

March 23, 1954

R. G. PIETY
SIMULATOR

2,673,031

Filed Jan. 2, 1953

4 Sheets-Sheet 1

Fig. 1.

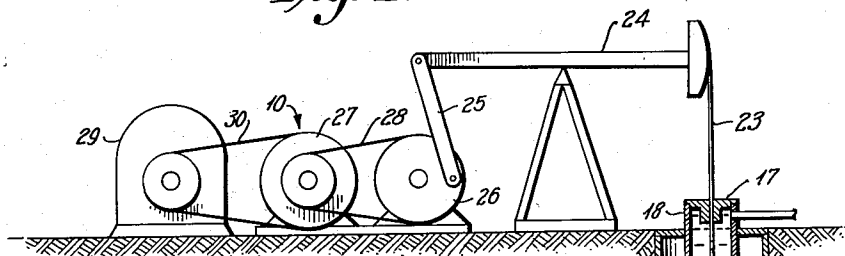


Fig. 5.

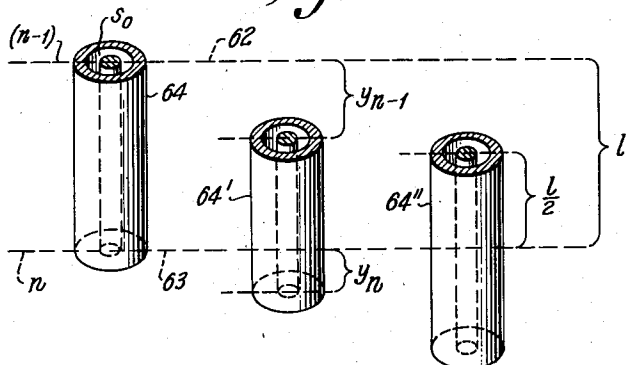
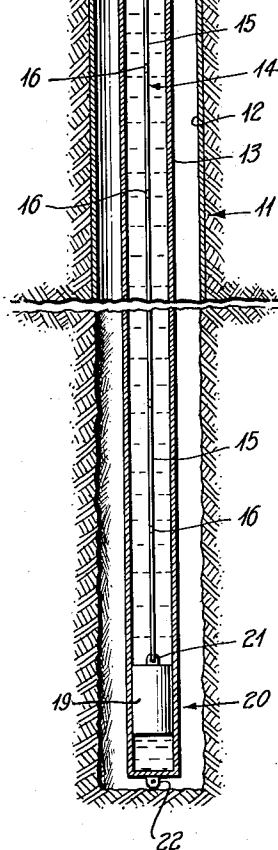
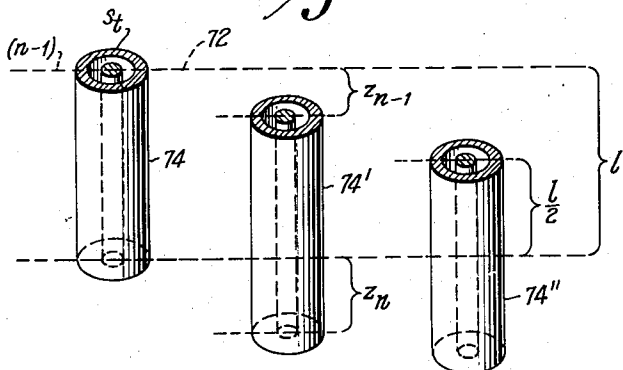


Fig. 6.



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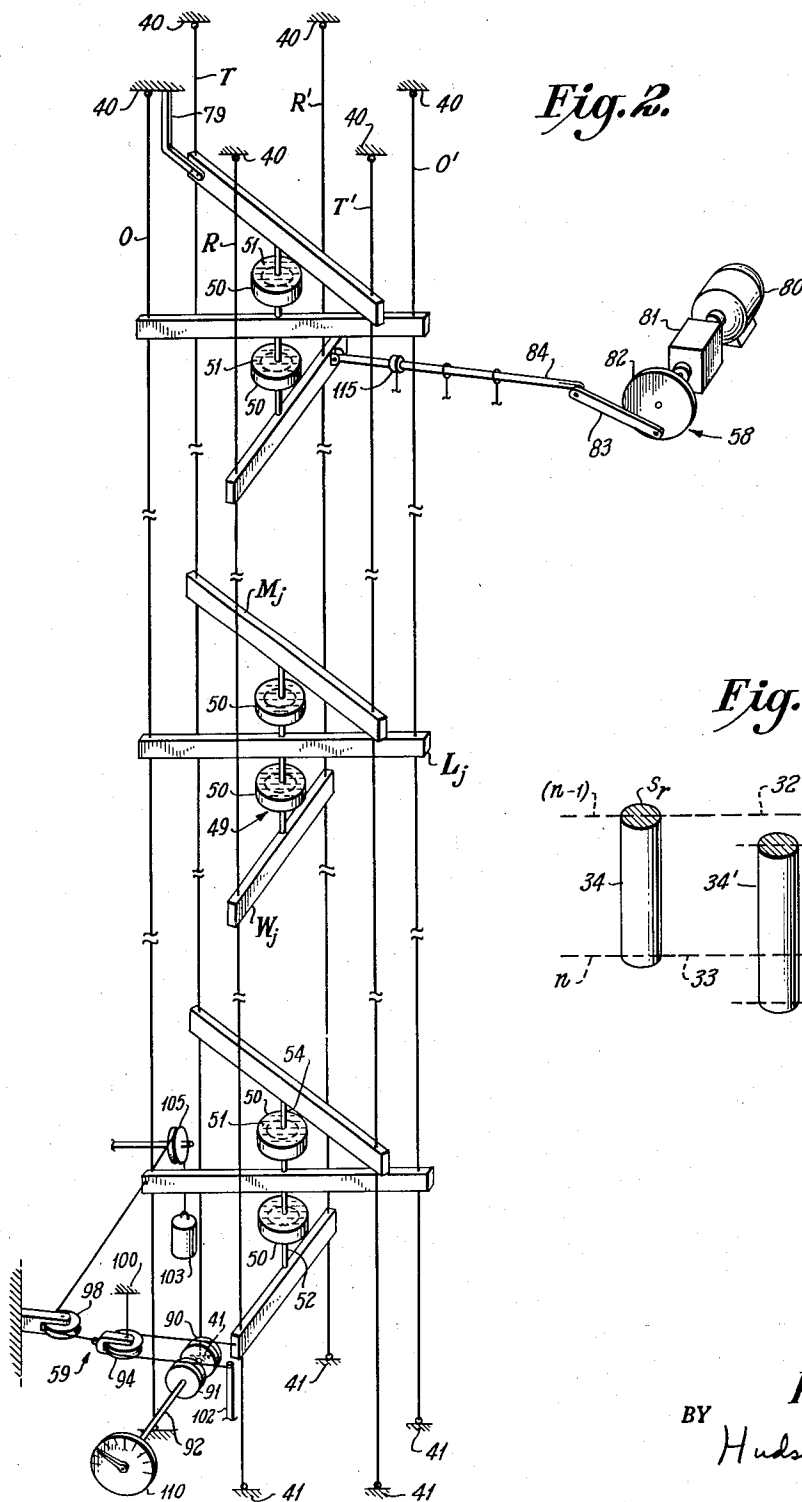
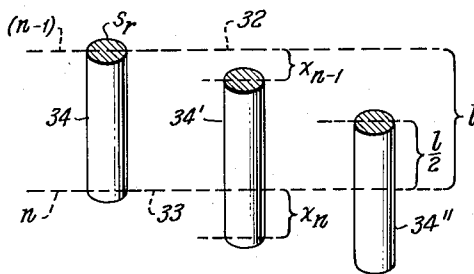


