Pumping Unit Torque Factors

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DEFINITION OF TORQUE FACTOR

When a load is applied to the well end of a pumping unit it results in a torque around the speed reducer crankshaft. This resultant torque is a function of the geometrical design of the unit and the crank angle. Under constant load conditions the torque is constantly changing since it varies with the crank angle.

Under static conditions and when considering only the applied load and the unit geometry (not considering the weight of each component part of the unit, the counterbalance being used, or the inertia effects) the torque around the crankshaft is the result of the applied load times a built-in multiplication factor. This multiplication factor is commonly known as the torque factor. Since the torque factors vary with the crank angle there is an infinite number of them. To simplify their use the American Petroleum Institute has devised a form for recording the torque factors at only every 15° crank angle.

Typical Pumping Unit

Fig. 1 is a schematic diagram of a typical pumping unit. Under static conditions a load W applied at the polished rod is counteracted by an equalizing force F at the pitman. The sum of the movements around the saddle is equal to O, therefore

$$(F \times B') - (W \times A) = O \qquad \text{Eq. (1)}$$

at the crankshaft

$$\text{Torque} = F \times R' \qquad \text{Eq. (2)}$$

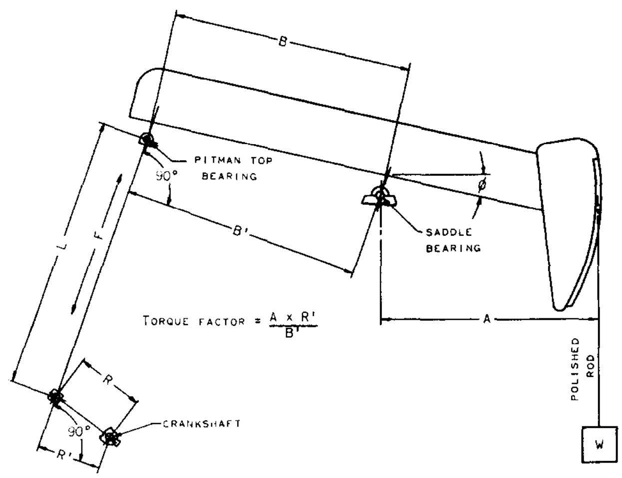

Fig. 1 SCHEMATIC DIAGRAM OF TYPICAL PUMPING UNIT

R' should be negative when the torque produced by F x R' is in a clockwise direction and position when counterclockwise.

However, solving Eq. (1) for F

$$F = W \times \frac{A}{B'} \qquad \text{Eq. (3)}$$

Substituting this value for F in Eq. (2) then

$$\text{Torque} = W \times \frac{A \times R'}{B'} \qquad \text{Eq. (4)}$$

In this equation $\frac{A \times R'}{B'}$ is the torque factor and it will be negative when force F produces a clockwise torque around the crankshaft as viewed in Fig. 1.

This simple, static analysis shows that in the absence of counterbalance and for a particular crank angle, the torque at the crankshaft will be equal to the well load times the torque factor. (Refer to Eq. 4) However, the torque factors are negative from approximately 180° to 360° and hence the torque would be negative through this part of the cycle.

Fig. 2 shows the effect on the maximum torque factors due to changing the pitman length. All other dimensions that influence the torque factors for this unit were held constant and the pitman length varied as shown. This illustrates the fact that the greater the pitman length

