Artificial Lift R&D Council

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Back to Basics:

Gearbox Torques and Counterbalancing

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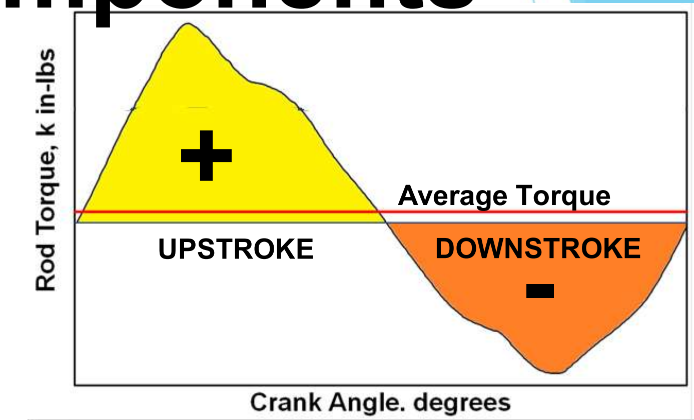
Gearbox Torque Components

- **Rod Torque** required to move PU

  T_r = TF (PR Load – SU)

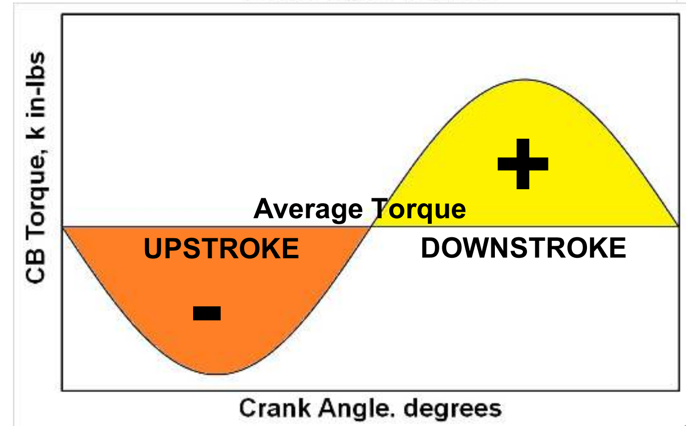
$$T_{avg} = \frac{\int_0^{2\pi} T_r \, d\theta}{2\pi}$$



