# Lifting Cost Reduction From Dynamic Balancing

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## ABSTRACT

There are several ways to reduce the lifting cost of a sucker rod pumping unit. One way is to reduce maintenance. Another way is to "tune-up" the unit. A simple way to "tune-up" the unit is to balance it properly. A unit that is balanced properly will produce fluids more economically by reducing the electrical power loss. Therefore, by balancing all the units in a field the electrical power loss will be reduced but the maintenance will be increased. Consequently, a method that minimizes the maintenance needed to balance a unit is desirable. This paper presents a method that will minimize the maintenance needed to dynamically balance a unit. This efficient balancing method uses the motor current, the unit geometry and the dynamometer card to reduce the magnitude of current or power fluctuations experienced by an electrically driven system. In other words, the closer the RMS current approaches an average current, the smaller the electrical power loss. Therefore, reducing the power loss with a minimum amount of maintenance will in turn reduce the lifting cost of a sucker rod pumping unit.

## INTRODUCTION

The crew that is directly in charge of sucker rod pumping units is usually over extended. Generally, the crew realizes that some of the units are out of balance, but they simply do not have enough time to spend balancing the units. Yet, the cost of operating an unbalanced unit is normally greater than operating a balanced unit. Therefore, some time should be spent on keeping the units balanced. This paper presents an efficient method to dynamically balance a sucker rod pumping unit that is driven by an electric motor. This efficient method uses two dynamometer cards and two current cards obtained at the working fluid level (FIGURES. 1,2,3,4). The cards must be obtained at the working fluid level because, the fluid level will directly affect the balancing. With these four cards, this method will give the crew the correct location of one adjustment counterweight that will dynamically balance the unit (FIGURE 5). By moving the one adjustment counterweight to the calculated location, the crew will efficiently set the upstroke peak current equal to the downstroke peak current (FIGURE 6).

## PREVIOUS METHOD

A common method of balancing a unit that is driven by an electric motor is to set the upstroke peak current equal to the downstroke peak current. If the peak currents are not equal, the unit is not balanced. To balance the unit, the location of at least one of the counterweights must be changed. Generally, the location of only one adjustment counterweight is changed if the unit is not badly out of balance. After the location of the adjustment counterweight is changed, the peak currents can be checked again. If the peak currents are still not equal, the location of the adjustment counterweight must be changed again. Using this less effective method, the crew may need to change the location of the adjustment counterweight several times in order to balance the unit. This repetitive relocation of the adjustment counterweight reduces the crew's ability to efficiently balance a unit.

## PROBLEM STATEMENT

The cost of operating an unbalanced unit is normally greater than operating a balanced unit. The cost difference is due to the difference in the electrical power loss. A balanced unit will experience less electrical power fluctuations. Consequently, a balanced unit will have a lower electrical power loss. Therefore, some time should be spent on keeping the units balanced. The problem that is addressed in this paper is how to efficiently balance a sucker rod pumping unit. Using the previous methodology to balance the unit, the crew may need to change the location of the adjustment counterweight several times. This paper presents a method that will balance a unit within two moves of the adjustment counterweight. Therefore, this method will often reduce the time needed to balance a unit. Since this method will often reduce the time needed to balance a unit, the crew can keep more units balanced. By keeping more units balanced, the crew can reduce the operating costs of several sucker rod pumping units.

## PROCEDURE

The following steps outline the new balancing method:

1. Measure the distance from the long end of the crank to the counterweight that will be moved (FIGURE 5).
2. Take a dynamometer card at the working fluid level. This is a load versus position plot (FIGURE 1).
3. Take a current card at the working fluid level. This is a current versus position plot (FIGURE 2).
4. Move the counterweight 1 to 3 feet from its original position.
5. Measure the distance from the long end of the crank to the counterweight that was moved (FIGURE 5).
6. Take another dynamometer card at the working fluid level (FIGURE 3).
7. Take another current card at the working fluid level (FIGURE 4).
8. Fill in the balancing calculation sheets (Appendix A)
9. Finally, to balance the unit, move the counterweight to the calculated number of inches from the long end of the crank. This calculated distance is obtained from the balancing calculation sheets.

## BALANCING CALCULATION SHEETS

A few numbers must be calculated to balance the unit. The balancing calculation sheets will make these calculations straightforward. All the calculations can be made with a hand held calculator that has a sine key. After completing the balancing calculation sheets, the unit can be balanced. The balancing calculation sheets are included in Appendix A of this paper. An example on how to use the the balancing calculation sheets are included in Appendix B. The assumptions and the equations used in the balancing calculation sheets are included in Appendix C.

## CONCLUSIONS

1. By keeping the units balanced, one can reduce the operating cost of a sucker rod pumping unit.
2. By reducing the time needed to balance a unit, one can reduce the maintenance cost of a sucker rod pumping unit.
2. A sucker rod pumping unit can be balanced within two moves of an adjustment counterweight with the procedure presented in this paper.
3. The maximum moment of the counterbalance can be obtained from the following cards and equations:

a. Dynamometer card taken at the working fluid level.
b. Current card taken at the working fluid level.
c. Crank torque equation.
d. Motor current vs. power equation.
e. Power vs motor torque equation.
f. Motor torque vs. crank torque equation.

4. There was less than 1% difference in maximum moment of the counterbalance obtained from the procedure presented as compared to the one obtained from a predictive sucker rod simulator for the example in Appendix B.

