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PULLEYS: MECHANICAL ADVANTAGES AND EFFICIENCY

OBJECT: To study and measure the ideal and actual mechanical advantages and the efficiencies of various combinations of pulleys.

METHOD: The applied forces required to lift a given load by various pulley combinations are measured and the actual mechanical advantages thus calculated. The corresponding ideal mechanical advantages are obtained from the geometrical configurations of the apparatus. The efficiencies are calculated from the ratio of the actual to the ideal mechanical advantages. An efficiency-load test is made of a completely threaded block and tackle.

THEORY: Combinations of pulleys provide very suitable apparatus for conveniently studying and measuring useful methods of transferring a force from one direction to another, for "multiplying" forces, for changing their relative speeds and for observing the efficiency of the transformation of energy involved. While with many machines it is possible to obtain a very large force from a small applied force and to do work in a more convenient and advantageous manner, it must be remembered that no machine can violate the fundamental law of the conservation of energy. If the machine makes it possible to overcome a large opposing force with a comparatively small applied force, it will always be found necessary to move the applied force a correspondingly larger distance than the opposing force moves. Hence in such cases it is necessary to keep clearly in mind the distinction between such important terms as force and work, work and power, and efficiency as opposed to mechanical advantage.

Work: Work is done when motion is produced against a resisting force. The measure of the work *W* which is done is given by the product of the applied force *F* and the displacement *s* produced in the direction of that force. In symbols

$$W = fs \tag{1}$$

Efficiency: The efficiency of a machine is the ratio of the useful work output of the machine to its total work input. This ratio is usually expressed as a percentage, in which case it is multiplied by 100, i.e.,

$$\text{Percentage efficiency} = \frac{\text{useful work output} \times 100}{\text{total work input}} \tag{2}$$

Notice that this definition is a ratio of *work,* and not of force. The limiting values of efficiency are from 0 to 1 or from 0 to 100 per cent.

Mechanical Advantage: The *mechanical advantage* of a machine should not be confused with its *efficiency*. Mechanical advantage is essentially a force ratio, while efficiency is a *work* ratio. It is helpful to consider both the actual and the ideal mechanical advantages of a machine. Actual mechanical advantage (A.M.A.) is defined as the ratio of the opposing or resisting force F_o to the applied force F_a. Symbolically

$$A.M.A. = F_o / F_a \tag{3}$$

The ideal, or theoretical, mechanical advantage (I.M.A.) of a machine would be the value of this ratio only in the ideal case where the machine was frictionless. For such an ideal case the work output of the machine would equal the work input or

$$F_o S = F_a s \tag{4}$$

where *S* represents the displacement of the opposing force and *s* the displacement of the applied force. From this equation it follows that

$$\frac{F_o}{F_a} = \frac{s}{S} \tag{5}$$

in the ideal case. The ratio *s/S*, the distance moved by the applied force to that moved by the opposing force, is called the ideal or theoretical mechanical advantage

$$I.M.A. = s / S \tag{6}$$

For any actual machine the work output is necessarily less than the work input and hence the actual mechanical advantage is always less than the ideal advantage. In the case of simple machines the ideal mechanical advantage may be expressed in terms of the geometrical constants of the machine.

It is evident that if each of the distances in Eq. (6) be divided by the time required to travel that distance, a ratio of the *velocity* of the applied force to the velocity of the opposing force would be obtained. Consequently the ideal mechanical advantage is also equal to the *velocity ratio* of the applied to the opposing forces.

Mechanical advantage should not be confused with efficiency. The limiting values of mechanical advantage range from zero to an infinitely large amount. Note that an advantage of 1 is very common and quite desirable in many cases and that an advantage of less than 1 is not a "disadvantage" but quite helpful in certain machines where a large velocity ratio is desired instead of a large force ratio.

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Fig. 1. Single fixed pulley

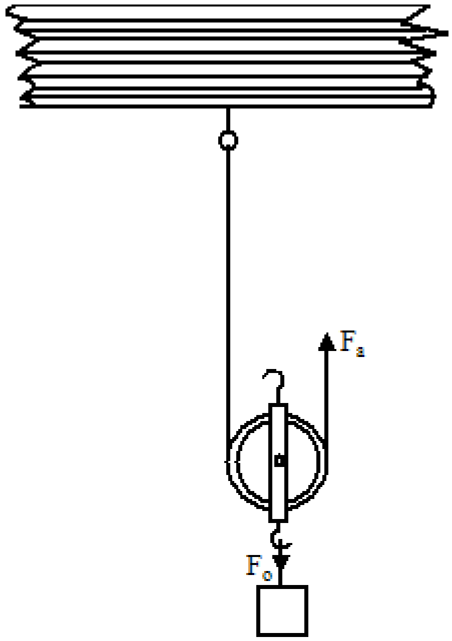

Fig. 2. Single movable pulley

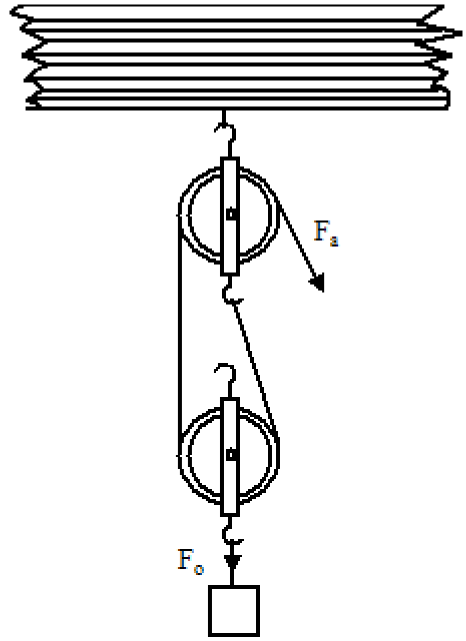

Fig. 3. One fixed and one movable pulley

Relation Between the Mechanical Advantages and Efficiency: From the definition of efficiency