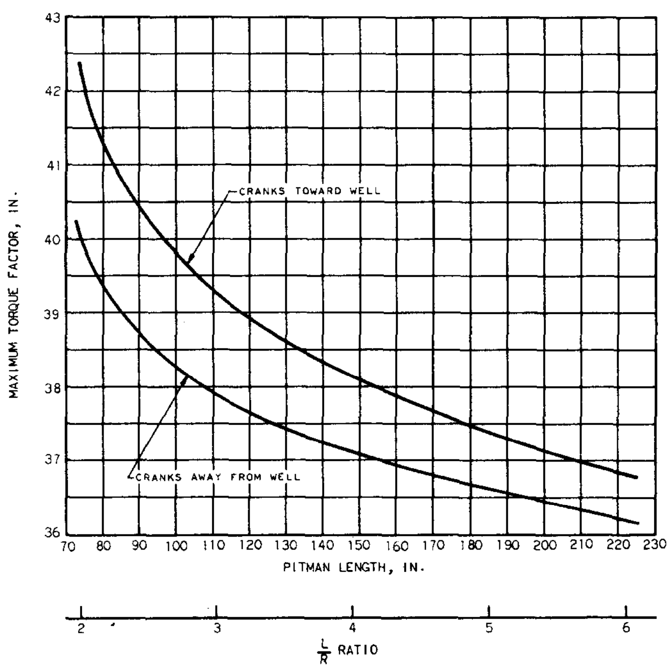

Fig. 2 TORQUE FACTOR VS. PITMAN LENGTH

the smaller the maximum torque factors, or the greater the $\frac{L}{R}$ ratio the smaller the maximum torque factors.

COUNTERBALANCE

The well load on the upstroke or when raising the sucker rods consists of approximately the weight of the rods and the fluid; while on the downstroke the weight of the rods only. (Refer to Fig. 3) These values will be used to simplify the explanation of the function of counterbalance. In actual practice the loads can vary appreciably from these static values due to the effects of sticking pumps, flow restrictions, acceleration factors, rod stretch, inertia forces, etc.

The function of counterbalance is to reduce the load to the speed reducer and the prime mover. Fig. 3 is a schematic illustration of the use and effect of counterbalancing. It will be noted that under simple correctly counterbalanced conditions the maximum load carried by the speed reducer is equal to one-half the weight of the fluid. Also note that the maximum speed reducer loads are equal on the up and down strokes.

Absence of Counterbalance

In the absence of any counterbalance, the torque around the crankshaft of the speed reducer would range from a positive torque resulting from the weight of the rods plus fluid times the maximum torque factor for the up-stroke, to a negative torque resulting from the weight of the rods times the maximum torque factor for the downstroke. It is obvious then that the counterbalance reduces and equalizes the peak torque loads on the speed reducer. Then optimum counterbalance could be defined as that counterbalance that would minimize and equalize the peak torques on the speed reducer on the up and down strokes. This has been recognized for years and many methods have been used for determining optimum counterbalance.