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# APPENDIX A

## BALANCING CALCULATION SHEET A-1

ORIGINAL DATA (COUNTERWEIGHT HAS NOT BEEN MOVED):

FROM CURRENT CARD 1:

MOTOR & MEASURE:

| PH | V | PF | RPM | SPM | D1 |
|---|---|---|---|---|---|
| | | | | | |

| | P1 | PC1 |
|---|---|---|
| UPSTROKE | | |
| DOWNSTROKE | | |

FROM API SPEC 11E (OR MANUFACTURER):

| | θ1 | TF1 | τ | W1 | B |
|---|---|---|---|---|---|
| UPSTROKE | | | | | |
| DOWNSTROKE | | | | | |

SECOND DATA (COUNTERWEIGHT HAS BEEN MOVED ONCE):

FROM CURRENT CARD 2:

MOTOR & MEASURE:

| PH | V | PF | RPM | SPM | D1 |
|---|---|---|---|---|---|
| | | | | | |

| | P2 | PC2 |
|---|---|---|
| UPSTROKE | | |
| DOWNSTROKE | | |

FROM API SPEC 11E (OR MANUFACTURER):

| | θ2 | TF2 | τ | W2 | B |
|---|---|---|---|---|---|
| UPSTROKE | | | | | |
| DOWNSTROKE | | | | | |

PH = NUMBER OF PHASES OF MOTOR (eq. PH=3)
V = VOLTAGE (volts)
PF = POWER FACTOR (eg. PF=0.85)
D1 = FIRST DISTANCE FROM LONG END OF CRANK TO COUNTERWEIGHT (in)
RPM = SPEED OF MOTOR (rpm)
SPM = PUMPING SPEED (spm)
P1 = POSITION AT PEAK CURRENT FROM CARD 1 (in)
PC1 = PEAK CURRENT FROM CARD 1
θ1 = CRANK ANGLE AT THE PEAK CURRENT FROM CARD 1 (degrees)
TF1 = TORQUE FACTOR AT CRANK ANGLE θ1 (in)
τ = ANGLE OF COUNTERWEIGHT ARM OFFSET (degrees)
W1 = POLISHED ROD LOAD AT P1 FROM DYNAMOMETER CARD 1 (lb)
B = STRUCTURAL UNBALANCE (lb)

## BALANCING CALCULATION SHEET A-2

$Tn1_{U,D} = (RPM/SPM)[(\sqrt{PH})(PC1_{U,D})(V)(PF)/(1000) - 3]/2.16$ ............(EQ. 1)

$M1_{U,D} = [TF1_{U,D}(W1_{U,D}-B) - Tn1_{U,D}]/SIN(\theta 1+\tau)_{U,D}$ ............(EQ. 2)

$\overline{M1} = [M1_U + M1_D]/2$ ............(EQ. 3)

$MB1 = [TF1_U(W1_U - B) - TF1_D(W1_D - B)]/[SIN(\theta 1+\tau)_U - SIN(\theta 1+\tau)_D]$ ..(EQ. 4)

ORIGINAL DATA (COUNTERWEIGHT HAS NOT BEEN MOVED):

UPSTROKE

$Tn1_U$ = ______ = (______)/(___)[($\sqrt{\ \ }$___)(______)(_____)(___)/(1000) - 3]/2.16

$M1_U$ = ______ = [(______)((________)-(_____))-(________)]/SIN[(______)+(___)]

DOWNSTROKE

$Tn1_D$ = ______ = (______)/(___)[($\sqrt{\ \ }$___)(______)(_____)(___)/(1000) - 3]/2.16

$M1_D$ = ______ = [(______)((________)-(_____))-(________)]/SIN[(______)+(___)]

UPSTROKE & DOWNSTROKE AVERAGE

$\overline{M1}$ = ______ = [(______) + (______)]/2

BALANCED MAXIMUM MOMENT OF THE COUNTERBALANCE

MB1 = ______ = [(______)((________)-(_____))-(________)((________)-(_____))]
/[SIN((______)+(___))-SIN((______)+(___))]

Tn1 = NET TORQUE AT THE CRANKSHAFT (in-lb)
M1 = MAXIMUM MOMENT OF COUNTERBALANCE (in-lb)
MB1 = BALANCED MAXIMUM MOMENT OF COUNTERBALANCE (in-lb)

## APPENDIX A (Cont.)

BALANCING CALCULATION SHEET A-3

MB = [ MB1 + MB2]/2 ..................................................(EQ. 5)

DB = { [ (D2 - D1) ($\overline{MB}$ - $\overline{M1}$)/($\overline{M2}$ - $\overline{M1}$) ] + D1} ..............(EQ. 6)

SECOND DATA (COUNTERWEIGHT HAS BEEN MOVED ONCE):

UPSTROKE

$Tn2_U$ = ________ = (______)/(___)[(√____)(______)(_____)(___)/(1000) - 3]/2.16

$M2_U$ = ________ =[(______)((________)-(_____))-(_______)]/SIN[(______)+(___)]

DOWNSTROKE

$Tn2_D$ = ________ = (______)/(___)[(√____)(______)(_____)(___)/(1000) - 3]/2.16

$M2_D$ = ________ =[(______)((________)-(_____))-(_______)]/SIN[(______)+(___)]

UPSTROKE & DOWNSTROKE AVERAGE

$\overline{M2}$ = ________ = [(_______) + (_______)]/2

BALANCED MAXIMUM MOMENT OF THE COUNTERBALANCE

MB2= ________ =[(_______)((_______)-(_____))-(_______)((________)-(_____))]

/[SIN((______)+(____))-SIN((______)+(____))]

ORIGINAL DATA & SECOND DATA AVERAGE

MB=__________=[(________)+(________)]/2

BALANCED DISTANCE

DB = [ ] = {[(| ______ |-| ______ |)(| ________ |-| ________ |)

/(| ________ |-| ________ |)]+| ______ |}

MB = AVERAGE BALANCED MAXIMUM MOMENT OF COUNTERBALANCE (in-lb)

**DB** = BALANCED DISTANCE FROM THE LONG END OF THE CRANK TO COUNTERWEIGHT (in)

## APPENDIX B

EXAMPLE

The following procedure can be used to fill in the balancing calculation sheets:

NOTE: When a value is measured, found, calculated or obtained place it into its appropriate position on the balancing calculation sheets. In other words, fill in the balancing calculation sheet.

