RESEARCH ARTICLE OPEN

Modeling and simulation analysis of an oil tubing coupling detector based on the LVDT method

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Abstract:

Automated drilling is one of the oil industry's most important innovation targets. Tubing coupling detection is a crucial key component in the automation process of workover operations, by accurately detecting the position of a tubing coupling in real time, this brings convenience for operating stuff to control or provides preconditions for automatic control. In this paper, a tubing coupling detector that is designed based on linear variable displacement transformer (LVDT) principles has been proposed to meet the requirement of accurately detecting and identifying the position of the tubing coupling during workover operations. The tubing coupling contains 3 coils that are wound on a tube or inner layer pipe and an outer casing, wherein a tubing string and a tubing coupling can penetrate through. The middle coil or primary coil is excited by an alternating voltage and the other two coils (secondary coils) detects the induced electromotive force as the tubing string passes by, the difference in the resultant electromotive force from the two secondary coils can aid in determining the position of the tubing coupling. Ansys Maxwell software is used to analyse the feasibility of this tubing coupling detection detector by analysing the induced output voltage in the secondary coils (detection coils). The simulation results shows that the proposed coupling detection device can be used to detect the position of the tubing coupling position.

***Keywords* — Tubing coupling, Modeling, Simulation, LVDT**

I. INTRODUCTION

Advances in the petroleum industry have allowed access to oil and gas drilling locations and previously inaccessible reservoirs due to technological limitations. For example, technological advances have allowed the drilling of offshore wells at increasing water depths and in increasingly harsh environments, permitting oil and gas owners to successfully drill for otherwise inaccessible energy resources. Drilling hydrocarbons in the energy industry requires many specialized tools to allow for the production of the hydrocarbons sought. The specialized tools allow for drilling to proceed at a rapid pace [1]. Well, intervention and workover operations are performed often with the direct objective of optimizing oil or gas production and keeping it to satisfactory levels. Workover operation is crucial work, which directly affects the operation level of the oilfield. Under the traditional working mode, most of the workover is done manually because of the huge technical constraints. In traditional workover operations, the lifting, lowering, and unloading of pipe string occupy 70% of the operation time, and the above operations need to be completed manually, which seriously restricts the efficiency of the workover operation. The investment of human resources in workover is huge, the labour intensity is high, and the efficiency is low, so it is difficult to create huge benefits for oilfield enterprises [2]. With the increasing emergence of automation technology, a variety of automation devices have been developed, the automation development of workover rigs mainly focuses on the automation of pipe string processing systems. The first step in this pipe string automation process is to develop and design a tubing coupling detection transducer. The configuration of the coupling positioner makes the horizontal movement and up and down lifting more convenient and efficient, and accurately determines the coupling position. In the last decade, many studies have focused on the development of electromagnetic sensors for position detection of tubing coupling. Fu Jing Shun developed a spiral inductance coil that uses the principle of magnetic detection to use as a coupling detector [4]. Sunil Kumar Khare proposed a drill string status detection system based on machine vision [5]. However, some of these systems have limitations and challenges in accurate measurement due to several factors, i.e. changes in weather conditions that affect image quality, and the system's calibration is a bit tedious. Jin Jiaqi developed a video detection system to determine the position of the tubing coupling [6]. However, this method has limitations of high costs because of the hardware that needs to be used for this process to be feasible. In this study, we present a tubing coupling detection method based, on the principles of a Linear Variable Displacement Transformer (LVDT). The analytical expression relating to the output voltage and geometrical parameters of LVDT are derived and solved using Ansys Maxwell. This paper highlights all the details of the design and simulation of the tubing coupling and its validation.

