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NOTES ON THE EFFICIENCY OF LIFTING TACKLE.

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In the construction and repair of heavy machinery, such as marine engines, we are constantly obliged to use lifting appliances to carry out the work. The same, of course, could be said of all constructive work—but he did not propose here to treat either of the hodman who carried the bricks and mortar of a tall building on his shoulders up a series of inclines, nor of the fixed steam derrick which now so often did the work—but to confine his attention to such hand tackle as would be used in and about a workshop, or be supplied as part of the outfit accompanying a steamship's machinery, such as screw-jacks, blocks and tackle, etc. And by efficiency, he meant principally mechanical efficiency, or the proportion of useful work actually done by the machine to that exerted on it, though strength and handiness might also be referred to. Every one who has had to lift heavy weights in a limited space and with a limited staff of labour must often have observed that the output of such machines is very disappointing, even when in good condition, and that when they are in what is too often their condition, dirty, rusty, and either free from lubrication, or with the oil on them everywhere but where it is wanted, to call them efficient at all is really to take a liberty with language. In shops where the tackles, screw-jacks, etc., are in constant use, the economy of keeping them in good working condition is soon brought home to the management, but where the heavier tackles are only used at rare intervals, and out of sight and mind most of the time, as in a steamer's engine-room, they are often found wanting in some respects when needed, and though the work may be carried through in the long run, a quite unnecessary and incommensurate amount of energy, physical and spiritual, is expended and dissipated into heat in the operation.

As regards the theoretical mechanical advantage or "purchase" gained by lifting tackles, this is usually easily calculated from the velocity ratio of the receiving and delivering parts of the machine, the part where energy is impressed upon it, and that where it is expended upon the work to be done, but the knowledge so gained is only half knowledge without knowing the practical hindrances that discount it. He found, however, that even this theoretical advantage is a mystery to many engineers, who, no doubt, know well enough the practical use of such tackles, and that the study of applied mechanics, the very rudiments of an engineer's education, is too often neglected by those, for instance, who proposed to take out certificates of competency as marine engineers. It was this observation that led him to revise his own studies on the subject, and to bring it before this Association in the hope of getting some useful hints for his own benefit, and to show that the unknown quantities which we so easily neglect on paper, are of supreme importance—the knowledge of elementary theory must be supplemented by practical experiment if it is to be of any use to us. The simplest lifting machines, if we may call them so, are the lever and the wedge. The lever, in its simplest form, that of the pinch or crow-bar, has the unique advantage of being almost frictionless, its motion on its fulcrum being usually a rolling one, and when this fulcrum or heel and the bar itself were rigid, and the bar balanced, all the work put in at one end of the arrangement is returned at the other, in other words, its efficiency is 100 per cent. But this very rolling, unless on a knife edge as in a weighing machine, introduces a complication in the calculation of the mechanical advantage or purchase gained. Take, for instance, an ordinary crowbar lifting a weight—here the purchase was the ratio of the weight lifted to the vertical effort on the long arm of the lever, and is inversely proportional to the horizontal projections of the arms—but as soon as movement takes place, owing to change of position of the fulcrum by the curved knee of the bar rolling on its support, the ratio was altered, though the efficiency remained the same, and to calculate the rate at which the purchase varied would require considerable mathematical skill. He mentioned this to show what food for thought we have even in the simplest mechanism. Another matter for thought is, why do we gain any effect by using a lever? We usually say, "Because of the leverage," like the texicographer's famous definition of an archdeacon—a clergyman who exercises archdeaconal functions—involving the expression without in any way enlightening us. It is because of the great fundamental principle of all machinery that the energy developed, or work done, is exactly equal to that introduced or impressed upon the machine, and if none is lost in internal work or friction, we retained the same output as we put in. It is difficult to convince "the man in the street," he did not say the engineer, of course, that mechanical work, that is the energy which is