UPS = UPSTROKE & DNS = DOWNSTROKE

1. Obtain the pumping speed (SPM).
2. Obtain the motor information:
   a. motor speed (RPM).
   b. motor voltage (V).
   c. motor power factor (PF).
   d. number of phases (PH).
3. Measure the distance from the long end of the crank to the counterweight that will be moved (D1).
4. Find the position of the upstroke peak current (UPS P1) from current card 1 (FIGURE 2).
5. Find the position of the downstroke peak current (DNS P1) from current card 1 (FIGURE 2).
6. Find the upstroke peak current (UPS PC1) from current card 1 (FIGURE 2).
7. Find the downstroke peak current (DNS PC1) from current card 1 (FIGURE 2).
8. Calculate the crank angle of the upstroke peak current (UPS θ1) from the API Spec 11E formulas or with the program (UNIT.FOR) in Appendix D.
9. Calculate the crank angle of the downstroke peak current (DNS θ1) from the API Spec 11E formulas or with the program (UNIT.FOR) in Appendix D.
10. Calculate the torque factor of the upstroke peak current (UPS TF1) from the API Spec 11E formulas or with the program (UNIT.FOR) in Appendix D.
11. Calculate the torque factor of the downstroke peak current (DNS TF1) from the API Spec 11E formulas or with the program (UNIT.FOR) in Appendix D.

# APPENDIX B (Cont.)

12. Obtain the angle of the counterweight arm offset ($\tau$) from the manufacturer.
13. Obtain the structural unbalance (B) from the manufacturer.
14. Find the upstroke polished rod load at P1 (UPS W1) from dynamometer card 1 (FIGURE 1).
15. Find the downstroke polished rod load at P1 (DNS W1) from dynamometer card 1 (FIGURE 1).
16. Repeat steps 3-15 for the second data set.
17. Calculate the upstroke net torque at the crank shaft (UPS Tn1) from EQ. 1 (in Appendix A) using the original data set.
18. Calculate the upstroke maximum moment of the counterbalance (UPS M1) from EQ. 2 (in Appendix A) using the original data set.
19. Calculate the downstroke net torque at the crank shaft (DNS Tn1) from EQ. 1 (in Appendix A) using the original data set.
20. Calculate the downstroke maximum moment of the counterbalance (DNS M1) from EQ. 2 (in Appendix A) using the original data set.
21. Calculate the upstroke and downstroke average of the maximum moment of the counterbalance ($\overline{M1}$) from EQ. 3 (in Appendix A) using the original data set.
22. Calculate the balanced maximum moment of the counterbalance (MB1) from EQ. 4 (in Appendix A) using the original data set.
23. Repeat steps 17-22 for the second data set.
24. Calculate the average maximum moment of the counterbalance (MB) EQ. 5 (in Appendix A) . This is an original data set and the second data set average.
25. Calculate the balanced distance from the long end of the crank (DB) from EQ. 6 (in Appendix A) .

<u>BALANCING CALCULATION SHEET B-1</u> (EXAMPLE)

ORIGINAL DATA (COUNTERWEIGHT HAS NOT BEEN MOVED):

MOTOR & MEASURE:

| PH | V | PF | RPM | SPM | D1 |
|---|---|---|---|---|---|
| 3 | 440 | .9 | 1160 | 9 | 26 |

FROM CURRENT CARD 1:

| | P1 | PC1 |
|---|---|---|
| UPSTROKE | 15 | 3250 |
| DOWNSTROKE | 49 | 2300 |

FROM API SPEC 11E (OR MANUFACTURER):

| | θ1 | TF1 | τ | W1 | B |
|---|---|---|---|---|---|
| UPSTROKE | 52.2 | 30.86 | 0 | 11100 | 800 |
| DOWNSTROKE | 245.6 | -27.70 | 0 | 5250 | 800 |

SECOND DATA (COUNTERWEIGHT HAS BEEN MOVED ONCE):

MOTOR & MEASURE:

| PH | V | PF | RPM | SPM | D2 |
|---|---|---|---|---|---|
| 3 | 440 | .9 | 1160 | 9 | 2 |

FROM CURRENT CARD 2:

| | P2 | PC2 |
|---|---|---|
| UPSTROKE | 17 | 2350 |
| DOWNSTROKE | 50 | 3250 |

FROM API SPEC 11E (OR MANUFACTURER):

| | θ2 | TF2 | τ | W2 | B |
|---|---|---|---|---|---|
| UPSTROKE | 55.9 | 31.83 | 0 | 11600 | 800 |
| DOWNSTROKE | 243.5 | -26.98 | 0 | 5750 | 800 |

PH = NUMBER OF PHASES OF MOTOR (eq. PH=3)
V = VOLTAGE (volts)
PF = POWER FACTOR (eg. PF=0.85)
D1 = FIRST DISTANCE FROM LONG END OF CRANK TO COUNTERWEIGHT (in)
RPM = SPEED OF MOTOR (rpm)
SPM = PUMPING SPEED (spm)
P1 = POSITION AT PEAK CURRENT FROM CARD 1 (in)
PC1 = PEAK CURRENT FROM CARD 1
θ1 = CRANK ANGLE AT THE PEAK CURRENT FROM CARD 1 (degrees)
TF1 = TORQUE FACTOR AT CRANK ANGLE θ1 (in)
τ = ANGLE OF COUNTERWEIGHT ARM OFFSET (degrees)
W1 = POLISHED ROD LOAD AT P1 FROM DYNAMOMETER CARD 1 (lb)
B = STRUCTURAL UNBALANCE (lb)

# APPENDIX B (Cont.)

## BALANCING CALCULATION SHEET B-2 (EXAMPLE)

$Tn1_{U,D} = (RPM/SPM)[(\sqrt{PH})(PC1_{U,D})(V)(PF)/(1000) - 3]/2.16$ ............(EQ. 1)

$M1_{U,D} = [TF1_{U,D}(W1_{U,D}-B) - Tn1_{U,D}]/SIN(\theta 1+\tau)_{U,D}$ ............(EQ. 2)

$\overline{M1} = [M1_U + M1_D]/2$ ............(EQ. 3)

$MB1 = [TF1_U(W1_U-B) - TF1_D(W1_D-B)]/[SIN(\theta 1+\tau)_U - SIN(\theta 1+\tau)_D]$ ..(EQ. 4)

ORIGINAL DATA (COUNTERWEIGHT HAS NOT BEEN MOVED):