- **CB Torque** required to rotate CWs

  $T_{CB} = - T_{CB\ max} \sin(\text{Crank Angle})$

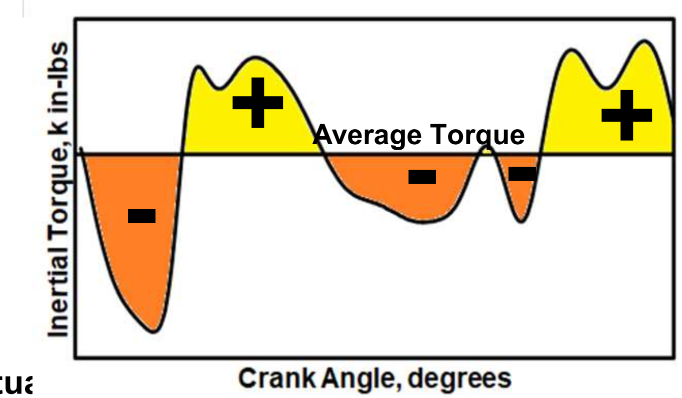
  $T_{avg} = 0$



- **Inertial Torques** indicate changes in kinetic energy

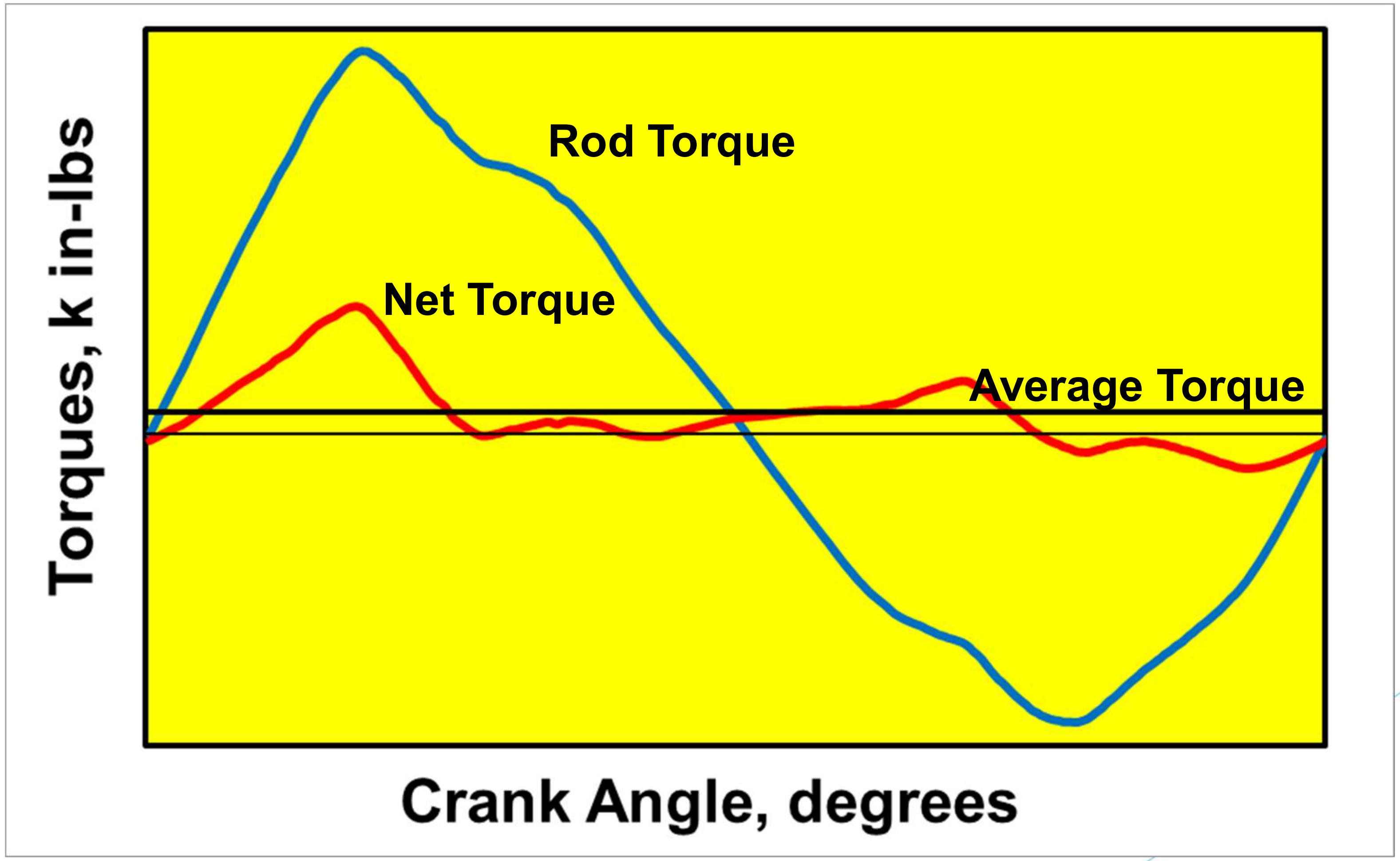
  $T_{avg} = 0$

$$T_{ir} = \frac{12}{32.2} I \frac{d^2\theta}{dt^2}$$



Net Gearbox Torque: Sum of All Torques

Since average CB and inertial torques are both ZERO,
Average Net Gearbox Torque equals **Average Rod Torque.**



Power Conditions in Pumping Cycle

- Avg. Motor Power found from Avg. Rod Torque:

$$P_{avg}\,[\mathrm{HP}] = \frac{T_{avg}\,[\mathrm{k\ in\ lbs}]\,SPM\,\pi}{198}$$

- Conservation of energy on pumping unit (assuming no losses)

$$PRHP = P_{avg}$$ (PRHP from measured dynamometer card)