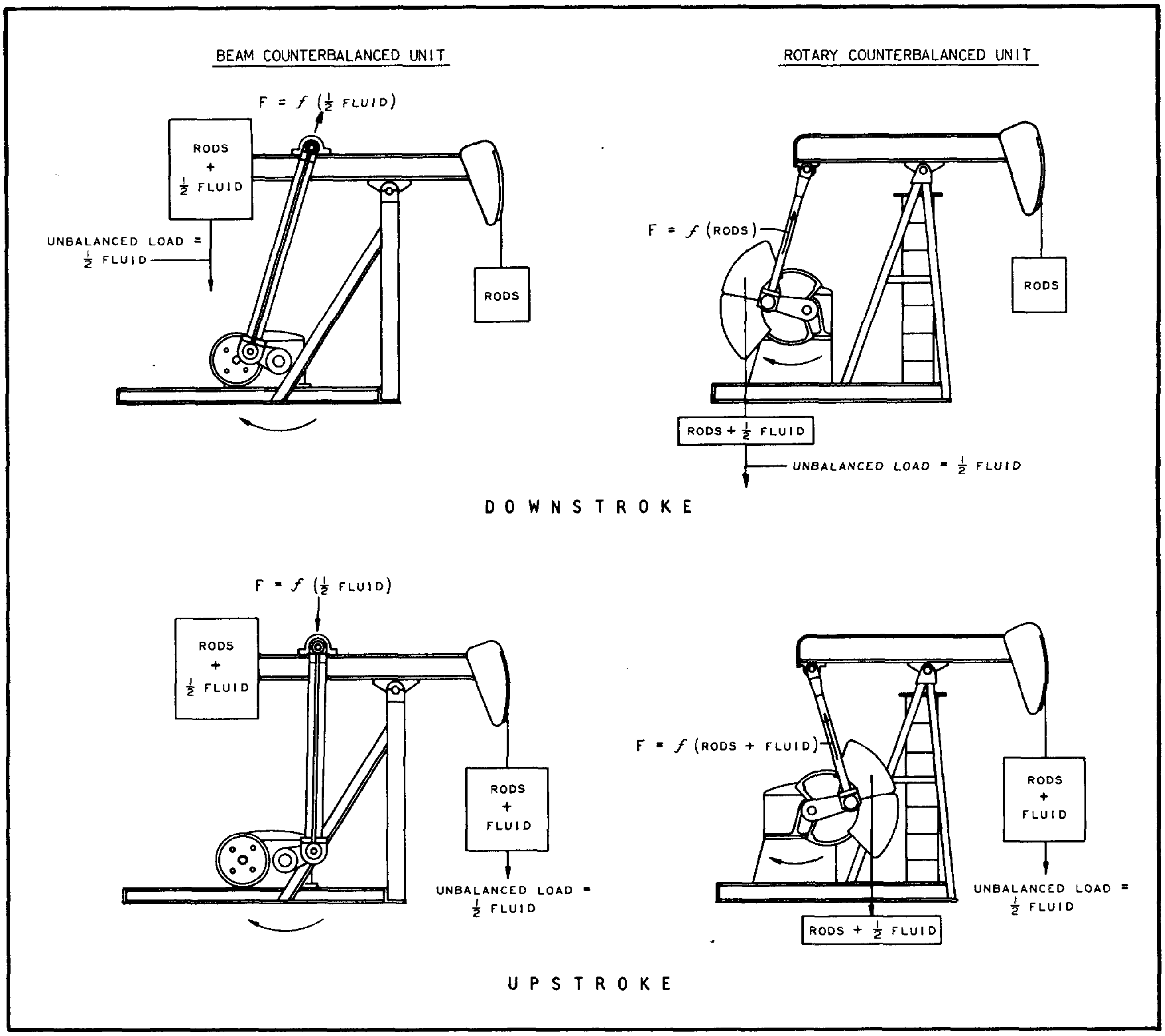

FIG. 3 EFFECT OF COUNTERBALANCE ON BEAM TYPE PUMPING UNITS

Another factor that enters into pumping unit load calculations is the weight of the component parts of the pumping unit. On most units when the brake is off and there are no counterweights or polished rod loads applied, the cranks will fall to the bottom, thus indicating that the back end of the beam and the connected linkage is heavier than the front end. Therefore, in order to exactly balance the beam in a horizontal position some weight would be required at the polished rod. This amount of weight will be termed "beam off-balance." Beam off-balance has the same effect as beam counterweights and can be treated in the same manner.

SPEED REDUCER CALCULATING TORQUES

The following equations can be used to calculate the net torques to the speed reducers on beam type pumping units.

For rotary counterbalanced units

$$T = tf\ (W - P) - M \sin \theta \qquad \text{Eq. (5)}$$

(This equation could more accurately be stated as "$P \cos \phi$" instead of "P", but the error is negligible as stated and therefore Eq. (5) is preferred for simplification purposes in this discussion.)