Fig. 2.

Fig. 3.



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Fig. 4.

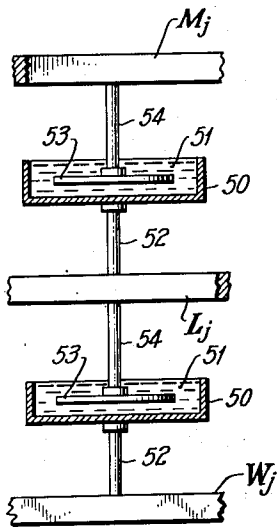
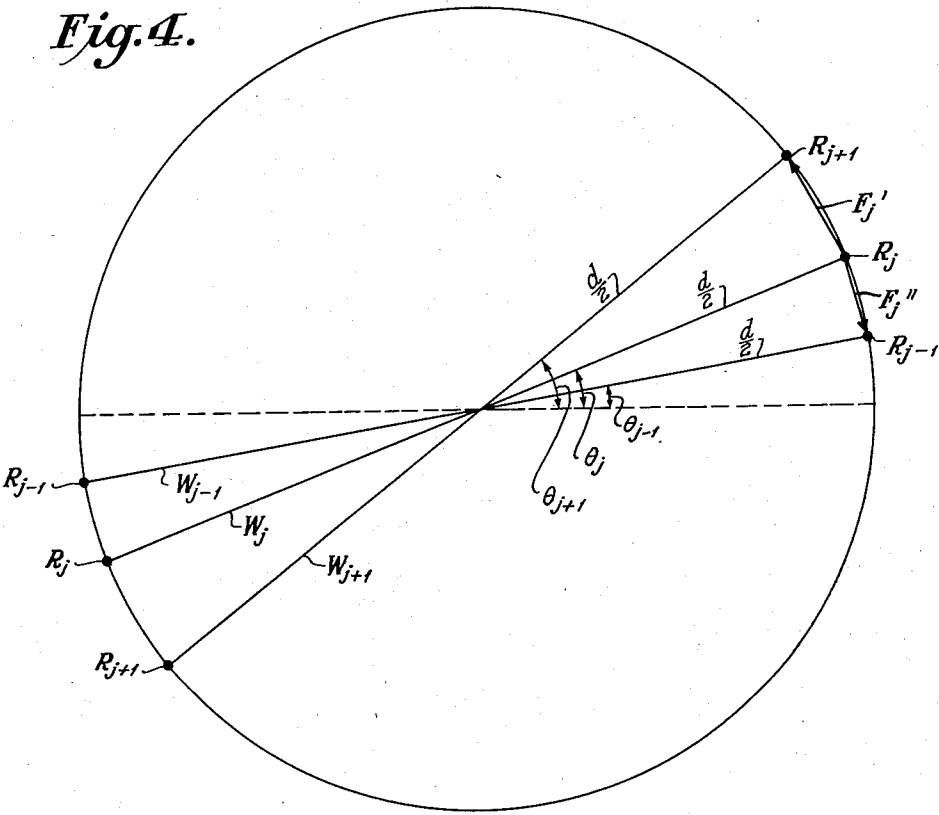


Fig. 7.

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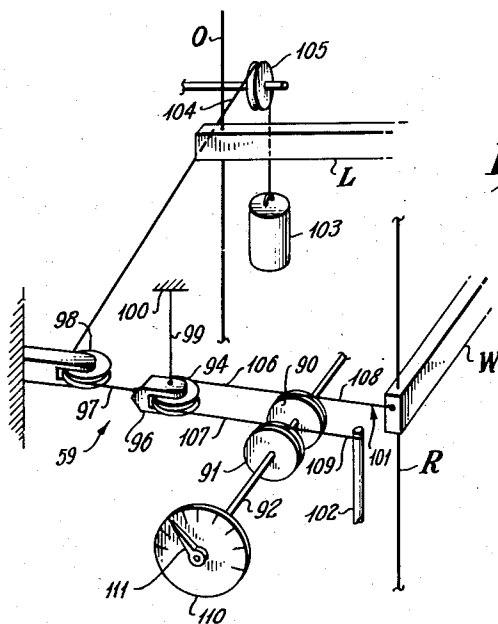
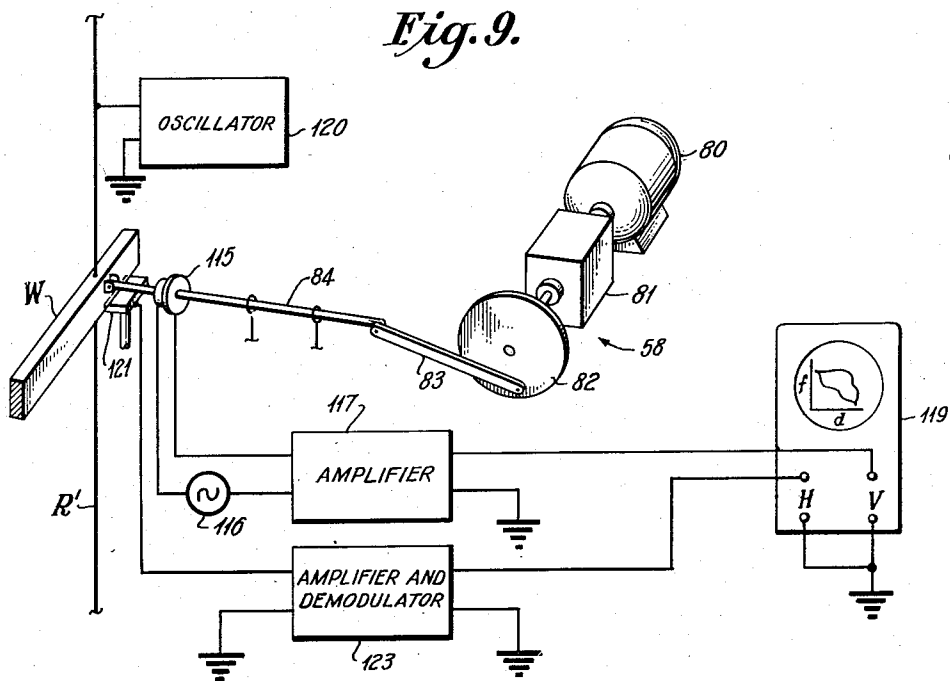
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4 Sheets-Sheet 4