measured by the product of pressure and motion, was a real entity, and not a mere convention; while pressure and motion by themselves were but mere ideas, of no objective reality until they are combined. The pressure in a boiler under hydraulic test may seem a very real thing—but it does not produce a motion in the molecules of the metal—if the stress does not produce a strain, it was a mere philosophical motion. The term "pressure" is certainly a useful one, and one we could ill afford to do without, but it can only be defined as a "tendency," and is only apparent to us through the motions it produces. But the product of the stress and the strain is work, and this is what tries the boiler under test. To the practical man this might seem a mere philosophical notion itself, but the so-called practical man has often a lot to learn, he found. Well, then, if a loaded lever like a scale-beam or a steel yard is, in equilibrium, it is because the same amount of work would have to be expended in raising either end of the system, and there being nothing to determine the bar to move either way, it necessarily stands still. As we say, the '.moment" round the fulcrum of either weight is the same, but this word "moment" is just a convenient expression that explains nothing. To move the bar some external work must be done on it and set it oscillating; and then, too, at any instant, the kinetic energy accumulated in the moving weights is equal to the work so impressed, less that expended in friction at the points of suspension and in agitating the surrounding air, which gradually converts the energy of work into that of heat, and brings the bar to rest again. The same thing holds for all machines—the sum of the external or useful work done, and that done internally, as in overcoming friction, or being stored up in springs, or accumulated in moving masses, must equal the work put into it. When a lever is hung in bearings, like the pump levers of an engine, the effect of sliding friction occurs at once, and the efficiency is necessarily less than when rocking on a knife edge or rolling on a curved surface. The work so lost is proportional to the radius of the gudgeon, and to the sum of the pressures on the ends of the lever and also that due to its own weight. Consequently, if this sum be a large one, though the effort needed to balance the weight may be very small, the friction may be very considerable, and the efficiency much impaired. This fact, that the friction is usually a function, not of the effort only, but of the effort and resistance combined, is what makes the necessary effort in practice so much greater than what theory leads us to expect, the fact being, of course, that we use an incomplete theory, and one that neglects indispensible facts.

Another apparently simple appliance for lifting weights or applying energy, is the wedge, but in its primitive form it is used in conjunction with the hammer or maul, and the combination leads us at once into quite another field, where percussive action, elasticity, and dynamic forces that almost defy calculation, come into action. The wedge, actuated by simple pressure, is useful sometimes, as for producing an easily graduated motion of slight extent, but the linear motion of a fine wedge being so great in proportion to its useful component, and the frictional resistance bearing a definite ratio, usually a large one, to the whole weight lifted, and acting over the whole travel of the wedge, it may, and often does, form nearly the whole of the resistance to motion, and leaves the efficiency low indeed. Suppose, for instance, we try to lift a weight by a dead pressure on a wooden edge inserted between two surfaces of wood. The co-efficient of friction may be as much as .5, corresponding to an "angle or repose" of 30 deg., and both sides of the wedge encounter this resistance, making it equal to unity, so that simply to move the wedge requires greater effort than to lift the weight through an equivalent distance directly. The useful work is that due to the taper of the wedge, but a vast amount of dead work has to be done before it takes effect. If the taper be 1 in 10, the work necessary to lift W lbs. 1 foot, is practically, with the above amount of friction, 10 W + W = 11 W foot-lbs, so that $\frac{10}{11}$ of the whole work is lost, and the efficiency is only $\frac{1}{11}$th or 9%. This is sometimes expressed by saying "Counter-efficiency" is 11, i.e., 11 times the useful work must be expended in the operation. The effort required, or pressure on the end of the wedge, instead of being $\frac{1}{10}$ W, is now 1 $\frac{1}{10}$, and there is no mechanical advantage whatever. In practice, where the wedge would be driven with a hammer, its elasticity and compression and the ensuing vibration, would lessen the frictional resistance indefinitely, and the effort driving it would be accumulated work in the hammer head, which is a different thing from a dead pressure. The hammer must remain in contact with the wedge for some definite time after impact, during which it is, as we say, giving up its