UPSTROKE

$Tn1_U = 132836 = (1160)/(9)[(\sqrt{3})(3250)(440)(0.9)/(1000) - 3]/2.16$

$M1_U = 234159 = [(30.86)((11100)-(800))-(132836)]/SIN[(52.2)+(0)]$

DOWNSTROKE

$Tn1_D = 93955 = (1160)/(9)[(\sqrt{3})(2300)(440)(0.9)/(1000) - 3]/2.16$

$M1_D = 238524 = [(-27.70)((5250)-(800))-(93955)]/SIN[(245.6)+(0)]$

UPSTROKE & DOWNSTROKE AVERAGE

$\overline{M1} = 236341 = [(234159) + (238524)]/2$

BALANCED MAXIMUM MOMENT OF THE COUNTERBALANCE

$MB1 = 259356 = [(30.86)((11100)-(800))-(-27.70)((5250)-(800))]$
$/[SIN((52.2)+(0))-SIN((245.6)+(0))]$

Tn1 = NET TORQUE AT THE CRANKSHAFT (in-lb)
M1 = MAXIMUM MOMENT OF COUNTERBALANCE (in-lb)
MB1 = BALANCED MAXIMUM MOMENT OF COUNTERBALANCE (in-lb)

## BALANCING CALCULATION SHEET B-3 (EXAMPLE)

$MB = [MB1 + MB2]/2$ ............(EQ. 5)

$DB = \{[(D2 - D1)(\overline{MB} - \overline{M1})/(\overline{M2} - \overline{M1})] + D1\}$ ............(EQ. 6)

SECOND DATA (COUNTERWEIGHT HAS BEEN MOVED ONCE):

UPSTROKE

$Tn2_U = 96001 = (1160)/(9)[(\sqrt{3})(2350)(440)(0.9)/(1000) - 3]/2.16$

$M2_U = 299209 = [(31.83)((11600)-(800))-(96001)]/SIN[(55.9)+(0)]$

DOWNSTROKE

$Tn2_D = 132836 = (1160)/(9)[(\sqrt{3})(3250)(440)(0.9)/(1000) - 3]/2.16$

$M2_D = 297661 = [(-26.98)((5750)-(800))-(132836)]/SIN[(243.5)+(0)]$

UPSTROKE & DOWNSTROKE AVERAGE

$\overline{M2} = 298170 = [(299209) + (297661)]/2$

BALANCED MAXIMUM MOMENT OF THE COUNTERBALANCE

$MB2 = 277026 = [(31.83)((11600)-(800))-(-26.98)((5750)-(800))]$
$/[SIN((55.9)+(0))-SIN((243.5)+(0))]$

ORIGINAL DATA & SECOND DATA AVERAGE

$MB = 268191 = [(259356)+(277026)]/2$

BALANCED DISTANCE

$DB = \boxed{13.5} = \{[(|2|-|26|)(|268191|-|236341|)$
$/(|297661|-|236341|)]+|26|\}$

MB = AVERAGE BALANCED MAXIMUM MOMENT OF COUNTERBALANCE (in-lb)
DB = BALANCED DISTANCE FROM THE LONG END OF THE CRANK TO COUNTERWEIGHT (in)

MBSIM = 266459
MBSIM = MB FROM THE SUCKER ROD SIMULATOR USED FOR PERCENT ERROR.

**PERCENT ERROR IN MB = 0.65%**

# APPENDIX C

## THEORY

The objective of this paper is to present an efficient balancing method. A common method used to balance a unit that is driven by an electric motor is to set the peak upstroke current equal to the peak downstroke current. Setting the peak currents equal is equivalent to setting the peak crank torques equal (FIGURE 7). To be able to set the peak crank torques equal, a reasonable crank torque equation is needed. The following crank torque equations were compared to obtain a reasonable crank torque equation. The first crank torque equation was obtained from Svinos[1] .

$$Tn(\theta) = TF(\theta)[W(\theta)-B]-M\sin(\theta+\tau)-I_g\ddot{\theta}+TF(\theta)I_b\ddot{\theta}_4/A$$

The second crank torque equation was obtained from API Spec. 11E[2] .

$$Tn(\theta) = TF(\theta)[W(\theta)-B]-M\sin(\theta+\tau)$$

The API crank torque equation and the Svinos crank torque equation neglect the change in the structural unbalance B with the change in the crank angle and the friction in the saddle, tail and pitman bearings. The API equation also neglects the two last terms in the Svinos equation. These two terms represent the inertial effects of the unit. The API Spec. 11E states that "for units having 100 percent crank counterbalance and when the crank speed variation is not more than 15 percent of average, these factors can be neglected without introducing errors greater than 10 percent[2] ." Since the complexity of the problem increases substantially when the inertial terms are considered, these terms will be neglected in this paper. When the inertial terms are neglected the API crank torque equation can be used to obtain crank torque curves (FIGURES 7,8,9). Therefore, to reduce the complexity of the balancing method, the API equation was chosen to be the reasonable crank torque equation.

To balance a unit using previous methods, peak currents must be set equal. Setting peak currents equal is equivalent to setting peak crank torques equal. To find the peak crank torques, a crank torque curve must be calculated. To calculate a crank torque curve the following values should be obtained from the manufacturer:

1. TF - Torque Factor (in)
2. B - Structural Unbalance (lb)
3. $\tau$ - Angle of Crank Counterweight Arm Offset (degrees)

Another value needed to calculate a crank torque curve is the polished rod load (W). The polished rod load (W) can be measured with a dynamometer that is taken at the working fluid level. This card must be taken at the working fluid level because, the fluid level will directly affect the balancing. The final value needed to calculate the crank torque curve is the maximum moment of the counterbalance (M). The maximum moment of the counterbalance (M) can also be measured with a dynamometer. Measuring M is a tedious procedure. If this time consuming measurement of M is made, the crank torque curve can be calculated. With the crank torque curve the crew can check to see if the peak torques are equal. If the peak torques are equal, the unit is balanced. If the peak torques are not equal, the crew must move at least one counterweight to try to balance the unit. If the unit is not badly out of balance, only one adjustment counterweight needs to be moved. When the crew moves an adjustment counterweight, the polished rod loads (W) and the maximum moment of the counterweight (M) will change. Therefore, the torque curve will have new peak torques. To obtain the new peak torques the previous inefficient procedure must be repeated. To balance the unit, the crew may need to repeat this inefficient procedure several times. Therefore, previous methods used to balance a unit are time consuming.