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UNITED STATES PATENT OFFICE

2,673,031

SIMULATOR

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14 Claims. (Cl. 235—61)

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This invention relates to a simulator which is a mechanical analogue of a pumping system. In one specific aspect it relates to a simulator which is a mechanical analogue of the tubing, sucker rod, oil column, and pump in a deep well pumping unit.

A typical deep well pumping system includes a series or "string" of metal rods, referred to in the art as sucker rods, which extend through tubing positioned in the well, the lower end of which carries a pumping unit. The tubing, in turn, is suspended within a well casing end, under some conditions, the lower portion of the interspace between the tubing and casing may contain a column of oil. At the top of the well, the sucker rod string extends through a stuffing box and is driven by a prime mover, such as an electric motor or an internal combustion engine, through a flywheel or "bull wheel." The flywheel, in turn, drives a crank or counterbalance which is coupled through a walking beam to the top end of the sucker rod string.

As the pumping operation is carried out, a column of oil rises in the region between the tubing and the sucker rod string, thus producing a viscous drag upon both the tubing and sucker rod string. The weight and elasticity of the sucker rod string, as well as the tubing and oil column, produce elastic strains in the pumping unit so that the sucker rod string and tubing behave in a manner somewhat analogous to elongated springs.

This elastic movement of the sucker rod string and tubing oftentimes results in failure of one or more sucker rods and, more often, in inefficient operation of the pumping system. It has not been possible, in the past, to predict the effect of changes in various operating variables of the system with any degree of accuracy, except by purely empirical or "cut and try" methods, for the obvious reason that the movement of the sucker rod string several miles below the surface of the earth cannot be observed nor is it possible to observe the manner of operation of the downhole pump.

It has been proposed to construct a mechanical model of the pumping system so that adjustments of various operating variables of the scale model would produce effects thereon similar to the effects of changes in corresponding variables

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upon the actual pumping system. Unfortunately, to obtain any useful results by such a system, it can be demonstrated mathematically that the scale model itself would be of such large size and prohibitive cost as to render construction thereof entirely impractical. However, it has been discovered in accordance with the present invention that a mechanical analogue of a pumping system can be established on a practical scale. In this analogue system a series of bars are connected in spaced relation between three pair of lines representing, respectively, the oil column, the tubing, and the sucker rod string. The individual pairs of lines are coupled by damping members which represent the viscous drag of the oil column on both the tubing and sucker rod string. The torques tending to rotate the various bars from their normal positions represent stresses imposed upon corresponding elements of the sucker rod string, tubing and oil column, while the angular velocities and rotations of the bars represent the velocities and displacements of corresponding parts of the pumping unit. In corresponding fashion, other parameters of the analogue or mechanical system represent corresponding variables and constants of the prototype pumping unit.

Accordingly, it is an object of this invention to provide a mechanical system which is an analogue of an actual well pumping unit, which system may be utilized to predict the effect of changing various operating conditions of the pumping system.

It is a further object to provide apparatus of the type described which is simple to construct, reliable in operation, and which employs a minimum number of inexpensive components.

Various other objects, advantages and features of the invention will become apparent from the following detailed description taken in conjunction with the accompanying drawings, in which:

Figure 1 is a vertical sectional view, partially in elevation, of a typical deep well pumping system;

Figure 2 is a schematic view of the analogue system simulating the operation of the deep well pumping unit;

Figures 3, 4, 5, and 6 are diagrammatic views illustrating features of this invention;

Figure 7 illustrates apparatus employed to

couple viscously the various lines of the analogue system;

Figure 8 illustrates apparatus simulating the downhole pump; and

Figure 9 is a schematic representation of the analogue surface pumping unit and indicating system.

Referring now to Figure 1, there is illustrated, in a schematic manner, a typical deep well pumping system to which the simulator of this invention is applicable, this system including a driving mechanism 10 located at the surface and a downhole pumping unit 11. Unit 11 includes the usual well casing 12 within which is mounted a tubing 13 having a sucker rod string 14 suspended therein, the latter including a number of sucker rods 15 connected together by joints 16. The upper end of string 14 extends through a stuffing box 17 in a casing head 18 and the lower end is attached to a plunger 19 forming a part of a pump 20 which includes an upper or traveling valve 21 and a bottom or stationary valve 22. The uppermost sucker rod or "polished" rod 23 is driven by mechanism 10 which includes a walking beam 24 secured at one end to the polished rod and at its other end is secured to a pitman 25 which is driven by a crank or counter-balance 26. Crank 26 is driven by a flywheel 27, as through a chain drive 28; and flywheel 27, in turn, is driven by a prime mover 29, as by a second chain drive 30. Prime mover 29 may be an electric motor, an internal combustion engine, or any other suitable type of engine.