momentum to it, but the total work done by the wedge, useful and frictional, must equal that stored in the hammer in its descent. It is a common error to reckon the force of a blow as a pressure, and to confound kinetic energy and weight—if a body falls—if a poor fellow jumps from the top of a burning building 150 feet high— the "man in the street" starts inquiring how much his weight was multiplied by the fall, and some scientists profess to give him an answer. The momentum which is a mere mathematical ratio, of no objective meaning, is what they mean, but the accumulated work, due to the distance fallen is the real factor in the case. The wedge, by itself, then, is not of much consequence as a lifting machine, but is only a convenient mode of applying the output of some other mechanism or store of energy through. We coil our wedge or inclined surface on a mandril, and make a screw of it, turning in a nut, but still the screw without a lever would be a poor affair, so we apply a "tommy" bar to the head of the screw to give the effort a greater radius of action, and have the screw-jack. The theoretical advantage or power gained, as we say, by this machine, can be calculated from the ratio of the pitch of screw to the circumference described by the end of the lever, but the efficiency depends on the frictional resistance; and is seldom more than 25 per cent.—that is, the actual pressure on the lever is about 4 times or more than that which is theoretically necessary; and the rubbing surfaces may even seize and set fast, when the efficiency would of course be nil. To measure this frictional resistance and elaborate a formula for it, a comprehensive series of careful experiments would be necessary—but assuming that the ordinary laws of friction are applicable, let us see what we can do with the data at hand. Let us take a screw of $\frac{1}{2}$ in. pitch, square thread, outside diameter $2\frac{1}{8}$ inch and $1\frac{7}{8}$ inch at bottom of thread, so that its mean radius is 1 inch, worked by a lever 20 in. long, and carrying a weight of 2,000 lbs. on cap with an annular bearing on top of screw of 4 square inches area, and also a mean radius of 1 in., which would correspond to outside and inside diameter of about $2\frac{5}{8}$ in. and $1\frac{5}{16}$. in. The weight produces a frictional resistance both at the thread and at the cap bearing. The intensity of pressure at the cap will be 2000/4, equal to 500 lbs. per sq. inch, which is not too high at slow speeds to altogether squeeze out a lubricant of good body, so we may take the co-efficient of friction as $1\frac{1}{10}$—Rankine quotes .08 or $\frac{1}{12}$ as the co efficient for smooth surfaces lubricated. We shall take the co-efficient at the thread to be the same, the bearing area is usually much greater here than at the cap, owing to the pressure being spread over several convolutions of the thread at once, and the lubrication should be at least as good. The frictional resistance at the cap will then be 2000/10 = 200 lbs., and it acts through a space of $2\frac{\pi}{1}$ inches, or 6.2832 inches = .5236 foot. So the foot lbs. work lost here in one revolution will be 200 × .5236 = 104 72. At the thread there is a greater pressure than at the cap owing to its carrying the weight of the screw also, but we may neglect that at present. There is, however, a greater normal pressure between the surfaces than that due to the direct weight, because there is also a turning effort or tendency to run down, which friction resists, and the normal pressure is the resultant of that and of the weight. This normal pressure bears the same proportion to the weight as the length of one turn of the thread does to its projected circle's circumference. With a fine thread the difference is not much—in this case the two lengths are 6.303 inches and 6.2832 inches, and the pressure on the thread is $2000 \times \frac{6.303}{6.2832} = 2006$ lbs. Then $\frac{1}{10}$ of this, or 200 6 lbs. is the frictional resistance here, and the distance it is overcome through in one revolution being 6 303″ or 525 foot, the product 105.3 foot lbs. is the work absorbed at the thread, if we suppose the effort applied parallel to the surfaces in contact, but as it is applied perpendicular to the axis and at an angle with these surfaces, some of the effort goes to increase the normal pressure between them still further. We may arrive at the true amount by graphic construction or trigonometrical calculation, but with fine pitched screws the slight excess may be neglected Hence the combined frictional loss at thread and cap is 105.3 + 104.7 or 210 foot lbs. per revolution. The useful work is 2000 lbs. lifted ½" equal to 83.3 foot lbs., and the total work impressed on lever in one revolution is therefore 293 ft. lbs. The circumference of circle described by end of lever being 10.47 feet, we would need an effort of 293 10.47, equal to 28 lbs., to move the weight, which 83.3 10.47, equal a little under 8 lbs., would have done had there been no friction, and the efficiency is $\frac{83.3 \times 100}{293.3}$ = about 28 per cent.