- Avg. power requirement over the pumping cycle equals PRHP.
- **Counterbalancing and inertia do not affect required average power to operate the system!**

An Example Case

$$P\left[\mathrm{HP}\right] = \frac{T\left[\mathrm{k\ in\ lbs}\right] SPM\ \pi}{198}$$




Avg Speed, 1/min	5.54		5.54	158		158	1200	~ 1,200 RPM
Avg Torque, k in-lbs			69.70	2.44		2.44	0.32	0.32
Avg Power, HP	6.1		6.1	6.1		6.1	6.1	7.1

Measured values including energy losses

Mechanical Efficiency of the Surface System

- Mechanical Power Transmission Efficiency of the surface system (Pumping Unit, Gearbox, V-Belt Drive)

$$\eta_{mech} = \frac{PRHP}{P_{avg}} = \frac{6.1}{7.1} = 0.86$$

- Required Avg. Motor Power **including Power Losses**

$$P_{avg} = PRHP \,/\, \eta_{mech}$$

Will a Motor w. Avg. Power = PRHP/η_{mech} Suffice?

- Electric motors are rated for permissible temperature rise caused by thermal (rms) current. I_{rms} = sqrt I^2 (**negative currents, too, heat motor**)
- Motor power directly proportional to Current (Motor Voltage constant)

Power/Current = const. at average and rated conditions:

$$P_{avg} / I_{avg} = P_{np} / I_{rms}$$

- From this:

$$P_{np} = P_{avg}\, I_{rms} / I_{avg} = P_{avg}\, CLF = PRHP / \eta_{mech}\, CLF_e$$

- **Motor must be oversized to P_{np} to keep its thermal load under control.**

Concept of the Cyclic Load Factor

- Current vs Torque function of motors is linear, CLF can be calculated from Net Torque (Current not usually measured)

  CLF = rms Torque / avg. Torque

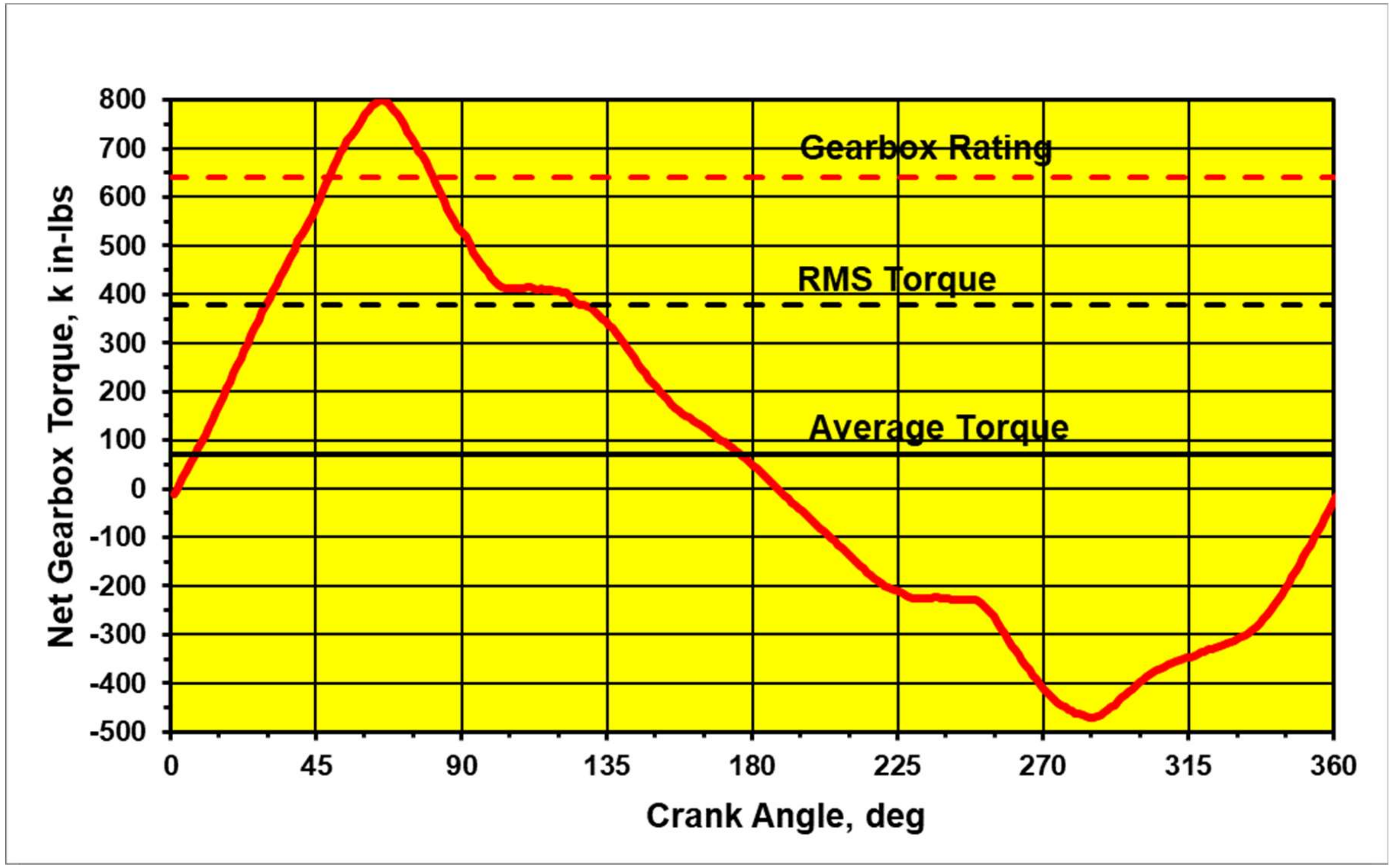
- CLF indicates "smoothness" of Net Torque