In accordance with this invention, the operation of the downhole unit 11 is mechanically simulated by the apparatus of Figure 2. The displacement torques on various members of the analogue system represent stresses on corresponding parts of the pumping unit, the rotations of various members of the analogue system represent displacements of corresponding parts of the actual pumping system, and angular velocities in the analogue system represent the velocities of corresponding parts of the mechanical system. In order for the two systems to be analogues of one another, it is necessary that the equations describing the behavior of the analogue system be similar to the equations describing the behavior of the actual pumping unit. Thereupon, by suitably adjusting the coefficients of various terms of the analogue system, as by changing the parameters of various parts of the analogue system, a condition is obtained whereby the displacement torques, rotations, angular velocities and other parameters of the analogue system correspond to the stresses, displacements, velocities and other related variables of the pumping unit. At this time, the two systems are analogues of one another and further changes in the parameters of the analogue system produce effects thereon which enable accurate prediction of the effects of corresponding changes in the pumping unit.

In the simulator of Figure 2, a first pair of lines T and T' represents the tubing 13, a second pair of lines O and O' represents the oil column, and a third pair of lines R and R' represents the sucker rod string 15. These letters are employed throughout the following description as subscripts to represent the line to which they are applicable, such as the tubing, oil or rod line. The following notation is used in the equations to

be derived which define the motion of the two systems:

Pumping System	Analogue System
l —length of sucker-rod, oil column or tubing segment.	d —length of sucker rod, oil column, or tubing bars.
x_n, y_n, z_n —displacement of sucker rod, oil column, and tubing segment, respectively.	θ_i, ϕ_i, ψ_i —rotation of sucker rod, oil column, and tubing bars, respectively.
w_r, w_o, w_t —weight per unit length of sucker rod, oil column and tubing segments, respectively.	I_i, A_i, C_i —moment of inertia of sucker rod, oil column and tubing bars, respectively.
u_n, v_n, w_n —velocity of sucker rod, oil column and tubing segments, respectively.	U_i, V_i, D_i —angular velocity of sucker rod, oil column, and tubing bars, respectively.
a_n, b_n, c_n —acceleration of sucker rod, oil column, and tubing segments, respectively.	$\alpha_i, \beta_i, \delta_i$ —angular acceleration of sucker rod, oil column, and tubing bars, respectively.
p_n, p_o —stress in sucker rod and tubing segments, respectively.	W, L, M —sucker rod, oil column and tubing bars, respectively.
q_n —compression in oil column segment.	
e_r, e_o, e_t —elastic modulus of the sucker rod, oil column, and tubing, respectively.	
s_r, s_o, s_t —cross sectional area of sucker rod, oil column, and tubing segments, respectively.	
g —gravity constant.	K_r —viscosity constant relating to movement between sucker rod and oil column bars.
k_r —viscosity constant relating to movement between sucker rod and oil column segments.	K_o —viscosity constant relating to movement between oil column and tubing bars.
k_o —viscosity constant relating to movement between oil column and tubing segments.	
k_t —viscosity constant relating to movement between tubing segments and fluids outside the tubing.	

In the mathematical analysis of the pumping unit and analogue system which follows, the respective equations are derived by the method of finite differences. In accordance with this method the casing, tubing, and sucker rod string are divided into a large number n of segments. During operation of the pumping unit each segment of the sucker rod, tubing, and oil column moves upward or downward in accordance with the mechanical laws governing the system. It has been discovered that corresponding equations describe the motion of the rotating line analogue system.

In particular, considering the n th segment 34 of the sucker rod, as defined by the dotted lines 32 and 33, Figure 3, let it be assumed that at a given instant the lower end of this n th segment is displaced downward from its equilibrium position a distance x_n and the upper end of the segment is displaced downward from its equilibrium position a distance x_{n-1} . This displaced position is represented by 34'. Such a displacement results in a stretching of the n th segment by an amount $x_n - x_{n-1}$, which in turn results in a strain

$$\frac{x_n - x_{n-1}}{l}$$

so that the total stress in the n th segment becomes:

$$P_n = \frac{s_r e_r (x_n - x_{n-1})}{l} \quad (1)$$

In like manner a corresponding equation can be written for the $(n+1)$ th segment as follows:

$$P_{n+1} = \frac{s_r e_r (x_{n+1} - x_n)}{l} \quad (2)$$

In the pumping unit of Figure 1 let it further be assumed that the downward velocity of the rod at the n th station is u_n and that the upward velocity of the oil column is v_n , which results in

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an upward viscous drag on the n th rod segment of magnitude $k_r l(u_n + v_n)$. From these data the motion of a rod segment 34'' which straddles the line 33 can be deduced, this segment extending a distance

$$\frac{l}{2}$$

both above and below the n th station, Figure 3. Segment 34'' has acting upon its total tension p_{n+1} on its bottom end, a total tension p_n on its top end, the aforementioned upward viscous drag, and a downward weight $w_r l$, the resultant force produces a downward acceleration a_n at the mid-point of the segment in accordance with equation:

$$p_{n+1} - p_n = \frac{w_r l a_n}{g} + k_r l(u_n + v_n) - w_r l \quad (3)$$

The basic sucker rod equation is realized by combining Equations 1, 2, and 3 to obtain:

$$\frac{s_r e_r}{l}(x_{n+1} - 2x_n + x_{n-1}) = \frac{w_r l a_n}{g} + k_r l(u_n + v_n) - w_r l \quad (4)$$

Equation 4 has its counterpart in the analogue system of Figure 2. This analogue system comprises three pair of lines R, R'; T, T'; and O, O' representing, respectively, sucker rod string 14, tubing 13, and the oil column between tubing 13 and string 14. These lines preferably are constructed of an electrically conductive material such as steel wire, and each is attached at its upper end to a support member 40 and anchored at its lower end to a member 41 whereby the individual lines are disposed in parallel vertical spaced relation. A series of bars W_j are secured to lines R and R' to extend between the two lines in horizontal spaced relation with one another. Corresponding bars L_j and M_j extend between respective lines O, O' and T, T' in like manner. For convenience of construction the three pairs of lines are mounted so that the axial lines of the individual bars make equal 60° angles with one another, although such spacing is by no means essential to satisfactory operation of this invention. Each of the adjacent bars W_j and L_j are viscously coupled to one another as are adjacent bars L_j and M_j . This coupling is provided by a plurality of devices 49, one of which is illustrated in detail in Figure 7. A pan 50 filled with a liquid 51, such as oil, is supported above bar L by a rod 52 and a plate 53 is suspended from bar M by a rod 54 so as to be free to rotate in liquid 51 whenever bars L and W rotate relative to one another. Bars W and L are coupled in like manner. A drive mechanism 58 is connected to the uppermost W bar to impart a reciprocating rotation thereto at right angles to the longitudinal axis of the bar representative of the pumping unit 10, and a stepless pawl mechanism 59 is connected between the lowermost W and L bars to represent the reacting forces exerted by the downhole pump assembly 20. Mechanisms 58 and 59 are described in greater detail hereinafter.