This paper presents a method that will minimize the time needed to balance a unit. This method will minimize the time by balancing the unit within two moves of the adjustment counter weight. This method also eliminates the need to make the time consuming measurement of M.

This paper presents an easier method to obtain M. The maximum moment of the counterbalance (M) can be obtained from the API torque equation. The torque factor (TF), structural unbalance (B), and the angle of crank counterweight arm offset ($\tau$) can be obtained from the manufacturer. The polished rod loads (W) can be measured with a dynamometer card that is taken at the working fluid level. Therefore, the only unknowns are the crank torque (Tn) and the maximum moment of the counterbalance (M). Since the crank torques can be measured indirectly, the maximum moment of the counterbalance (M) can be calculated from the API crank torque equation. The crank torques can be measured indirectly from the current card that is taken at the working fluid level. The currents from this current card can be transformed into crank torques with the following procedure:

1. Change the current into power with the following electric motor equation.

$$P = \sqrt{PH}\ V\ I\ PF$$

P = Power (Watts)
PH = Number of Phases [eg. PH=3]
V = Voltage (Volts) [eg. V=440]
I = Current (amps)
PF = Power Factor [eg. PF=0.9]

# APPENDIX C (Cont.)

2. Change the power into motor torque with a motor performance equation (FIGURE 10)[3] .

$$Tm = (P/1000 - 3)/2.16$$

P = Power (Watts)
Tm = Motor Torque (in-lb)

3. Change the motor torque into crank torque with the speed ratio (SR).

$$Tn = SR\ Tm$$

Tm = Motor Torque (in-lb)
SR = Speed Ratio RPM/SPM
RPM = Angular velocity of the motor (rpm)
SPM = Strokes per Minute (spm)
Tn = Crank Torque (in-lb)

With the crank torques, the maximum moment of the counterbalance (M1) can be calculated from the API crank torque equation. Before the adjustment counterweight is moved, the distance (D1) from the long end of the crank to the adjustment counterweight can also be measured. Then the adjustment counterweight can be moved one to three feet. The new distance (D2) from the long end of the crank to the adjusted counterweight can also be measured. Moving this counterweight will change the maximum moment of the counterbalance. The new maximum moment of the counterweight (M2) can be calculated again from the API crank torque equation. If the unit is still unbalanced, the peak torque on the upstroke ($PTn_u$) will not be equal to the peak torque on the downstroke ($PTn_D$)

$$PTn_u(\theta_u, M2) \neq PTn_D(\theta_D, M2)$$

$$PTn_u(\theta_u, M2) = TF(\theta_u)[W(\theta_u)-B]-M2\sin(\theta_u+\tau)$$

$$PTn_D(\theta_D, M2) = TF(\theta_D)[W(\theta_D)-B]-M2\sin(\theta_D+\tau)$$

To balance the unit, the correct maximum moment of the counterweight (MB) must used. When this correct moment is used, the peak torque on the upstroke ($PTn_u$) is equal to the peak torque on the downstroke ($PTn_D$).

$$PTn_u(\theta_u, MB) = PTn_D(\theta_D, MB)$$

$$PTn_u(\theta_u, MB) = TF(\theta_u)[W(\theta_u)-B]-MB\sin(\theta_u+\tau)$$

$$PTn_D(\theta_D, MB) = TF(\theta_D)[W(\theta_D)-B]-MB\sin(\theta_D+\tau)$$

$$TF(\theta_u)[W(\theta_u)-B]-MB\sin(\theta_u+\tau) = TF(\theta_D)[W(\theta_D)-B]-MB\sin(\theta_D+\tau)$$

The equation above can now be solved for the balanced maximum moment of the counterweight (MB).

$$MB = \frac{\{TF(\theta_D)[W(\theta_D)-B] - TF(\theta_u)[W(\theta_u)-B]\}}{\{\sin(\theta_u+\tau) - \sin(\theta_D+\tau)\}}$$

Once the balanced maximum moment of the counterweight has been found, the only other piece of information needed is the corresponding location of the adjusted counterweight. This distance (DB) from the long end of the crank to the adjusted counterweight can be found by realizing that the maximum moment of the counterweights are a linear function of distance. With this knowledge, the following equation of a line can be easily derived.

$$DB = \{[(D2 - D1)(MB - M1)/(M2 - M1)] + D1\}$$

**NOTE: Symbols are defined on the balancing calculation sheets (Appendix A).**

# APPENDIX D

DATA FILE FOR UNIT.FOR

```
1       IUNIT......UNIT FLAG:  CONVENTIONAL:IUNIT=1,  MARK II:IUNIT=2
160     PTRAT.......PEAK TORQUE RATING (thousands of in*lb)
200     PRLRAT....POLISHED ROD LOAD RATING (hundreds of lb)
64.     STROKE....STROKE LENGTH OF UNIT (in)
96.     XA........UNIT DIMENSION (in)
114.    XP........UNIT DIMENSION (in)
96.05   XC........UNIT DIMENSION (in)
96.     XI.........UNIT DIMENSION (in)
151.34  XK........UNIT DIMENSION (in)
32.     XR........UNIT DIMENSION (in)
1       JR.........ROTATION OF UNIT:  CLOCKWISE:JR=1  COUNTER:JR=-1
1       DTHETT....ANGLE INCREMENT USED FOR POS. & TF. TABLE (deg)
0.      TAU...........COUNTER WEIGHT TO CRANK PHASE ANGLE (deg)
```