  The smaller the CLF the smoother the Net Torque

$$CLF = \frac{\sqrt{\dfrac{\int_{\theta=0}^{2\pi} [T_{net}(\theta)]^2 \, d\theta}{2\pi}}}{\dfrac{\int_{\theta=0}^{2\pi} T_{net}(\theta)\, d\theta}{2\pi}}$$

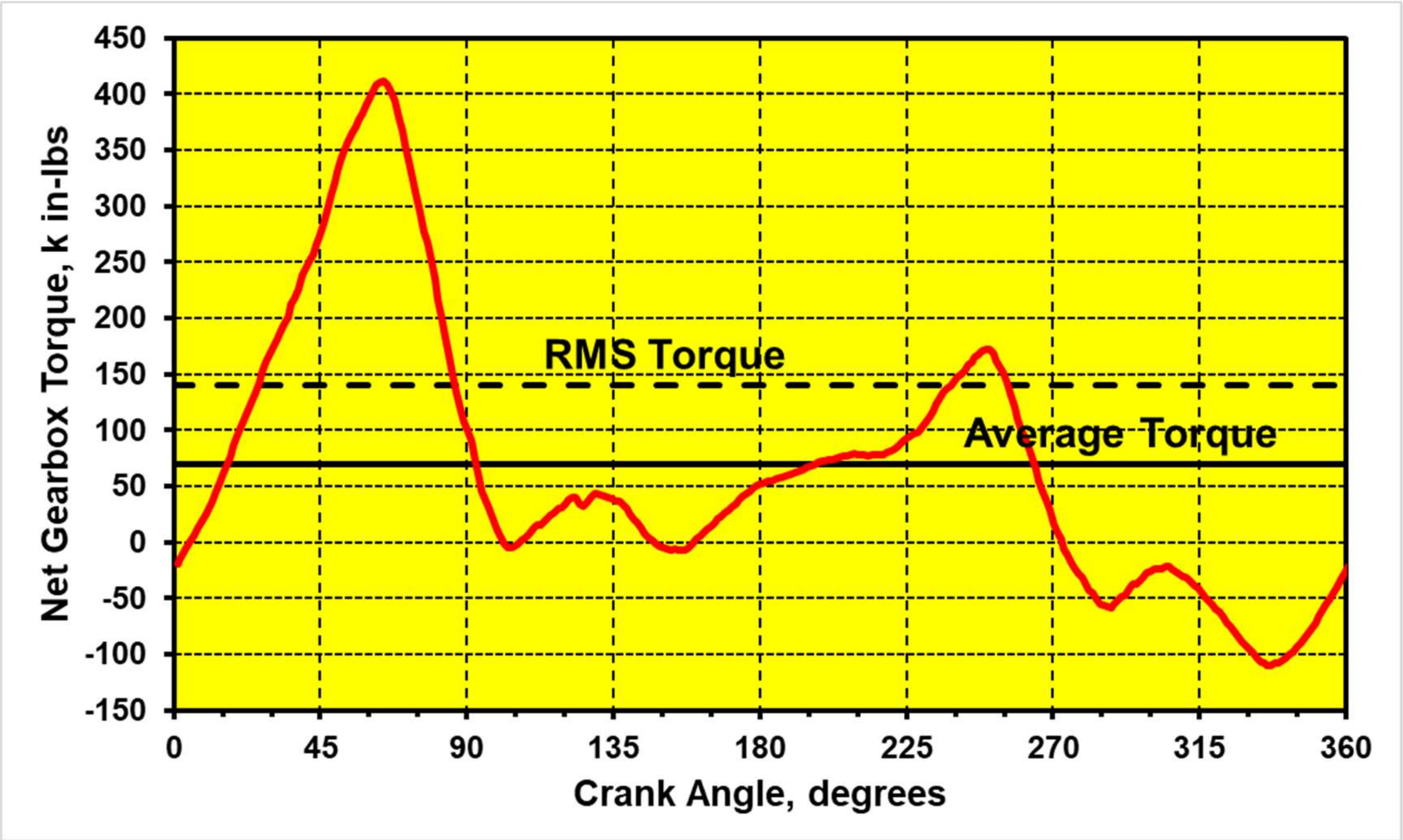
- Range of CLF values:
  - Constant Torques ($T_{avg} = T_{rms}$) CLF = 1
  - Fluctuating Torques ($T_{rms} > T_{avg}$) CLF > 1
- **Way to Change CLF**
  - **Modify Counterbalancing by changing Max. CB Moment**

