6(2) 24
[3] Bruce R. Munson, Ted H. Okiishi, Wade W. Huebsch and Alric P. Rothmayer 2013. Fundamentals of Fluid Mechanics seventh edition John Wiley & Sons, Inc

[4] Maurer 1980, W.C. Advanced drilling techniques. United States

[5] J. Paulo Davim, 2018. Machining: Fundamentals and Recent Advances, Springer

[6] Dahl HD, Edmond TO, inventors; Conoco Inc, assignee. Guidance system for a horizontal drilling apparatus. United States patent US 3,907,045. 1975 Sep 23

[7] Lijo Paul, J. Babu and J. Paulo Davim 2020. Non-conventional Micro-machining Processes, Springer InMaterials Forming, Machining and Post Processing 109-139

[8] K. Sathishkumar, G. Dinesh, 2019. Design and Material analysis of a Suspension System in Scooter by using Finite Element Analysis Method. International Research Journal of Multidisciplinary Technovation 1(1) 25-37.