In Figure 4 there is shown a schematic representation of the torques on and displacement of the W_j bar interposed between lines R and R'. Figure 4 is a plan view of a portion of the simulator wherein bars W_{j-1} , W_j and W_{j+1} are shown as lines to facilitate explanation and wherein these respective bars are rotated from a reference line 60 through angles θ_{j-1} , θ_j and θ_{j+1} . The net force F_j which tends to displace bar W_j horizontally from line 60 is equal to the difference

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between the displacement force F_j and the restoring force F_j'' , that is:

$$F_j = F_j' - F_j'' \quad (5)$$

5 For small displacements

$$F_j' = \frac{d}{2}(\theta_{j+1} - \theta_j)$$

and

$$F_j'' = \frac{d}{2}(\theta_j - \theta_{j-1})$$

so that forces F_j' and F_j'' represent the torques acting in a horizontal direction on bar W_j and will be so considered hereinafter. Equation 5 thus becomes:

$$F_j = \frac{d}{2}(\theta_{j+1} - 2\theta_j + \theta_{j-1}) \quad (6)$$

Torque F_j is made up of a dynamic reaction $I_j a_j$ and a viscous loading term $K_r(U_j + V_j)$, assuming bars W_j and L_j are rotating in opposite directions, such that Equation 6 becomes:

$$\frac{d}{2}(\theta_{j+1} - 2\theta_j + \theta_{j-1}) = I_j a_j + K_r(U_j + V_j) \quad (7)$$

If the vertical distances between adjacent bars on the individual pairs of lines are equal and the rotations are small the horizontal displacement forces on each bar are proportional to the above-mentioned torques. It is to be understood that the quantity I represents the moment of inertia of the bars considering the pans or plates secured thereto.

A comparison of Equations 4 and 7 reveals that they are analogous term by term except that the last term of Equation 4 is missing from Equation 7. However, because this missing term represents the static load created by the mass of the sucker rod it can be neglected for purposes of analysis. The important quantity under consideration is the variation in excess loading over the static value. In view of the analogy between Equations 4 and 7 it becomes evident that a study of various quantities such as rotations, angular velocities and torques affecting the simulator rotating lines R and R' provides information regarding corresponding quantities in the prototype sucker rod string.

Similar equations can be derived with respect to the compressive stress on the individual segments of the oil column and the motion of a general segment of the oil column. With reference to Figure 5, considering the n th segment 64 of the oil column as defined by the dotted lines 62 and 63, let it be assumed that at a given instant the lower end of this n th segment is displaced downward from its equilibrium position a distance y_n and that the upper end of the segment is displaced downward from its equilibrium position a distance y_{n-1} . This displaced position is represented by 64'. Such a displacement results in a compression of the n th segment by an amount $y_n - y_{n-1}$, which in turn results in a strain

$$\frac{y_n - y_{n-1}}{l}$$

so that the total compressive stress in the n th segment is

$$q_n = \frac{s_o e_o (y_n - y_{n-1})}{l} \quad (8)$$

In like manner a corresponding equation can be written for the $(n+1)$ th segment as follows:

$$q_{n+1} = \frac{s_o e_o (y_{n+1} - y_n)}{l} \quad (9)$$

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The equation of motion of the oil column segment 64'' which extends a distance

$$\frac{l}{2}$$

above and below line 63 is governed by the viscous drag on the oil due to the sucker rod movement which, as previously indicated, is $k_r l(u_n + v_n)$ and the viscous drag on the oil due to the friction against the tube which is represented by $k_o l(u_n + \mu)$. The bottom of this last mentioned segment is subjected to a compressive force q_{n+1} and the top of the segment is subjected to a compressive force $-q_n$. Finally, the weight of the oil per unit length must be considered in the equation of motion which, therefore, becomes:

$$q_{n+1} - q_n = \frac{w_o l b_n}{g} + k_r l(u_n + v_n) + k_o l(u_n + \mu_n) - w_o l \quad (10)$$

The basic oil column equation is realized by combining Equations 8, 9, and 10 to obtain:

$$\frac{s_o e_o}{l} (y_{n+1} - 2y_n + y_{n-1}) = \frac{w_o l b_n}{g} + k_r l(u_n + v_n) + k_o l(u_n + \mu_n) - w_o l \quad (11)$$

Equation 11 also has its counterpart in the analogue system of Figure 2. The equation of motion of the rotating bars L corresponds to Equation 6 and can be written as follows:

$$G_i = \frac{d}{2} (\phi_{i+1} - 2\phi_i + \phi_{i-1}) \quad (12)$$

Torque G_i is made up of a dynamic reaction $A_i \beta_i$, a first viscous loading term $K_r(U_i + V_i)$ and a second viscous loading term $K_o(V_i + D_i)$ such that Equation 12 becomes:

$$\frac{d}{2} (\phi_{i+1} - 2\phi_i + \phi_{i-1}) = A_i \beta_i + K_r(U_i + V_i) + K_o(V_i + D_i) \quad (13)$$

A comparison of Equations 11 and 13 reveals that they are analogous term by term except that the last term of Equation 11 is missing from Equation 13. However, since this missing term represents the static load created by the mass of the oil column it can also be neglected in the analysis. In view of the analogy between Equations 11 and 13 it becomes evident that lines O, O' simulate the action of the oil column in the pumping system.