The Effect of Counterbalancing
Case 1: Cranks Only, No CWs



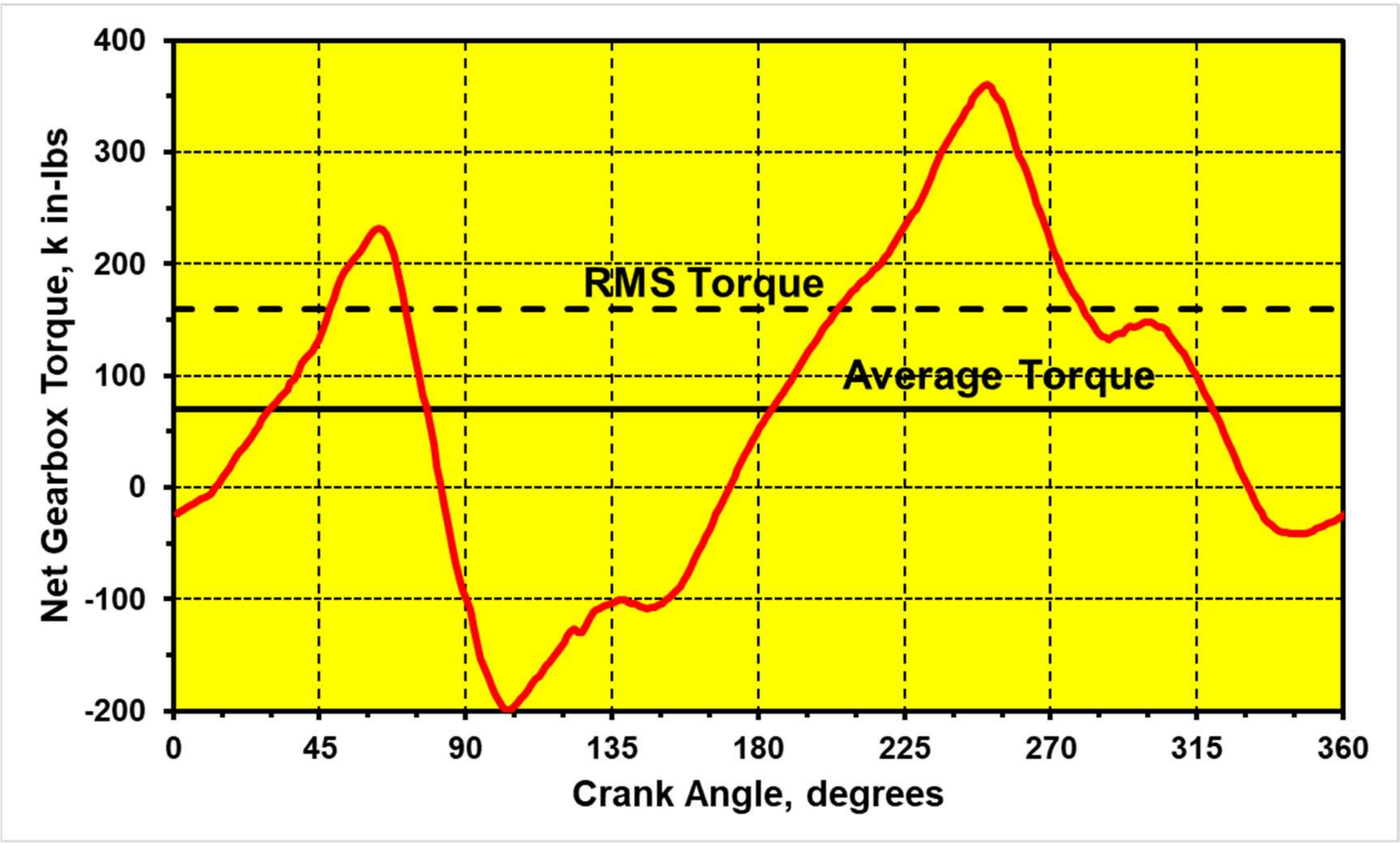
Max CB Moment k in-lbs	470.8
Avg. Torque k in-lbs	69.6
RMS Torque k in-lbs	378
CLF	5.43
Nameplate Power, HP	38.5
Rod Heavy, Overloaded	

The Effect of Counterbalancing
Case 2: Under-Balanced



Max CB Moment k in-lbs	900
Avg. Torque k in-lbs	69.6
RMS Torque k in-lbs	139
CLF	2.00
Nameplate Power, HP	14.2
Rod Heavy	

The Effect of Counterbalancing
Case 3: Over-Balanced



Max CB Moment k in-lbs	1,100
Avg. Torque k in-lbs	69.6
RMS Torque k in-lbs	159
CLF	2.28
Nameplate Power, HP	16.2
Weight Heavy	