$$Efficiency = \frac{workoutput}{workinput} = \frac{F_o S}{F_a s} = \frac{F_o}{F_a} \times \frac{S}{s} \qquad (7a)$$

This may be written

$$Efficiency = \frac{F_o}{F_a} \div \frac{s}{S} = \frac{A.M.A}{I.M.A} \qquad (7b)$$

This ratio is usually multiplied by 100 and thus expressed as a percentage.

The Mechanical Advantage of the Pulley and the Black and Tackle: The ideal mechanical advantage of the single fixed pulley, Fig. 1, is evidently 1, since the applied force and the opposing force must necessarily move the same distance. In the case of the single movable pulley, Fig. 2, the ideal mechanical advantage is 2, since twice as much slack would have to be taken up by the free rope on the right as the distance moved upward by the opposing force. In the case of a group of several fixed and movable pulleys constituting a simple block and tackle, as in Fig. 4, the ideal mechanical advantage is equal to the number of strands of rope supporting the *movable* block. That this is true in Fig. 4 is apparent from the fact that for each unit distance F_o is raised, each of the ropes, a, b, c and d will have unit distance of slack and hence F_a will have to be pulled a distance 4 units to take up all this slack.

APPARATUS: Two blocks of triple-tandem pulleys and cord to constitute a block and tackle (Fig. 5), a 2000g spring balance, a set of slotted masses (or masses with hooks) ranging from 2g to a total of 1000g, a suitable arrangement for supporting the pulleys, and two 50g mass holders are required.

PROCEDURE: 1. Using a single fixed pulley, attach a comparatively large load, say 1kg. Add enough force to the other side of the pulley to pull up the load, after it is once started, with uniform speed. Include the weights of the scale pans as a part of each force. Do not bother to adjust the "applied" force or load to more than a reasonable accuracy.
Calculate the actual mechanical advantage and compare it with the ideal mechanical advantage. Compute the efficiency.

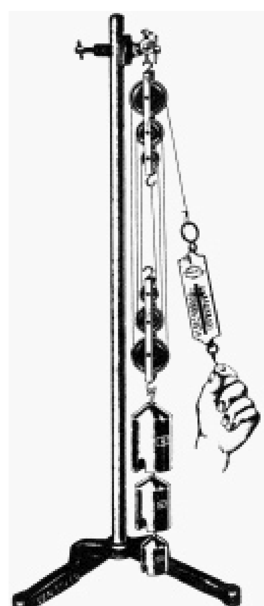

Fig. 5. Block and tackle

The data may be recorded as follows: (a) configuration of pulleys; (b) opposing force; (c) applied force; (d) actual mechanical advantage; (f) efficiency.

2. Repeat the observations using a single moveable pulley, as in Fig. 2. To measure F_a use a spring balance. Use the same load. Do not include the weight of the movable block as a part of the useful load.

Fig. 6. Single pulley

3. Repeat, using a single fixed and a single movable pulley, as in Fig. 3.

4. With the same load, use several other combinations of pulleys until the maximum number of ropes are utilized. Compare mechanical advantages and calculate efficiencies each time.

5. Using the pulleys completely threaded, take a series of observations with loads (including the scale pan, but not the movable block) ranging from zero up to values as large as conveniently possible. Compute the efficiency each time. How does the efficiency change with the load? Explain.

6. In the report, plot a curve showing the variation of efficiency with load. Carefully interpret this curve.

QUESTIONS: 1. Since the frictional force is directly proportional to the load lifted how ought the effects of friction to enter into the determination of the shape of the efficiency-load curve in this experiment?

2. Instead of measuring the applied force necessary to lift the load up, it would have been possible to use an applied force so adjusted that the load would move down with uniform speed. Prove the statement that the average of these two forces is the applied force which would be necessary to keep the opposing force in equilibrium if there were no friction.

3. Give the main reason why the efficiency of the single fixed pulley in this experiment is so much higher than that of the single movable pulley.

4. Given a block and tackle consisting of three pulleys each, threaded in the conventional manner so as to have an ideal mechanical advantage of 6, suppose that the positions of the opposing and applied forces are interchanged, i.e., the applied force acts on the movable pulley and the opposing force is attached to the free end of the rope formerly used for the applied force. What is the ideal mechanical advantage of the new arrangement? What are the relative velocity ratios of the two arrangements? How should their efficiencies compare?

5. Make a sketch of a block and tackle having (a) an ideal mechanical advantage of 5; (b) an advantage of ½.

Fig. 7. Double pulley