For beam counterbalanced units

$$T = tf\ [W - \cos \phi\ (P + C)] \qquad \text{Eq. (6)}$$

where

T = net torque to speed reducer, in.-lb.
tf = torque factor for crank angle of θ, in.
W = polished rod load, lb
P = beam off-balance effect at polished rod with beam horizontal, lb
M = moment of the crank counterweights around the crankshaft when θ is 90°, or cranks in horizontal position, in.-lb.
θ = crank angle, measured as angular displacement in clockwise direction from 12 o'clock position, viewed with the wellhead to the right, deg
C = counterbalance effect of counterweights at polished rod with beam in horizontal position or with angle ϕ equal to 0°, lb
ϕ = angle of walking beam in relation to horizontal plane, deg

It will be noted that Eq. (5) for rotary or crank counterbalanced units shows that the net speed reducer torque T is the difference between two opposing moments. The first part of the equation "tf (W - P)" is the torque developed by the difference between the well load and the beam off-balance, while "M sin θ" is the opposing counterbalance moment.

In Eq. (6) it can be noted that the net speed reducer torque T is that torque resulting from the difference between the well load and the effective counterbalance times the torque factor.

EFFECT ON UNIT EFFICIENCY

To illustrate the full significance of torque factors, rotary type counterweighted units X and Y will be applied to the same well. The significant dimensions of these units are

	Unit X	Unit Y
A (front center)	108 3/4 in.	93 in.
B (back center)	111 in.	96 in.
L (pitman length)	129 1/4 in.	103 in.
R (crank radius)	37 in.	37 in.
P (beam off-balance)	800 lb	425 lb
Maximum stroke	74 in.	74 in.

The well loads to be considered are as shown in Fig. 4, which represents a hypothetical dynamometer card. The torque factors and positions of rods for the various crank positions for units X and Y are shown in Table 1. The position of the crank is the angular displacement measured clockwise from the 12 o'clock position, viewed with the wellhead to the right as in Fig. 1. The position of rods is expressed as a decimal part of the stroke above the lowermost position.

This method of tabulating this data is generally in accordance with the form which has been approved by API and shown in Fig. 2-A in API Standard 11-E. Constant loads are considered on the up and down strokes in Fig. 4 so that a direct comparison of the unit geometries can be made. As witnessed by the tabulated torque factors, the maximums do not always occur at the same crank angles for units of different geometry. Unit X has its maximum torque factors as tabulated at crank angles of 75° and 285°, while unit Y has maximums of 60° and 285°. In considering an actual dynagraph whereby the maximum well load is coincident with a crank angle of 60°, it would be to the advantage of unit X and the disadvantage of unit Y.

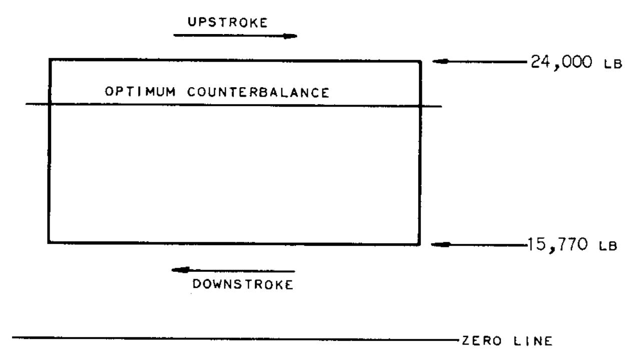

Fig. 4 HYPOTHETICAL DYNAGRAPH

Optimum Counterbalance

The first step in applying units X and Y to the well represented in Fig. 4 is to determine the optimum counterbalance for each unit. As previously stated optimum counterbalance will result in equal peak speed reducer torques on the up and down strokes. Therefore, using Eq. (5)

Torque (upstroke) = Torque (downstroke)

$$tf_u\ (W_u - P) - M \sin \theta_u = tf_d\ (W_d - P) - M \sin \theta_d \qquad \text{Eq. (7)}$$

For any selected crank angles for the up and down strokes all values in Eq. (7) would be known except M, therefore it is possible to solve for M. It is advisable to use those crank angles having maximum torque factors for the up and down strokes for the initial calculation. After finding M, use this value in Eq. (5) along with the other known data required and solve for the speed reducer torques for each crank angle throughout the cycle. If the peak speed reducer torques are not found to be equal on the up and down strokes then the optimum counterbalance moment M has not been determined. Using the new crank angles coincident with the peak speed reducer torques on the up and down strokes and Eq. (7), recalculate for M. It may be necessary to repeat this procedure several times before the optimum M can be found.