PART OF THE OUTPUTFILE FROM UNIT.FOR

DESIGNATION OF UNIT:  C - 160D - 200 -  64

| POSITION OF CRANK (DEGREES) | POSITION OF RODS (INCHES) | TORQUE FACTOR (INCHES) |
|---|---|---|
| 0.000 | 0.019 | -1.282 |
| 1.000 | 0.003 | -0.543 |
| 52.000 | 14.891 | 30.803 |
| 53.000 | 15.419 | 31.089 |
| 54.000 | 15.952 | 31.357 |
| 55.000 | 16.489 | 31.609 |
| 56.000 | 17.030 | 31.844 |
| 243.000 | 50.216 | -26.818 |
| 244.000 | 49.756 | -27.161 |
| 245.000 | 49.290 | -27.496 |
| 246.000 | 48.818 | -27.822 |
| 247.000 | 48.340 | -28.140 |
| 359.000 | 0.047 | -2.018 |
| 360.000 | 0.019 | -1.282 |

PROGRAM UNIT.FOR

```
$DEBUG
C+++++++++++++++++++++++++++++++++++++++++++++++++++++
C ++                         UNIT.FOR                      ++
C ++       THIS PROGRAM CALCULATES A UNIT TABLE             ++
C +++++++++++++++++++++++++++++++++++++++++++++++++++++
      DIMENSION THETAT(365),PRT(365),TF(365)
      CHARACTER*12 FNAMIN,FNAMOUT
C   READ IN THE DATA FILE:
C   IUNIT.....UNIT FLAG:
C         CONVENTIONAL & SPECIAL GEOMETRY-IUNIT=1
C           MARK II-IUNIT=2
C   PTRAT.....PEAK TORQUE RATING (thousands of in*lb)
C   PRLRAT....POLISHED ROD LOAD RATING (hundreds of lb)
C   STROKE....STROKE LENGTH OF UNIT (in)
C   XA........UNIT DIMENSION (in)
C   XP........UNIT DIMENSION (in)
C   XC........UNIT DIMENSION (in)
C   XI........UNIT DIMENSION (in)
C   XK........UNIT DIMENSION (in)
C   XR........UNIT DIMENSION (in)
C   JR........STANDARD ROTATION OF UNIT:
C         CLOCKWISE-JR=1, COUNTERCLOCKWISE-JR=-1
C   DTHETT....ANGLE INCREMENT USED FOR POS. & TF. TABLE (deg)
C   TAU.......COUNTER WEIGHT TO CRANK PHASE ANGLE (deg)
  5 CONTINUE
      WRITE(*,100)
      READ(*,101) FNAMIN
      OPEN(7,ERR=15,FILE=FNAMIN,STATUS='OLD')
      GOTO 20
 15 CONTINUE
      WRITE(*,102) FNAMIN
      GOTO 5
 20 CONTINUE
      READ(7,*) IUNIT
      READ(7,*) PTRAT
      READ(7,*) PRLRAT
      READ(7,*) STROKE
      READ(7,*) XA
      READ(7,*) XP
      READ(7,*) XC
      READ(7,*) XI
      READ(7,*) XK
      READ(7,*) XR
      READ(7,*) JR
      READ(7,*) DTHETT
      READ(7,*) TAU
      CLOSE(7)
      PI = 4*ATAN(1.)
      IPTRAT = PTRAT
      IPRLRAT = PRLRAT
      ISTROKE = STROKE
```