II. LVDT OVERVIEW

The LVDT, an inductive sensor positioning sensor, is a transformer with one excitation, or primary coil fed by a sinusoidal voltage source and two secondary coils wound on support [7]. The core of the transformer is a movable part made of magnetic material, which is bound to the element whose position is to be measured. When the core moves toward a coil, the amplitude of the magnetic flux, produced by the primary winding and linked to that coil, increases. Accordingly, the voltage across it increases too, while the amplitude of the voltage across the other coil decreases. The difference between the secondary coil voltages allows for the evaluation of the core position [8].

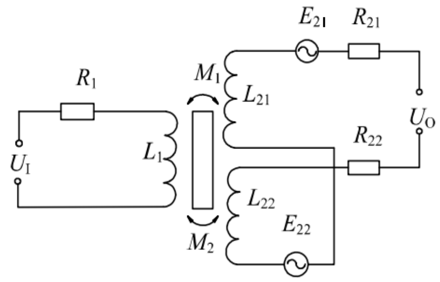

Fig 1. LVDT equivalent circuit diagram

Where U_1 is the excitation voltage of the primary coil, R_1 is the resistance value of the primary coil, L_1 is the inductance value of the primary coil, R_{21} and R_{22} are the resistance values of the two secondary coils respectively, L_{21} and L_{22} are the inductance values of the two secondary coils respectively, E_{21} and E_{22} represent the electromotive force generated by the tubing coupling in the two secondary coils, and U_O represents the output voltage of the sensor.

The primary coil current I_1 can be calculated as follows

$$I_I = \frac{U_1}{R_1 + jwL_1} \tag{1}$$

Then the induced electromotive force of the two secondary coils is

$$E_{21} = -j\omega M_1 I_1 \tag{2}$$
$$E_{22} = -j\omega M_2 I_1 \tag{3}$$

The differential output voltage of the coil is

$$U_O = E_{21} - E_{22} = -\frac{jw(M_1 - M_2)U_1}{R_1 + jwL_1} \tag{4}$$

$$U_0 = \frac{w(M_1 - M_2)U}{\sqrt{R_1^2 + (wL_1)^2}} \tag{5}$$

When the core is in the middle position, then $M_1 = M_2 = M$ therefore $U_0 = 0$, the differential voltage effective value of LVDT is zero. When the core moves towards the secondary coil 1, then $M_1 > M_2$, $U_O > 0$.

$$M_1 = M + \Delta M$$
$$M_2 = M - \Delta M$$

therefore

$$U_0 = \frac{2w\Delta M U_1}{\sqrt{R_1^2 + (wL_1)^2}} \tag{6}$$

Where: ΔM - inductance of the secondary coil and primary coil when the core moves. When the core moves towards the secondary coil 2, $M_1 < M_2$, $U_O < 0$.then

$$M_1 = M - \Delta M$$
$$M_2 = M + \Delta M$$

therefore

$$U_0 = -\frac{2w\Delta M U_1}{\sqrt{R_1^2 + (wL_1)^2}} \qquad (7)$$

The theory shows that LVDT affects the mutual inductance coefficients M_1 and M_2 of secondary coils 1 and 2 through the change of core position, which resultantly changes the differential output voltage, a relationship between core displacement and differential output can be established and the results can achieve the purpose of measuring displacement or identifying the position of an object.