Crank Angles

The crank angles used for determining the optimum M for unit X were found to be 55° and 245°; while on unit Y the angles were 50° and 245°.

After finding the optimum counterbalance for each unit, Eq. (5) can be used to calculate the net speed reducer torques throughout the cycle for each unit. Fig. 5 shows the resultant speed reducer torque curves when units X and Y are applied to the well represented in Fig. 4.

The peak speed reducer torques on unit Y are 11.7% higher than those on unit X. This greater load would be expected to result in reduced life and increased maintenance costs on both the speed reducer and the prime mover.

It is also significant that the area under the speed reducer torque curve for unit Y is greater than that for unit X. Therefore the speed reducer and prime mover of unit Y will have to do more work to pump this well than would unit X. This would result in greater fuel or power consumption. This difference in the efficiencies of these two units is due to their geometrical designs.

Pumping units designed with low torque factors not only provide the hidden economies already mentioned, but in addition provide less severe stroke reversals due to smaller acceleration factors at the polished rod.

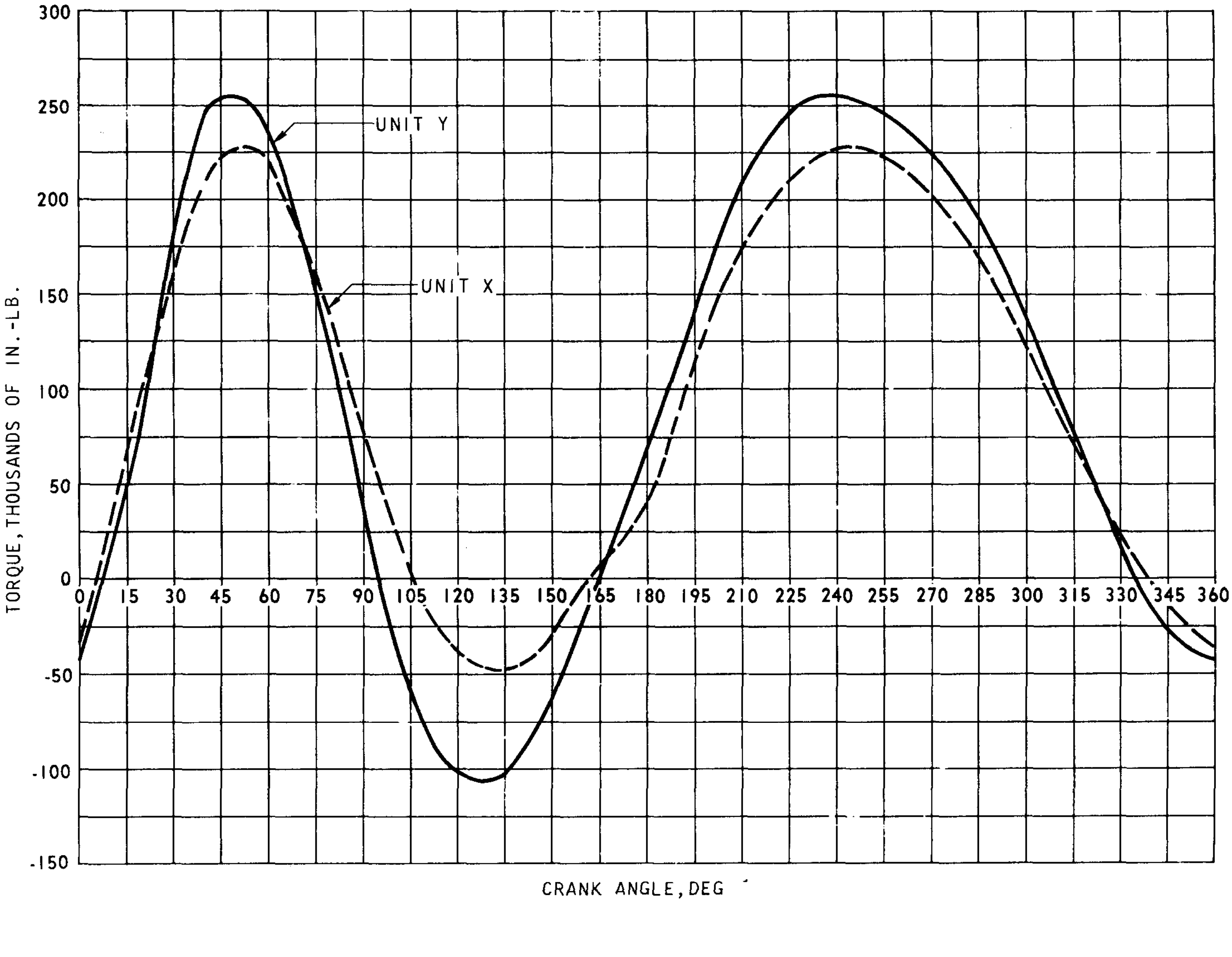

FIG. 5 INSTANTANEOUS NET SPEED REDUCER TORQUE CURVES

USE IN DYNAGRAPH ANALYSIS

Torque factor data can be used along with other data to make more accurate speed reducer load analyses.

