330:148 (g)
Machine Design

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2. Force, Work and Power

Objectives

- Understand the difference between force, work, and power.
- Recognize and be able to convert between mass and weight.
- Convert between English and metric units for force, work, and power.
- Understand the basic principles of fluid mechanics as they apply to hydraulic and air cylinders or similar products.
- Look up and/or calculate moments of inertia and section modulus for different shape parts.
- Apply the principles of work, force, and power to moving machines.

Weight, Force and Mass

- Weight, W = m g
- W = weight, lb or N
- M = Mass, lb or kg
- g = acceleration due to gravity,
  - 32.2 ft/s^2, 9.81 m/s^2
- Force, F = m a
- a = acceleration

Work and Power

- Work = Force × Distance ft-lb or N m
- Work done, W = F d
- Power is rate of doing work
- Power, P = $\frac{W}{t}$
- t = time

Power and Speed

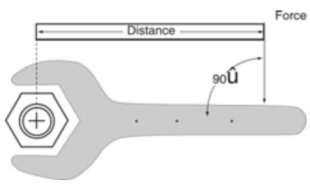
- 1 hp = 550 ft-lb/s
  = 6600 in-lb/s
  = 33,000 ft-lb/min
  = 396,000 in-lb/min
- Power in SI Units is Watts
- 1 hp = 746 W = 0.746 kW

Power and Speed

- P = T ω
- P = Power, ft-lb/s or W
- T = Torque, ft-lb or N m
- ω = Rotational speed in radians/second
- T = $\frac{P}{\omega}$
- ω = $\frac{2 \pi n}{60}$
- n = revolutions per minute

Torque

- Torque is a twisting moment
  - Rotates a part in relation to other
- T = F d
- F = force applied
- d = distance



Calculate the amount of torque in a shaft transmitting 750 W of power while rotating at 183 rad/s.

- $P = T\,\omega$
- Torque = 750 / 183 = 4.09836 N-m

Example Problem 2-1: Torque

- An automobile engine creates a torque of 300 ft-lb at a rotational speed of 3,500 rpm.
- In fourth gear, the transmission has a 1 to 1 ratio.
- The differential has a ratio of 3.6 to 1, which creates a torque in the axle of 1,080 ft-lb.
- What is the force being exerted on the road by the automobile tire if the diameter of the tire is 30 inches?

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- What is the force being exerted on the road by the automobile tire if the diameter of the tire is 30 inches?

$$T = Fd$$

$$F = \frac{T}{d}$$

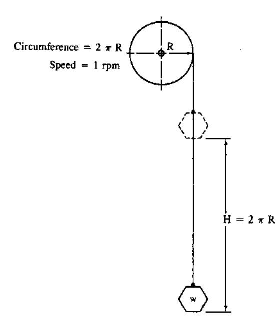
$$F = \frac{1080\ ft-lb}{\frac{30in}{2}\ \frac{(ft)}{(12\,in)}}$$

$$F = 864\ lb$$

- The tire exerts an 864-pound force on the road surface.

Power and Rotational Speed

- $P = T\,\omega$
- Since, $\omega = \frac{2\,\pi\,n}{60}$
- We get, $P = \frac{2\,\pi\,T n}{60}$



$$\text{Power} = \frac{\text{Work}}{\text{Time}} = \frac{W \times H}{t}$$

$$= \frac{W \times 2\pi \times R}{1\ \text{min}}$$

$$\text{Power} = 2\,\pi\,T\,n$$

$$\text{Horse power} = \frac{2\,\pi\,T\,n}{396{,}000}$$

$$\text{Horse power} = \frac{T\,n}{63{,}000}$$

T = torque (in-lb)

n = rotational speed, rpm

Example Problem 2-2: Work and Power

- If the automobile in Example Problem 2-1 was going up a long, steep hill at this speed, how much work was done in the period of a second? What is the power?
- Force on the road, F = 864 lb

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Example Problem 2-2: Work and Power

- If the automobile in Example Problem 2-1 was going up a long, steep hill at this speed, how much work was done in the period of a second?
- As work is force times distance, calculate the distance traveled in one second.