The movement of the tubing is governed generally by the same equations as the movement of the sucker rod. With reference to Figure 6, considering the n th segment 74 of the tubing as defined by the dotted lines 72 and 73, let it be assumed that at a given instant the lower end of this n th segment is displaced downward from its equilibrium position a distance z_n and the upper end of the segment is displaced downward from its equilibrium position a distance z_{n-1} . This displaced position is represented by 74'. Such a displacement results in a stretching of the n th segment by an amount $z_n - z_{n-1}$, which in turn results in a strain

$$\frac{z_n - z_{n-1}}{l}$$

so that the total stress in the n th segment becomes:

$$\rho_n = \frac{s_i e_i (z_n - z_{n-1})}{l} \quad (14)$$

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In like manner a corresponding equation can be written for the $(n+1)$ th segment as follows:

$$\rho_{n+1} = \frac{s_i e_i (z_{n+1} - z_n)}{l} \quad (15)$$

The equation of motion of the tube segment 74'', which extends a distance

$$\frac{l}{2}$$

above and below line 73 is governed by a total tension ρ_{n+1} on the bottom of the segment, a total tension ρ_n on the top of the segment, the viscous drag $k_o l(v_n + \mu_n)$ produced by friction of the oil column against the tubing and an upward viscous drag $k_i l \mu_n$ produced by oil or other fluid positioned between the casing and the tubing. This latter term need only be considered for the particular segments wherein oil is included between the casing and tubing. Accordingly, the equation of motion of this last mentioned segment is as follows:

$$\rho_{n+1} - \rho_n = \frac{w_i l c_n}{g} + k_o l(v_n + \mu_n) + k_i l \mu_n - w_i l \quad (16)$$

The basic tubing equation is realized by combining Equations 14, 15, and 16 to obtain:

$$\frac{s_i e_i}{l} (z_{n+1} - 2z_n + z_{n-1}) = \frac{w_i l c_n}{g} + k_o l(v_n + \mu_n) + k_i l \mu_n - w_i l \quad (17)$$

Equation 17 also has its counterpart in the analogue system of Figure 2. The equation of motion of the rotating bars M corresponds to Equation 6 and can be written as follows:

$$H_i = \frac{d}{2} (\psi_{i+1} - 2\psi_i + \psi_{i-1}) \quad (18)$$

Torque H_i is made up of a dynamic reaction $C_i \delta_i$ and a viscous loading term $K_o(V_i + D_i)$ such that Equation 18 becomes:

$$\frac{d}{2} (\psi_{i+1} - 2\psi_i + \psi_{i-1}) = C_i \delta_i + K_o(V_i + D_i) \quad (19)$$

A comparison of Equations 17 and 19 reveals that they are analogous term by term except that the last two terms of Equation 17 are missing from Equation 19. However, since this last missing term represents the static load created by the mass of the tubing it can also be neglected in the analysis as the next to the last term because μ_n is negligible. In view of the analogy between Equations 17 and 19 it becomes evident that lines T, T' simulate the action of the tubing in the pumping system.

From the foregoing description, it will be evident that the simulator illustrated in Figure 2 is an analogue of the pumping system of Figure 1. The actual pumping system obviously can be divided into as many segments as desired, each such segment being represented by a corresponding set of bars W, L, and M in the apparatus of Figure 2, the accuracy becoming greater with an increasing number of segments.

As stated, the rotating bar system thus far described simulates the sucker rod string together with its associated oil column and tubing. The top of the tubing string is anchored at the surface so that it must remain stationary, that is, its displacement must be zero at all times. This condition is represented in Figure 2 by anchoring the top bar M to bracket 79 to prevent rotation thereof.

The prototype sucker rod string is driven at its top end by drive mechanism 10 which includes

the prime mover, flywheel, crank and walking beam of Figure 1. For present purposes, it is assumed that the reaction of the sucker rod system upon the drive mechanism is negligible, which is true in certain practical applications and where results are desired only to a predetermined degree of accuracy, so that the motion at the top end of the sucker string can be expressed as a sinusoidal function. In the illustrated embodiment of this invention such driving motion is imparted to the sucker rod line by the mechanism 58 shown in Figure 9. An electric motor 80 is connected through a speed reducing gear train 81 to a rotatable disk 82. An arm 83 is pivotally connected at one end to disk 82 and at its other end to one end of a rod 84 which is constrained by guides 85 for axial movement. The other end of rod 84 is connected to the lowermost bar W of lines R, R' to impart reciprocating rotary motion thereto. From an inspection of Figures 1 and 9 it can be seen that motor 80, gear train 81, disk 82, arm 83 and rod 84 simulate, respectively, engine 29, cable 30, wheel 27, cable 28, crank 26, pitman 25 and walking beam 24 of the prototype pumping system.

A mechanical device known as a stepless pawl is employed to simulate the action of the valve and pump assembly disposed in the lower region of the bore hole. This stepless pawl is shown diagrammatically in Figure 8 as comprising a pair of rotatable pulleys 90 and 91 which are mounted on a common shaft 92. A third pulley 94 is connected by a yoke 96 and a wire 97 to the lowermost bar L at its end. Wire 97 passes around a guide pulley 98, and yoke 96 is freely suspended by a cable 99 attached to a support 100. An inextensible cable 101 is connected at one end to the lowermost sucker rod bar W at its end. From bar W cable 101 circles pulley 90, thence around pulley 94 back around 91 and is finally secured to an anchor post 102. A weight 103 is fastened to bar L by means of a cable 104 which passes over a fixed pulley 105.

Weight 103 serves to maintain a tension at points 106 and 107 in cable 101. When the sucker rod bar rotates away from this assembly tension appears at point 108 and slack at point 109. When the sucker-bar wire moves toward the assembly slack appears at point 108 and tension at point 109. Under the first condition pulleys 90 and 91 rotate in the direction indicated by the arrow. Under the second condition the cable slips over pulley 90 and both pulleys 90 and 91 are held stationary because there is tension in the cable on both sides of pulley 91 at points 107 and 109. This action is analogous to that of the pump assembly at the bottom of the sucker rod string. On the upstroke oil is lifted by the pump plunger and on the downstroke the oil is held stationary by the check valve. In the stepless pawl assembly the rotation of pulleys 90 and 91 is intermittent and in one direction only. Accordingly, the total rotation of these pulleys is a measure of the total quantity of oil produced. This rotation can be determined visually by positioning a suitable scale 110 adjacent a pointer 111 on pulley 90, or the rotation can be recorded through suitable mechanical or electrical linkage well known in the art. The oscillatory rotation imparted to the oil column wires is through this stepless pawl assembly analogous to the compressional waves set up in the oil column by the pump action in the prototype system.