Applying unit X to the well represented by the dynagraph in Fig. 6 the analysis would be made as follows. Vertical lines should be drawn tangent to the ends of the dynagraph as shown in Fig. 6. These are marked B and T and represent the bottom and top extremes of the stroke respectively. The full stroke is represented by the distance S. For a crank angle of 15° it is noted in Table 1 that the position of rods is .015 times S.

This means that the rods have actually moved .015 times the full stroke from the lowermost position represented by line B. Measure to the right, or from line B, .015 times the distance S and draw a vertical line. Its intersection with the up stroke curve marks the point at which the well load can be determined for a crank position of 15°. This well load and the corresponding torque factor of 10.740 taken from Table 1, a beam off-balance of 800 lbs, and the actual counterbalance M can be substituted into Eq. (5). In this manner it is possible to calculate the speed reducer torque at the various crank angles.

Maximum Moment

The value of M to be used in Eq. (5) for calculating the speed reducer torques is the maximum moment of the counterweights around the crankshaft at a crank angle of 90°. The counterbalance effect usually available on dynagraph cards is the total effect in pounds at the polished rod as measured with the dynamometer with the cranks at 90°. This total effect consists of beam off-balance and the effect of the counterweights.

The following equation can be used to convert the measured total counterbalance effect at the polished rod to a moment M around the crankshaft.

$$\text{Total CB effect} = P + \frac{M}{tf} \qquad \text{Eq. (8)}$$

where all values are for a crank angle of 90°.