Optimum Counterbalancing

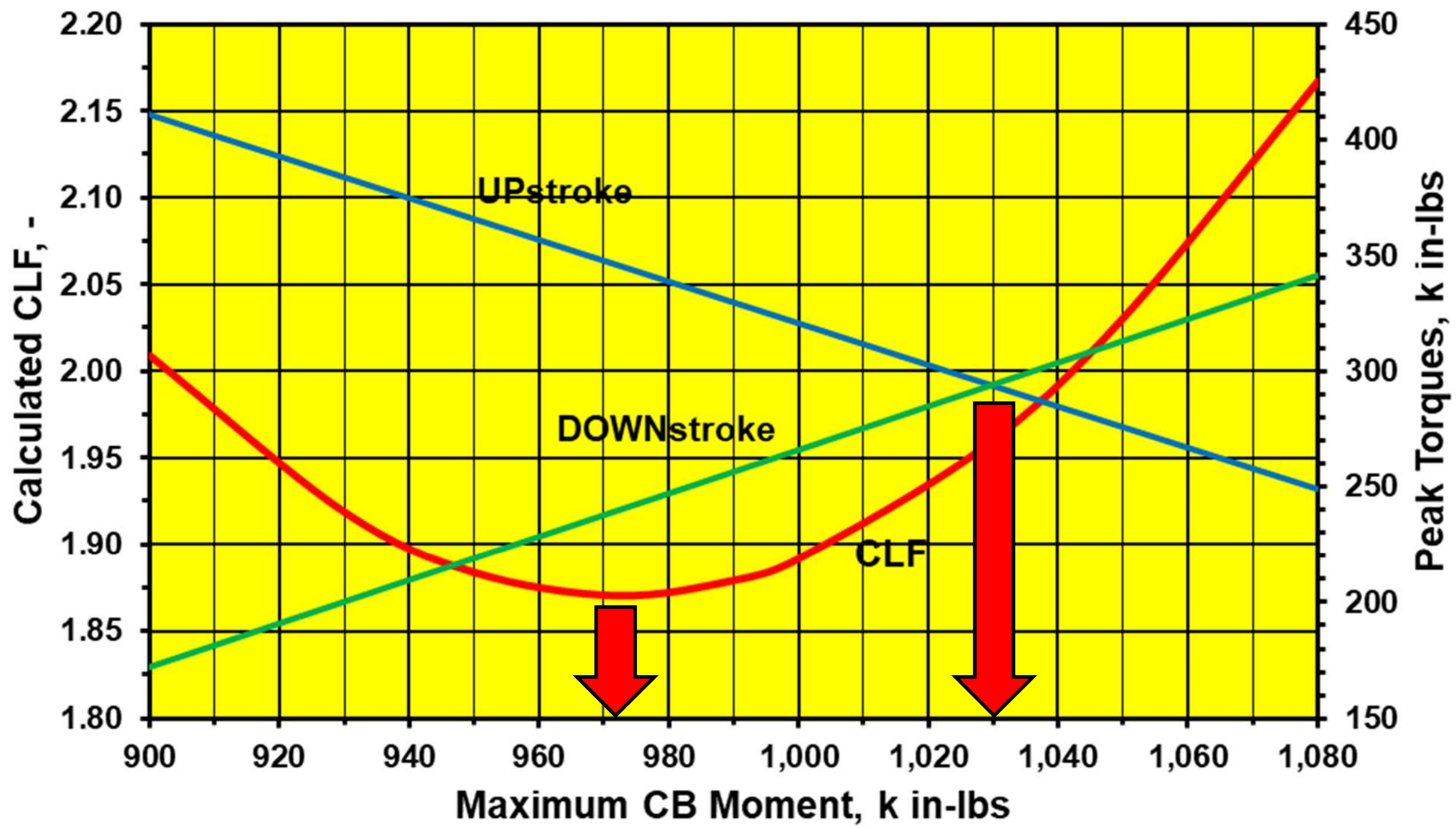
- Proper selection of CB moment reduces fluctuations to acceptable levels
- Criteria for optimum Gearbox Torque balancing
  - Traditional Optimization Methods: Peak Up-, and Downstroke Torques Equal
    - Mechanical Torque calculations
    - Current measurements
  - Minimum CLF Method: Minimize CLF, motor nameplate power