The only points in the surface pumping system

that are conveniently accessible for making measurements are the pumping engine and the polished rod. In this regard it has been concluded that dynamometer measurements on the polished rod provide the best indication of the system's behavior. A dynamometer card illustrating such behavior can be obtained by mounting a strain gage on the polished rod to measure the force axis. The displacement axis can be obtained by a suitable mechanical linkage system coupled to the polished rod to measure displacements. These two quantities are plotted together to provide a conventional dynamometer card.

Measurements corresponding to the polished rod dynamometer card are obtained in accordance with this invention. With reference to Figure 9 a stress responsive element 115 is shown as being mounted between disk 81 in the driver assembly and the uppermost sucker-rod bar W. Element 115 can be a carbon microphone button or a strain gage. Voltage source 116 is connected in series therewith. The tension on element 115 varies its electrical resistance in a manner which is proportional to the force applied to the sucker-rod wire. The resulting voltage signal is amplified by a suitable amplifier 117 and applied to the vertical deflection plates of a cathode ray oscilloscope 119 to provide the force axis. The displacement axis is obtained through a capacitive pickup. A high frequency electrical signal, 10 kilocycles, for example, is applied to the conductive sucker-rod wire R' by an oscillator 120. Each of the rotating bars W can thus be employed as one plate of a pickup condenser. This is made possible by constructing bars W of conductive material or by positioning such a conductive plate thereon in contact with wire R. In order to simulate the polished rod dynamometer card the bar W nearest the surface unit is selected. The second plate of the pickup condenser is in the form of a metallic plate 121 mounted directly under bar W. The opposing area presented by the bar and plate to one another therefore varies as the bar W oscillates. Accordingly, the amplitude of the electrical signal picked up by the capacitor plate 121 varies as the displacement of the driving point bar W. The output of the pickup is amplified and demodulated by a conventional circuit 123 to provide an electrical signal, the amplitude of which is representative of the displacement of the uppermost sucker-rod line bar W. This demodulated signal is applied to the horizontal deflecting plates of oscilloscope 119 to provide the displacement axis. As previously mentioned the individual displacements are small and thus represent the angular displacements and the applied forces represent torques.

The simulator of this invention thus provides a means for analyzing the behavior of a sucker-rod pumping system when the operating conditions and the actual dynamometer measurements of the polished rod are known. The simulator constants and scale factors first are determined from the phototype system constants and operation conditions are calculated from the known rod and tube sizes, oil density and pump stroke rate of the actual pumping system. The valve and pump operation then is varied until the signal provided by oscilloscope 119 corresponds to the actual dynamometer card of the polished rod. Such a correspondence can be obtained by varying the speed of operation of the pump unit. When the simulator and previously determined dynamometer measurements correspond to one another, the behavior of the vibrating loaded

lines can be observed and the motion of the rotating bars recorded through the use of capacitive pickups similar to that used to generate the polished rod displacement axis. In this manner the behavior of the downhole portion of the system can be studied and the type of behavior responsible for the various characteristic features of the dynamometer measurements can be determined. Furthermore, optimum operating conditions for the prototype pumping system can be determined by this same means and a dynamometer pattern derived which when obtained by the prototype pumping system assures such optimum conditions of operation.

While this invention has been described in conjunction with a present preferred embodiment thereof, it is to be understood that this description is illustrative only and is not intended to limit the invention.

What is claimed is:

1. Apparatus for simulating a downhole pumping system including a sucker rod string, tubing surrounding said sucker rod string, and an oil column between said rod and said tubing comprising three pair of flexible lines disposed in generally parallel vertical relationship, a plurality of bars attached between said lines in each pair of lines in spaced relation, each individual bar representing, respectively, a sucker rod segment, a tubing segment and an oil column segment, means viscously coupling the individual bars representing the sucker rod segments to adjacent individual bars representing the oil column segments to simulate the actual viscous drag between adjacent rod segments and oil segments, and means viscously coupling the individual bars representing the tubing segments to adjacent individual bars representing the oil column segments to simulate the actual viscous drag between adjacent tubing and oil column segments.

2. The combination in accordance with claim 1 wherein each of said coupling means comprises a liquid filled pan supported by one of said bars and a plate suspended from an adjacent bar and extending therefrom into said pan whereby relative motion between adjacent bars results in movement of said plate through the liquid in said pan to create a viscous drag between said pan and said plate.

3. Apparatus for simulating a segment of a downhole pumping unit including a rod segment, a tubing segment, and an oil column segment comprising, in combination, three bars, each representing one of said segments, means for suspending each of said bars for rotary movement in substantially a horizontal direction, means viscously coupling the bar representing the rod segment to the bar representing the oil column segment to simulate the actual viscous drag between the rod segment and the oil column segment, and means viscously coupling the bar representing the oil column segment to the bar representing the tubing segment to simulate the actual viscous drag between the oil column segment and the tubing segment.

4. The combination in accordance with claim 3 wherein each of said coupling means comprises a liquid filled pan supported by one of said bars and a plate secured to an adjacent bar and extending therefrom into said pan whereby relative motion between adjacent bars results in movement of said plate through the liquid in said pan to create a viscous drag between said pan and said plate.

5. Apparatus for simulating a downhole pump-

ing system including a sucker rod string, tubing surrounding said sucker rod string, an oil column between said rod and said tubing, a pumping unit driving the uppermost sucker rod, and a downhole pump driven by the lowermost sucker rod comprising three pair of flexible lines disposed in generally parallel vertical relationship, a plurality of bars attached between said lines in each pair of lines in spaced relation, each individual bar representing, respectively, a sucker rod segment, a tubing segment and an oil column segment, means viscously coupling the individual bars representing the sucker rod segments to adjacent individual bars representing the oil column segments to simulate the actual viscous drag between adjacent rod segments and oil segments, means viscously coupling the individual bars representing the tubing segments to adjacent individual bars representing the oil column segments to simulate the actual viscous drag between adjacent tubing and oil column segments, means to impart reciprocating rotary motion to the bar at one end of the pair of lines representing the sucker rod string to simulate the pumping unit driving the uppermost sucker rod, and means to measure motion of the bar at the second end of the line representing the sucker rod string which simulates the action of the downhole pump driven by the lowermost sucker rod.