The co-efficient of friction is the tangent of the angle of repose of the surfaces, or that angle with the horizon at which sliding would begin under the influence of gravity only. To get the true effort to overcome the friction of the thread and lift the weight, we take it as proportional to the tangent of the sum of the two angles —the pitch angle or that made by the thread with a line perpendicular to the axis—and the angle of repose. In the above case the pitch angle is 4 deg. 33 min., for the tangement of that angle is $\frac{\cdot 5}{6.2832}$ pitch divided by circumference = .07958, while the angle of repose is that whose tangement is .1, and is 5 deg. 42 min., the sum of these angles is 10 deg. 15 min., whose tangent is .18083, only slightly in excess of the sum of the tangents themselves at these small angles. This number, then, is the ratio of effort to weight if applied at radius of screw thread, or 1 inch, and if applied with a lever 20in. long, it will be proportionately reduced to 1.8083/20 – .009. With a load of 2000 lbs, this gives us 18lbs. as effort needed. The cap resistance being calculated and added as before brings up the effort to 28lbs.

The efficiency of the screw-jack, neglecting for the present the cap friction, that is, supposing the weight to revolve with the screw, as when one sits on a screw-up music stool and spins it round and up, is, if we call the angle of pitch m, and that of repose n, equal to $\frac{\tan m.}{\tan.(m \times n)}$ equal in the above case to $\frac{.07958}{.18083} = 44$ per cent.; with fine pitches and good lubrication this does not differ materially from $\frac{\tan.m}{\tan.(m+n)}$ but with coarse pitch or much friction it would greatly fall short of it. For instance, if the pitch angle was 45deg., that is, if the pitch was equal to 3.1416 times the diameter, and the co-efficient was $\frac{1}{10}$ as before, the sum of the tangents would be 1.1, but the tangent of the sum, 50deg. 42min., would be 1.222, and the efficiency would not be $\frac{1}{1.1}$ or 90 per cent, but $\frac{1}{1.222}$ or 82 per cent.

Here we see the efficiency is much greater than with the fine pitch, but there is no mechanical advantage gained by the screw itself, though there would be some "purchase" from the lever used to turn it. Screws of this long pitch are not, of course, used in screw-jacks, but occasionally are in mechanism, the common twist brace for drilling small holes being an instance. Thus we see nearly three-fourths of the effort and work done is lost in a fairly lubricated, not over-loaded jack; how much more must be when the oil is absent, and the pressure possibly concentrated on one edge of the thread or cap, making it seize and abrade, instead of sliding! If the thread is triangular in section the friction is much increased, the normal pressure between the surfaces being increased as the slant side of the thread section is to the depth of it. In the Whitworth thread the slant is about 1⅛ the depth, so the friction is increased about 13 per cent. over what a square thread would give, and the efficiency correspondingly lowered. The greater strength of the section is some compensation for this, but the "buttress" thread as formerly used in the breech blocks of big guns would be as strong as the ordinary shape, and have no more friction than the square thread; of course, it could be used for screws that overcome resistance in one direction only. I say "formerly used," for I notice modern breech-loaders have the ordinary isosecles triangular thread. Whitworth's early breech blocks had not only a buttress thread, but the face of it was undercut, so that it tended to bind the breech together under the pressure of firing instead of to burst it, as with the ordinary form, but this has been given up, owing, I presume, to its greater liability to jamb. The great loss of efficiency by friction is not without some compensation--it effectually prevents the weight overhauling the screw or running down of itself. If the efficiency is more than 50 per cent. this may occur, and some constant pressure on the turning bar be necessary to prevent it, when the weight was not being lifted. So it gives us a very efficient brake, but at an unreasonable expense. The efficiency is about the maximum when