$$P_{np} = PRHP / \eta_{mech} \, CLF$$

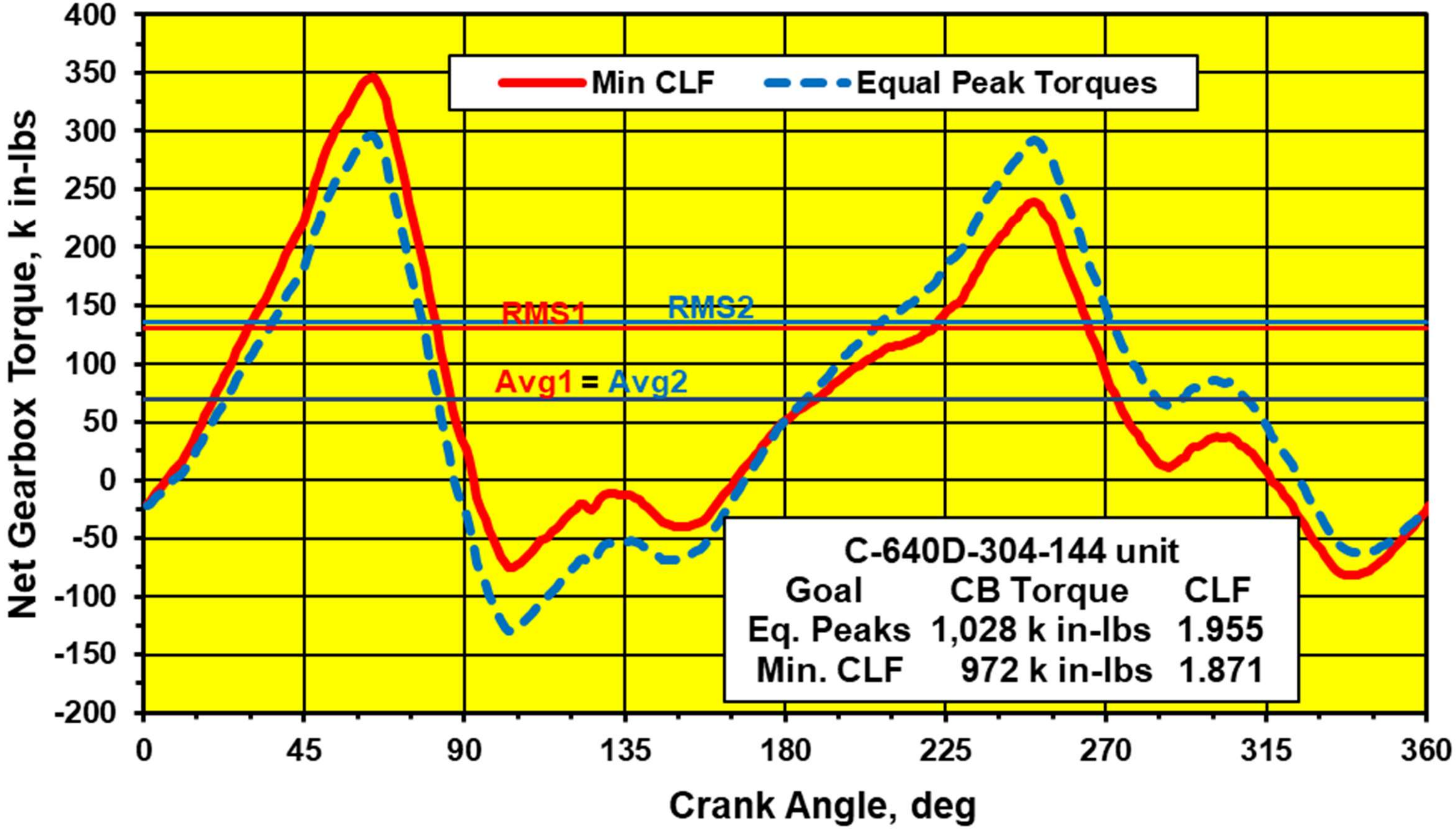
Different Balancing Scenarios for Example

Case	$T_{CB\ max}$	CLF	Min. Motor
	k in-lbs	-	HP
Cranks Only	470.8	5.430	38.5
Existing	1,039	1.990	14.1
Gibbs Method	1,030.0	1.961	13.9
Eq. Peaks	1,028.1	1.955	13.9
Min. CLF	972.0	1.871	13.3

Comparison of Optimization Objectives



Comparison of Optimization Objectives



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Conclusions

- Average motor power required to drive the pumping system is found from the PRHP and the surface power transmission efficiency:

$$P_{avg} = PRHP / \eta_{mech}$$

- The electric motor must be oversized to prevent its overheating due to the effects of fluctuating torque load:

$$P_{np} = P_{avg} * CLF = PRHP / \eta_{mech} * CLF$$

- ***CLF*** and P_{np} can be minimized by the proper selection of counterbalancing, i.e., the maximum CB moment.

Acknowledgement

The author wants to express his gratitude to Echometer Co., whose TAM software was used to support the calculation models presented here.

Thank you for your attention!

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