6. The combination in accordance with claim 5 wherein said means to impart reciprocating motion comprises a rod attached at one end to the bar attached at said one end of the sucker rod lines, said rod being constrained for linear movement, a cam coupled to said rod, and a motor coupled to said cam to provide rotation thereof whereby reciprocating motion is imparted to the bar attached at said one end of the sucker rod lines.

7. The combination in accordance with claim 6 further comprising an electrical resistance strain responsive element secured to said rod, a source of electrical energy connected in circuit with said strain responsive element, and circuit means to establish a voltage proportional to the stress on said strain responsive element.

8. The combination in accordance with claim 5 wherein, said means to measure motion of the bar attached at said second end of the lines representing the sucker rod string comprises first and second pulleys mounted on a common rotatable shaft, a third pulley having its shaft connected to the bar attached at said second end of the lines representing the oil column, a rigid support, an inextensible line secured at one end to the line representing said sucker rod string, said inextensible line circling said first pulley, said third pulley, and said second pulley in the order stated and being connected at its second end to said support, tension supplying means connected to said last mentioned bar to retain said inextensible line under tension, and means to measure rotation of said first and second pulleys which simulates the quantity of oil pumped.

9. Apparatus for simulating the action of a pump positioned in a bore hole and driven by a sucker rod string extending to the surface of the bore hole comprising two pair of vertical lines simulating respectively the sucker rod string and the column of oil pumped to the surface within the well tubing, means to impart reciprocating motion to one end of said pair of sucker rod lines to simulate the pump driving the uppermost sucker rod, said two pair of lines being

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viscously coupled to simulate the viscous coupling between the sucker rod and oil column, first and second pulleys mounted on a common rotatable shaft, a third pulley having its shaft connected to one of the oil column lines at the end thereof which represents the bottom of the bore hole, a rigid support, an inextensible line secured at one end to one of the sucker rod lines near the end thereof which represents the bottom of the bore hole, said inextensible line circling said first pulley, said third pulley, and said second pulley in the order stated and being connected at its second end to said rigid support, means to apply a tension to said last mentioned oil column line to retain said inextensible line under tension, and means to measure rotation of said first and second pulleys which simulates the quantity of oil pumped.

10. Apparatus for simulating a downhole pumping system including a sucker rod string, tubing surrounding said sucker rod string, an oil column between said rod and said tubing, and a pumping unit driving the uppermost sucker rod comprising three pair of flexible lines disposed in generally parallel vertical relationship, a plurality of bars attached between each line of said pairs of lines in spaced relation, each individual bar representing, respectively, a sucker rod segment, a tubing segment and an oil column segment, means viscously coupling the individual bars representing the sucker rod segments to adjacent individual bars representing the oil column segments to simulate the actual viscous drag between adjacent rod segments and oil segments, means viscously coupling the individual bars representing the tubing segments to adjacent individual bars representing the oil column segments to simulate the actual viscous drag between adjacent tubing and oil column segments, means to impart transverse reciprocating rotary motion to one end of the pair of lines representing the sucker rod string to simulate the pumping unit driving the uppermost sucker rod, and means to measure the rotation of any selected bar which represents the motion of the corresponding segment simulated thereby.

11. The combination in accordance with claim 10 wherein said last mentioned means comprising a source of electrical energy applied to the individual bar whose motion is to be measured, said bar being constructed at least in part of an electrically conductive material, a plate of electrically conducting material positioned adjacent said rotating bar thereby forming a condenser with said bar, and means to measure the potential induced on said plate representing the distance said bar is rotated from said plate.

12. Apparatus for simulating a downhole pumping system including a sucker rod string, tubing surrounding said sucker rod string, an oil column between said rod and said tubing, a pumping unit driving the uppermost sucker rod, and a downhole pump driven by the lowermost sucker rod comprising three pair of flexible lines disposed in generally parallel vertical relationship, a plurality of bars attached between each line of said pairs of lines in spaced relation, each individual bar representing, respectively, a sucker rod segment, a tubing segment and an oil column segment, means viscously coupling the individual bars representing the sucker

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rod segments to adjacent individual bars representing the oil column segments to simulate the actual viscous drag between adjacent rod segments and oil segments, means viscously coupling the individual bars representing the tubing segments to adjacent individual bars representing the oil column segments to simulate the actual viscous drag between adjacent tubing and oil column segments; means to impart reciprocating rotary motion to one end of the line representing the sucker rod string to simulate the pumping unit driving the uppermost sucker rod comprising a rod attached at one end to one end of one of said sucker rod lines, said rod being constrained for linear movement, a cam coupled to said rod, and a motor coupled to said cam to provide rotation thereof whereby reciprocating rotary motion is imparted to said sucker rod lines; and means to measure motion of the second end of the lines representing the sucker rod string which simulates the action of the downhole pump driven by the lowermost sucker rod comprising first and second pulleys mounted on a common rotatable shaft, a third pulley having its shaft connected to one of the lines representing the oil column, a rigid support, an inextensible line secured at one end to one of the lines representing said sucker rod string, said inextensible line circling said first pulley, said third pulley, and said second pulley in the order stated and being connected at its second end to said support, tension supplying means connected to the above mentioned line representing the oil column to retain said inextensible line under tension, and means to measure rotation of said first and second pulleys which simulates the quantity of oil pumped.

13. The combination in accordance with claim 12 wherein each of said coupling means comprises a liquid filled pan secured to one of said bars and a plate secured to an adjacent bar and extending therefrom into said pan whereby relative rotation between adjacent bars results in movement of said plate through the liquid in said pan to create a viscous drag between said pan and said plate.

14. Apparatus in accordance with claim 12 further comprising an oscilloscope, an electrical resistance strain responsive element secured to said rod, a source of electrical energy connected in circuit with said strain responsive element, and circuit means to establish a voltage proportional to the stress on said strain responsive element, said voltage being applied to one set of deflection plates of said oscilloscope, a second source of electrical energy applied to the bar attached to the lines representing the sucker rod string representing the uppermost sucker rod segment, said bar being constructed of an electrically conductive material, a plate of electrically conducting material positioned adjacent said last mentioned rotating bar thereby forming a condenser with said bar, and means to apply the voltage induced on said plate to the second set of deflection plates of said oscilloscope whereby the output of said oscilloscope simulates the combined forces on and displacements of the uppermost of said sucker rod segments.

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No references cited.