$$d = \frac{\pi \; 3500\, rpm \frac{30\, in}{rev} \frac{ft}{12\, in} \frac{\min}{60 \sec}}{\frac{3.6}{1}}$$

$$d = 127 \; ft$$

$$W = Fd \qquad (2\text{-}3)$$

$$W = 864\, lb \;\; 127\; ft$$

$$W = 109{,}728 \;\; ft - lb \; of \;\; work$$

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Example Problem 2-2: Work and Power (cont'd)

- The power to do this would then be:

$$P = \frac{Fd}{t} = \frac{W}{t} \qquad (2\text{-}4)$$

$$P = \frac{109{,}728 \; ft\text{-}lb}{1 \; sec} = 109{,}728 \; \frac{ft\text{-}lb}{sec}$$

or if:

$$550 \; \frac{ft\text{-}lb}{sec} = 1 \; hp$$

$$hp = \frac{109{,}728 \; \frac{ft\text{-}lb}{sec}}{550 \; \frac{\frac{ft\text{-}lb}{sec}}{hp}} = 200 \; hp$$

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Example Problem 2-2: Work and Power (cont'd)

- Compare it to motor output:

$$T = 63{,}000 \; \frac{P}{n}$$

where: n = rpm

T = in-lb

$$P = \frac{Tn}{63{,}000} \qquad (2\text{-}6)$$

$$P = \frac{300 \; ft\text{-}lb}{} \; \frac{12 \; in}{ft} \; \frac{3500 \; rpm}{63{,}000}$$

$$P = 200 \; hp$$

- Power output equaled the power at the tire/road surface.

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Pressure, Force and Area

- Pneumatic and Hydraulic Cylinders
- Force = Pressure × Area
- Work done = Force × Distance moved
- Distance moved = stroke length

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Example Problem 2-3: Force Pressure Relationship

- For the automobile engine from the prior example problems, calculate the pressure required in the cylinder under the following assumptions:
  1. The cylinder is 2 inches in diameter.
  2. The crankshaft has an effective radius of 4 inches.
  3. Maximum power is achieved when the piston is perpendicular to the crankshaft.
  4. At this point, all the power comes from this piston alone.
- If the T is 300 ft-lb and the effective length of the crankshaft is 4 inches, the force exerted by the piston would be:

$$T = Fd \qquad (2\text{-}5)$$

$$F = \frac{T}{d} = \frac{300 \; ft\text{-}lb}{4 \; in \; \frac{ft}{12 \; in}} = 900 \; lb$$

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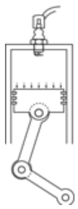
Example Problem 2-3: Force Pressure Relationship (cont'd)

• Analyze the cylinder:



$$F = PA$$

$$P = \frac{F}{A}$$

$$P = \frac{900\ lb}{\frac{\pi(2\ in)^2}{4}}$$

$$P = 286\ lb/in^2 = 286\ psi$$

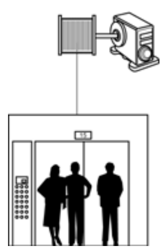
• What may be correct in our assumptions?
• Why is it likely that this value would be much higher in a typical engine?

Moments of Inertia and Section Modulus

- Properties of beams
- Moment of Inertia
- Section Modulus = $\frac{\text{Moment of Inertia}}{\text{Distance from the neutral axis}}$
- See Appendix 3 (p 469) for different sections

Problem 2-1

1. The elevator system shown has a combined weight for the car and occupants of 1,000 pounds. Ignore forces to accelerate the car and occupants.
   a. What is the force in the cable?
   b. To raise the car 150 feet, how much work was done?
   c. If it took 10 seconds to travel this distance, what power was required in ft-lb/sec, hp, and kilowatts?
   d. If the effective diameter of the cable drum is 18 inches, determine the torque in the input shaft.
   e. What is the rotational speed of this shaft?
   f. Calculate the power to turn this shaft, and compare this power to that determined above in part c.



Problem 2-1 (cont'd.)

a. Force in cable at rest: = 1000 lb

b. Work done, W = Fd
W = 1000 lb x 150 ft = 150,000 ft-lb

c. Power = $\frac{W}{t} = \frac{Fd}{t}$

$P = \frac{150{,}000\ \text{ft-lb}}{10s} = 15{,}000$ ft-lb/s

$P = 15{,}000\ \frac{\text{ft-lb}}{s}\ \frac{s\ hp}{550\ \text{ft-lb}}$

P = 27.3 hp

$P = 27.3\ hp\ .746\ \frac{kw}{hp} = 20.3\ kw$