III. COUPLING DETECTOR MODEL AND OUTPUT VOLTAGE ANALYSIS

A simple structural diagram of the coupling detection system based on the LVDT principle is shown in Fig. 2. It consists of an excitation coil (primary coil) in the middle, two detection coils (secondary coils 1 and 2, connected in reverse series) at the edge, and an oil pipe inserted in the center of the coil. In the figure, r_1 is the outer diameter of the coupling; r_2 is the outer diameter of the oil pipe, R_1 is the inner diameter of the coil; R_2 is the outer diameter of the coil; n is the length of the secondary coil; L_1 is the coupling length between coupling hoop and secondary coil; L_2 is the coupling length between coupling hoop and secondary coil 2; ABCD is the magnetic flux path between the primary coil and secondary coil 1; EFGH is the magnetic flux path between the primary coil and the secondary coil 2. When a sinusoidal alternating voltage is applied to the exciting coil, a sinusoidal alternating magnetic field will be generated around the coil. When the measured oil pipe passes through, an induced voltage will be generated inside the oil pipe, and the induced current will generate a new alternating magnetic field. The new alternating magnetic field will act on the detection coils (secondary coils 1 and 2), causing the coils to generate induced voltage and form induced electromotive force. Theoretically, when the oil pipe to be tested passes through, the mutual inductance coefficients(M_1 and M_2 of the two detection coils must be equal ($M_1 = M_2$). According to the principle of electromagnetic induction, the two induced electromotive forces generated will also be equal ($U_1 = U_2$). Since the two detection coils are connected in reverse series, the output voltage of the differential connection is 0 ($U_O = U_1 - U_2$). When the coupling part passes through, the magnetic flux in the upper secondary coil will be greater than that in the secondary coil due to the influence of the magnetic resistance, that is, $M_1 > M_2$ so that U_1 increases. Similarly, when the tubing coupling reaches the lower secondary coil, the magnetic flux in the lower secondary coil will be greater than the magnetic flux in the upper detection coil, that is, $M_1 < M_2$, and U_2 will increase. Thus, the voltage U_O output from the coil differential connection is detected.

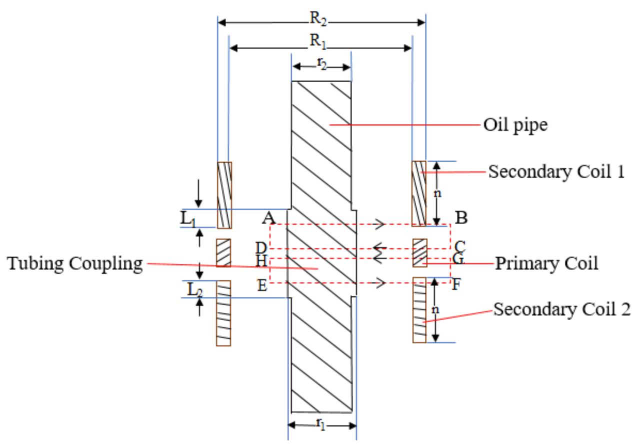

Fig. 2. Simplified diagram of the tubing coupling

By applying the Ampere circuit law on loop ABCD

$$N_1 I = \oint_{ABCD} H\,dl$$
$$= \int_A^B H_1\,dl_1 + \int_C^D H_2\,dl_2 \qquad (8)$$

Section AB and CD are mainly in the air so their permeability can be regarded as air permeability μ_o, equation 1 can therefore be written as

$$N_1 I = \int R_2 \frac{B_1}{r_1 \mu_0} dl_1 + \int R_2 \frac{B_2}{r_1 \mu_0} dl_2 \qquad (9)$$

Where N_1 is the number of turns of the primary coil. According to the magnetic flux continuity theorem and the above assumptions the magnetic flux B_1 and B_2 have equal and opposite amplitudes and opposite directions, therefore the resulting solution becomes

$$B_1 = \frac{N_1 I \mu_0}{2r_1 \ln\frac{R_2}{r_1}} \qquad (10)$$

The magnetic linkage that is therefore generated by secondary coil 1 is:

$$\psi_1 = \int L_1 \left(\frac{N_2}{n} B_1 2r_1\right) x\, dx = \frac{\mu_0 I N_1 N_2 L_1^2}{2n\, ln\frac{R_2}{r_1}} \quad (11)$$

Where N_2 is the number of turns of the secondary coil. Correspondingly it can be obtained that the magnetic linkage generated by secondary coil 2 is

$$\psi_2 = \frac{\mu_0 I N_1 N_2 L_2^2}{2n\, ln\frac{R_2}{r_1}} \quad (12)$$

The induced electromotive forces generated by the secondary coil are:

$$U_1 = j\omega\psi_1 = j\frac{\mu_0 \pi f I N_1 N_2 L_1^2}{n\, ln\frac{R_2}{r_1}} \quad (13)$$

$$U_2 = j\omega\psi_1 = j\frac{\mu_0 \pi f I N_1 N_2 L_2^2}{n\, ln\frac{R_2}{r_1}} \quad (14)$$