# APPENDIX D (Cont.)

```
      CALL TABL(NTAB,THETAT,PRT,TF,
     +       PI,DTHETT,IUNIT,JR,XI,XK,XC,XP,XR,XA)
      WRITE(*,103)
      READ(*,101) FNAMOUT
      OPEN(7,FILE=FNAMOUT)
      IF(IUNIT.EQ.1) WRITE(7,105)IPTRAT,IPRLRAT,ISTROKE
      IF(IUNIT.EQ.2) WRITE(7,106)IPTRAT,IPRLRAT,ISTROKE
      WRITE(7,*) ' '
      WRITE(7,*) '   POSITION     POSITION      TORQUE'
      WRITE(7,*) '   OF CRANK     OF RODS        FACTOR'
      WRITE(7,*) '   (DEGREES)    (INCHES)      (INCHES)'
         WRITE(7,*) '   ------------    ------------ -   -------------'
      DO 10 I=1,NTAB
        PRT(I) = PRT(I)*STROKE
        THETAT(I) = THETAT(I)*180/PI
        WRITE(7,107) THETAT(I),PRT(I),TF(I)
10    CONTINUE
100   FORMAT(4(/),7X,'INPUT THE NAME OF YOUR UNIT DATA FILE',
     &      /,7X,'***  12 CHARACTERS MAXIMUM   ***',/)
103   FORMAT(4(/),7X,'INPUT THE NAME OF YOUR UNIT OUTPUT FILE',
     &      /,7X,'***  12 CHARACTERS MAXIMUM   ***',/)
101   FORMAT(A)
102   FORMAT(//,7X,A,' WAS NOT FOUND',//,7X,'PLEASE ENTER THE',
     &      ' PRED DATA FILE AGAIN',///)
105   FORMAT('DESIGNATION OF UNIT:  C -',I4,'D -',I4,' -',I4)
106   FORMAT('DESIGNATION OF UNIT:  M -',I4,'D -',I4,' -',I4)
107   FORMAT(6X,F7.3,9X,F7.3,9X,F7.3)
      END
C
C++++++++++++++++++++++++++++++++++++++++++++++++++++++++
C ++                TABL.FOR                          ++
C++++++++++++++++++++++++++++++++++++++++++++++++++++++++
C
      SUBROUTINE TABL(NTAB,THETAT,PRT,TF,
     +       PI,DTHETT,IUNIT,JR,XI,XK,XC,XP,XR,XA)
      DIMENSION THETAT(1),PRT(1),TF(1)
C     REFERENCE: RP11E
C     CALCULATE ANLGE, POSTION AND TORQUE FACTOR TABLE FOR ANY UNIT
      TH  = ACOS(XI/XK)
        TH1  =  ACOS((XK**2+(XP+XR)**2-XC**2)/(2*XK*(XP+XR)))
        TH2  =  ACOS((XK**2+(XP-XR)**2-XC**2)/(2*XK*(XP-XR)))
      IF(IUNIT.EQ.1) THEN
        THMIN =   PI/2 - TH - TH1
        THMAX = 3*PI/2 - TH - TH2
      ELSEIF(IUNIT.EQ.2) THEN
        THMIN = 5*PI/2 - TH - TH2
        THMAX = 3*PI/2 - TH - TH1
      ENDIF
      NTAB=360/DTHETT+3
      DTHETT = DTHETT*PI/180.
      THOLD = -DTHETT
      IFLAG = 0
      FAI = ASIN(XI/XK)
      IF(IUNIT.EQ.2) FAI=PI-JR*ASIN(XI/XK)
        PSIB  =  ACOS((XC**2+XK**2-(XP+XR)**2)/(2.*XC*XK))
        PSIT  =  ACOS((XC**2+XK**2-(XP-XR)**2)/(2.*XC*XK))
      DO 10 I=1,NTAB
      IF(THETA1.LT.THMIN.AND.(THETA1+DTHETT).GT.THMIN
     &    .AND.I.GT.1) IFLAG = 1
      IF(THETA1.LT.THMAX.AND.(THETA1+DTHETT).GT.THMAX) IFLAG = 2
      IF(IFLAG.EQ.0) THEN
        THETA1 = THOLD + DTHETT
        THOLD = THETA1
      ELSE
        IF(IFLAG.EQ.1) THEN
          PRT(I) = 0.
          TF(I)  = 0.
          THETA1 = THMIN
          IFLAG = 0
          GOTO 5
        ENDIF
        IF(IFLAG.EQ.2) THEN
          PRT(I) = 1.
          TF(I)  = 0.
          THETA1 = THMAX
          IFLAG = 0
          GOTO 5
        ENDIF
      ENDIF
      THETAF = THETA1-FAI
        CBETA  =  (XC**2+XP**2-XK**2-XR**2+2.*XK*XR
     &        *COS(THETAF))/(2.*XC*XP)
      BETA = ACOS(CBETA)
        XJ  =  SQRT(XC**2+XP**2-2.*XC*XP*CBETA)
         X  =  ACOS((XC**2+XJ**2-XP**2)/(2.*XC*XJ))
      IF(IUNIT.EQ.2) X = ASIN(XP*SIN(BETA)/XJ)
      PHO = ASIN((XR*SIN(THETAF)/XJ))
      PSI = X-PHO
      IF(IUNIT.EQ.2.AND.JR.EQ.1) PSI = X+PHO
      ALPHA = BETA+PSI-THETAF
      IF(IUNIT.EQ.2) ALPHA = THETAF+JR*(BETA+PSI)
      IF(IUNIT.EQ.1) PRT(I) = (PSIB-PSI)/(PSIB-PSIT)
      IF(IUNIT.EQ.2) PRT(I) = (PSIT-PSI)/(PSIT-PSIB)
      TF(I) = XA*XR*SIN(ALPHA)/SIN(BETA)/XC
        IF(JR.EQ.-1.AND.IUNIT.EQ.1) TF(I)=-TF(I)
5     CONTINUE
      THETAT(I)=THETA1
      THETOUT = THETA1*180/PI
10    CONTINUE
      THETAT(NTAB) = 2*PI
      RETURN
      END
```