Solving for M

$$M = (CB - P)tf$$

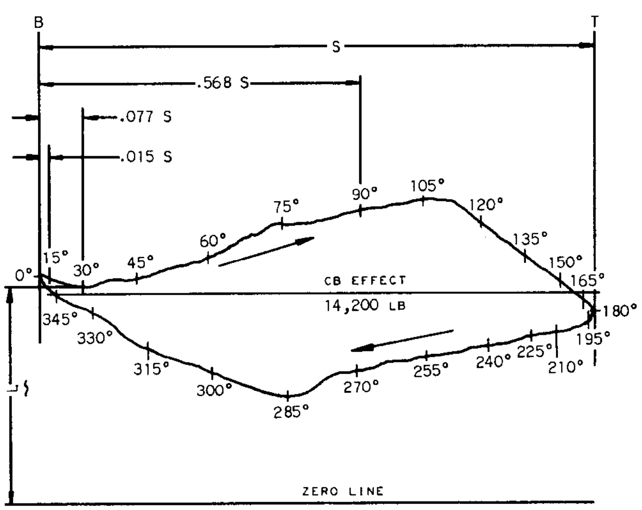

Fig. 6 DYNAGRAPH ANALYSIS USING PUMPING UNIT TORQUE FACTORS

TABLE 1

PUMPING UNIT STROKE AND TORQUE FACTOR

Position of Crank DEG	Position of Rods 74" Stroke		*Torque Factor 74" Stroke	
	Unit X	Unit Y	Unit X	Unit Y
0	.001	.006	- 2.051	- 2.683
15	.015	.020	10.740	10.850
30	.077	.082	23.020	24.406
45	.175	.187	32.481	34.384
60	.308	.316	37.384	39.015
75	.438	.455	38.309	38.756
90	.568	.587	35.775	35.198
105	.688	.702	31.575	29.938
120	.791	.797	26.322	24.618
135	.874	.874	20.860	19.307
150	.938	.936	14.910	14.014
165	.953	.976	8.677	8.737
180	.999	.996	1.709	2.693
195	.991	.995	- 5.557	- 4.105
210	.955	.969	-13.711	-12.049
225	.893	.910	-21.548	-20.389
240	.806	.825	-28.343	-27.890
255	.694	.715	-33.615	-33.480
270	.571	.589	-36.583	-36.646
285	.440	.455	-37.245	-37.358
300	.310	.327	-35.252	-35.680
315	.192	.207	-30.607	-31.368
330	.096	.106	-23.666	-24.561
345	.030	.035	-13.903	-14.986

* Torque factors whereby an upward pull by the pitman produces a clockwise moment, when viewing the unit with the well to the right, are considered as negative.

As an example, apply unit X to the dynagraph shown in Fig. 6 and use the torque factor tf from Table 1.

$$M = (14{,}200 \text{ lb} - 800 \text{ lb})\ 35.775 \text{ in.}$$

$$M = 479{,}385 \text{ in.-lb.}$$

To calculate the speed reducer torque at a crank angle of 30° and using unit X, proceed as follows:

(1) Follow the procedure described above to find the point on the dynagraph that is coincident with a crank angle of 30°. (.077 x S measured from line B)

(2) By measuring the vertical distance L from the zero line to the point of intersection with the dynagraph curve and using the dynamometer constant, determine the actual well load. (L x dynamometer constant = 14,590 lb)

(3) Using Eq. (5)

$$T = 23.020\ (14{,}590 - 800) - 479{,}385\ (.500)$$

$$T = 77{,}753 \text{ in.-lb. at a crank angle of } 30^\circ$$

After weighing a well and making a complete speed reducer torque analysis in the manner just described, unequal peak torques indicate that the unit is improperly counterbalanced. Greater maximum torque on the upstroke than on the downstroke indicates an underbalanced condition; while greater torque on the downstroke, an overbalanced condition. Using the two crank angles coincident with peak torques on the up and down strokes and identifying them as u and d respectively, Eq. (7) can be used to find a new counterbalance moment M. Using the new value for M and Eq. (5), calculate the speed reducer torques through the complete cycle to ascertain that the points u and d represent the peaks when using optimum counterbalance. Sometimes it is necessary to do this several times before the points of maximum torque with optimum counterbalance are found.

Counterbalance Effect

After finding optimum counterbalance effect M, solve for the counterbalance effect at the polished rod by using Eq. (8). This should be the optimum counterbalance effect as measured with the dynamometer at the polished rod with a crank angle of 90°. In order to insure the utmost in accuracy of counterbalancing this should be weighed with a dynamometer to correct for casting variations and other variables.

This method of calculation determines the theoretical net torques on the speed reducer and the optimum counterbalance required. This is a static analysis made from actual dynamic loads. The inertia effects of the surface equipment are not considered in this method and are required for a completely accurate analysis. However, this method which uses the pumping unit torque factors is much more accurate than approximate methods as often used.