Where f is the power frequency, and the output voltage is:

$$U_O = U_1 - U_2 \quad (15)$$

$$U_O = j\frac{\mu_0 \pi f I N_1 N_2}{n \ln\frac{R_2}{r_1}}(L_2^2 - L_1^2) \quad (16)$$

It can be observed from equation (16) that the root of coupling detector output voltage lies in the difference between the distance between the coupling and secondary coil 1 and between the secondary coil 2. From equation (16) it can be understood that only when the two distances are not equal can there be output voltage, and the magnitude of the square difference in the distance determines the size of the output voltage. The input frequency, primary coil turns, secondary coil turns and coil size are equivalent to the output voltage amplification factor. The output voltage can be adjusted within a given range by reasonably selecting these parameters.

IV. SIMULATION ANALYSIS

Finite element methods are versatile and the most commonly used numerical method among researchers and practitioners to solve complex problems in engineering and science [9]. In this study, the modeling methodology aims to derive the transfer characteristics of the coupling detector with certain dimensions and parameters. The transfer characteristic (or output characteristic) is a relationship between the displacement of the tubing coupling and the output resultant DC voltage. It is assumed that the two AC signals from the two secondaries are processed by full-wave rectification, smoothing the signals, and then subtracting them. Ansys Maxwell software is used to simulate the tubing coupling detector. The model is prepared in a 2D environment as shown in Fig. 3; the coupling has a cylindrical symmetry so half of the longitudinal section of the coupling is modelled. And with the use of the 2D model, the quantity of mesh can be decreased and the computational efficiency can be improved. Because the output property of the coupling detector is ultimately influenced by resistance and induction of the coil rather than the section shape of the coil, the circle section of the coil is equivalent to rectangular with the same area to decrease the quantity of mesh and improve the computational efficiency [10]. Since the oil pipe and coils are completely symmetrical, the two-dimensional model of the system is established by using RZ coordinate system as shown in Fig 3.

Table 1: Coupling detector structure and functional parameters

Parameters	Values
No. of turns of the primary coil	1000
No. of turns of the secondary coil	`1200
Length of the primary coil(mm)	40
Length of the secondary coils(mm)	100
Length of the tubing coupling(mm)	84
Length of the oil pipe(mm)	1500
The inner diameter of the coil(mm)	40
The outer diameter of the oil pipe(mm)	26
the outer diameter of the tubing coupling(mm)	30
Input voltage of the primary coil(V)	5
Frequency (kHz)	1

Table 1 shows the coupling detector structure and functional parameters and Table 2 shows the material properties of the main components.

Table 2: Coupling detector material selection

Part	**Material**
Primary coil	Copper
Secondary coils	Copper
Oil pipe	J55
Tubing coupling	J55
Base	1Cr18Ni9Ti
Outer shell	35CrMo