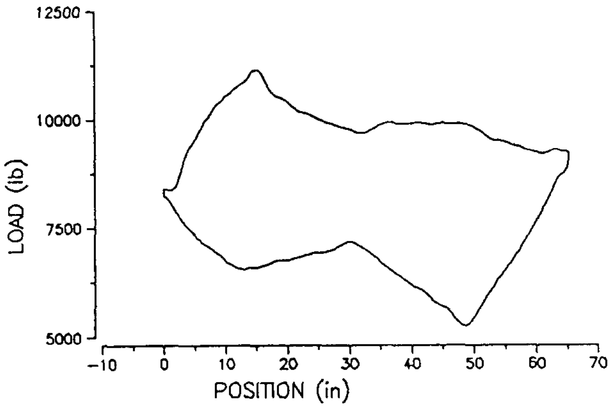


Figure 1 - Dynamometer card 1

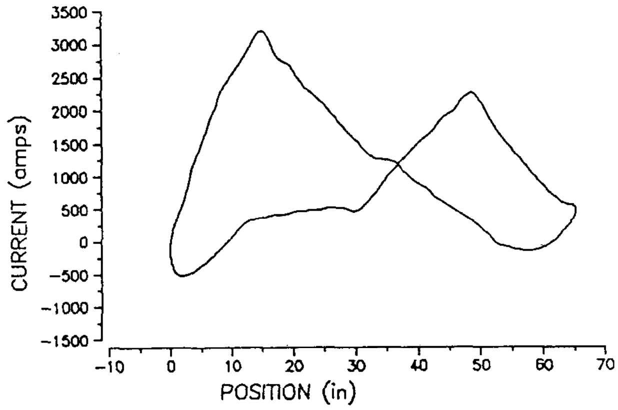


Figure 2 - Current card 1

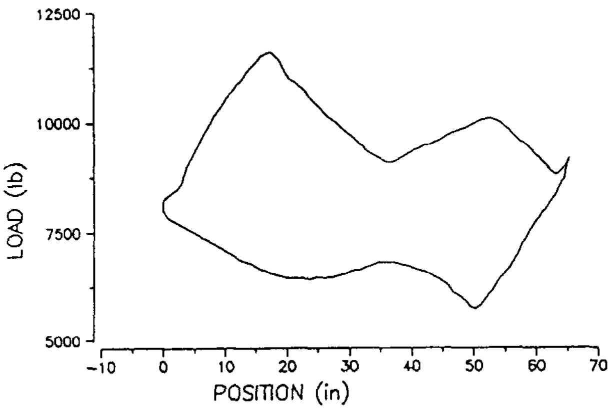


Figure 3 - Dynamometer card 2

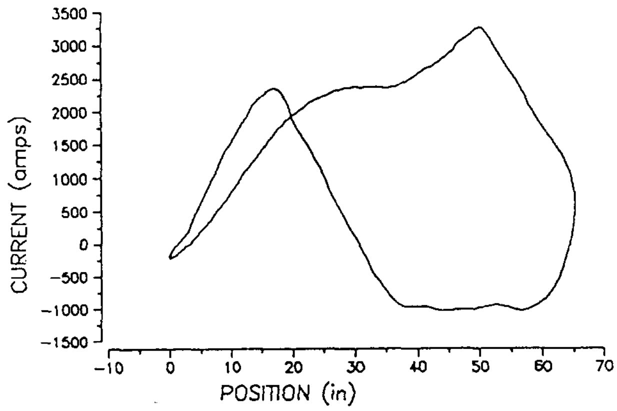


Figure 4 - Current card 2

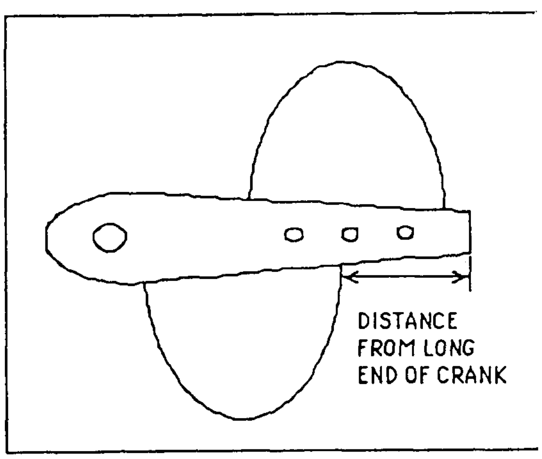


Figure 5

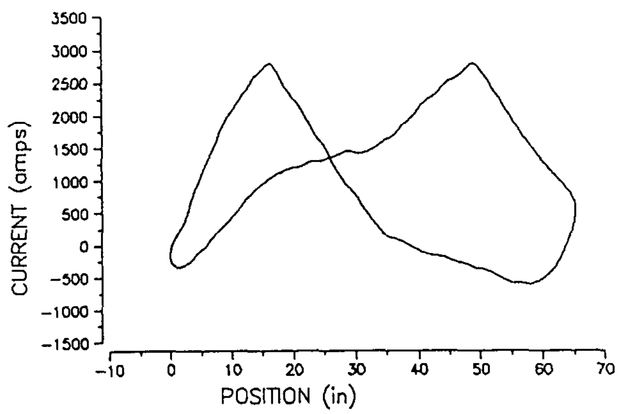


Figure 6 - Balanced current card

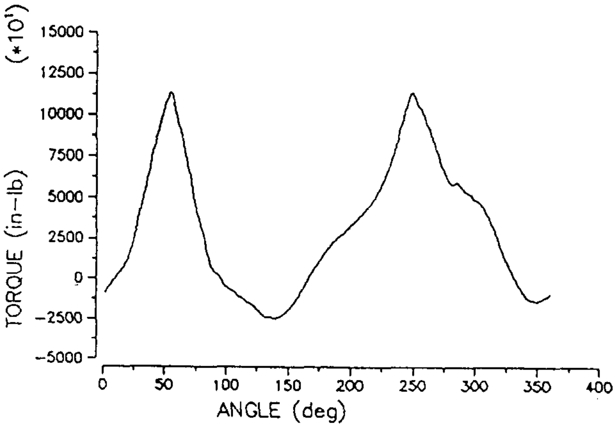


Figure 7 - Balanced torque curve

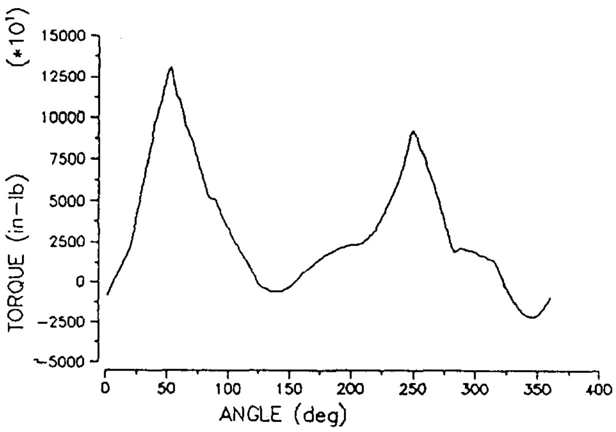


Figure 8 - Torque curve 1

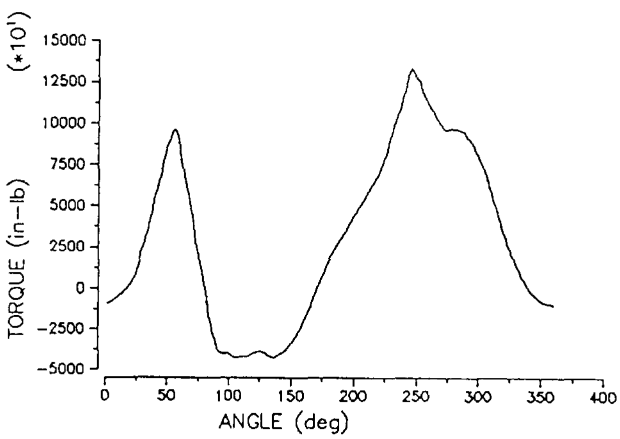


Figure 9 - Torque curve 2

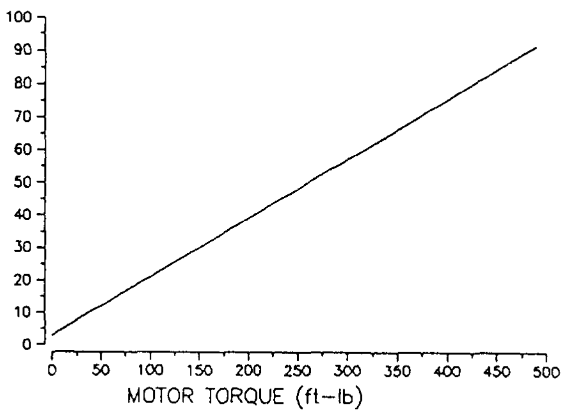


Figure 10 - Motor performance