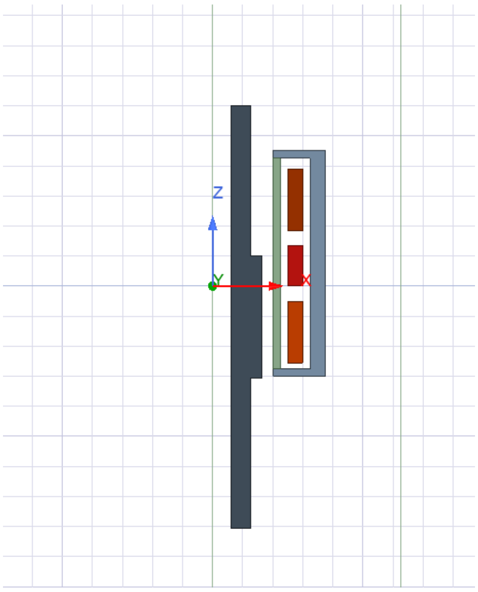

Fig. 3 2D structure of the coupling device in Ansys Maxwell

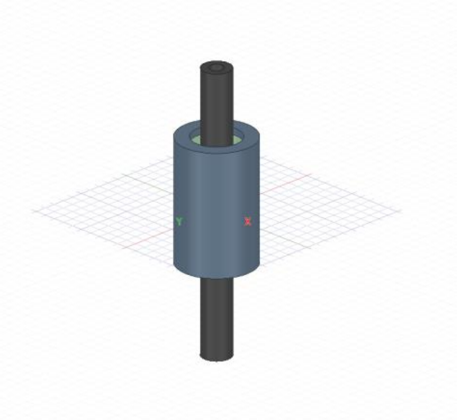

Fig. 4 Full 3D structure of the coupling device in Ansys Maxwell

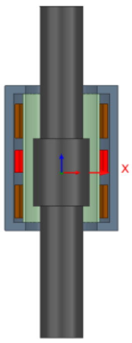

Fig. 5 Half 3D structure of the coupling device in Ansys Maxwell

Fig.4 and Fig.5 Shows the simplified 3D model of the proposed coupling detector device.

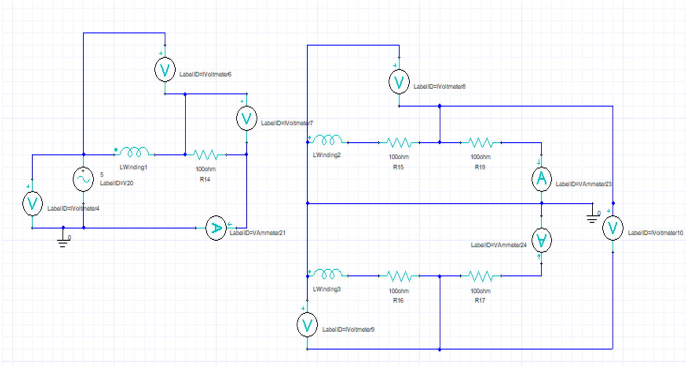

Fig. 6 Excitation circuit of the coupling detector

The transient magnetic analysis is used to analyze the output voltage of the tubing coupling and Fig.6 shows the external excitation circuit of the coupling detector designed in Maxwell Circuit Editor. The sinusoidal AC signal of 5Vrms and a frequency of 1KHz are used to excite the primary coil.

V. RESULTS AND DISCUSSION

In this study to accurately investigate the changes in the potential difference as the tubing coupling is passing through, the tubing coupling goes from -84mm to 84mm at 14-mm intervals when the position of the center is 0. Fig 7 shows the induced voltage-time graph as the oil pipe tubing coupling part moves upwards.

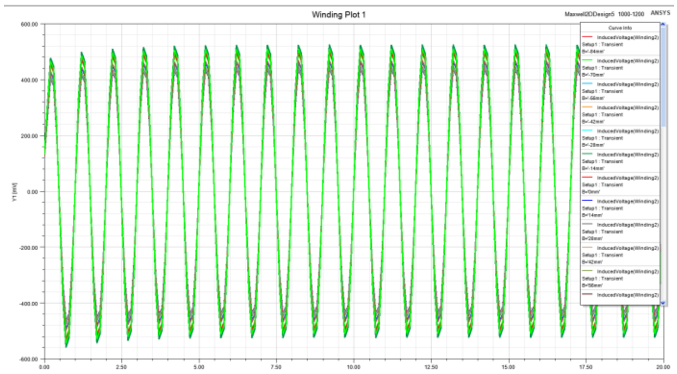

Fig. 7 FEM result of the induced voltage in secondary coils

When the coupling passes through the coupling detector, its output voltage is approximately linear, which can better reflect the position of the tubing coupling. See Table 3 for the corresponding data of the tubing coupling position output voltage.

Table. 3. Tubing coupling position and induced voltage

Tubing coupling/mm	Output Voltage/V	Tubing coupling/mm	Output Voltage/V
-84	-0.52	14	0.16
-70	-0.49	28	0.28
-56	-0. 44	42	0.35
-42	-0.36	56	0.43
-28	-0.28	70	0.48
-14	-0.18	84	0.53
0	0		

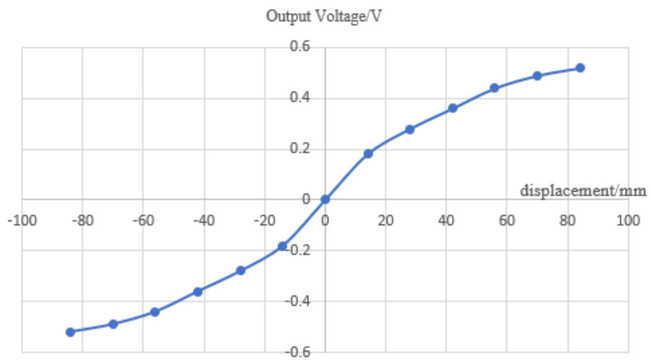

Fig. 8 Tubing Coupling Displacement vs Output Voltage graph

When the oil pipe gradually approaches the detection device, the magnetic flux of the primary coil and the secondary coil 1 turn chain is still closed through the air path, and the magnetic flux of the primary coil and the secondary coil 2 turn chain is closed through the air, oil pipe and air circuit. When it is closed, the magnetic permeability of the closed loop increases, the magnetic resistance decreases, and the mutual inductance is greater than the mutual inductance between the primary coil and the secondary coil 1. The two generate a voltage difference, thereby outputting a voltage, and the voltage increases with the forward movement of the oil pipe. When the output voltage reaches the maximum value, the oil pipe continues to enter the secondary coil 1 area. At this time, the magnetic flux of the primary coil and the secondary coil 1 turns is closed through the air, oil pipe, and air circuit, and the mutual inductance increases, thus reducing the output voltage. When the oil pipe completely coincides with the secondary coil 1, the output voltage decreases. When the oil pipe continues to advance and the coupling enters the detection area, the above process will be repeated because the outer diameter of the coupling is different from that of the oil pipe. And the difference between the two outer diameters is small, and the output voltage amplitude is significantly reduced. Fig 9 shows also the changes of induced current in the secondary coils as the tubing coupling passes through.

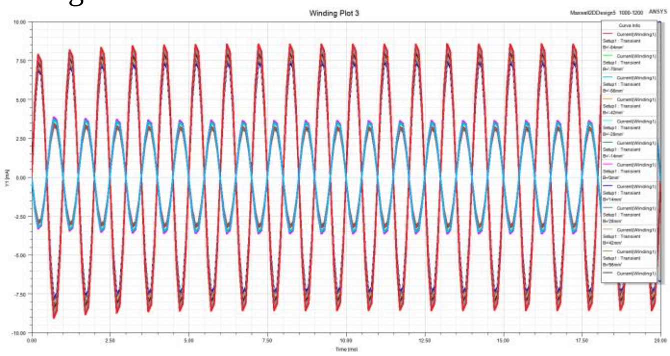

Fig.9 Induced current vs time graph

VI. CONCLUSIONS

Workover operations are very tedious and labor intensive, it's a high-risk activity that presents safety challenges to the workers. To lessen this burden, there is a need and challenge to automate workover operations, tubing coupling detection is a very important key in the automation process of the operations. This paper presents a framework for the design, and simulation of the coupling detector that can be used in determining the position of the tubing coupling in real-time. Finite element analysis is used in this work to analyze the resultant output voltage of the coupling detector.

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