Hysteresis for Rubber

Hysteresis is the failure of a material to expand and contract in the same way: that is, to follow the same path for expansion and contraction on a force/displacement graph. Work, by definition, is the force/displacement integral (the area under a data plot on a force/displacement graph). The difference in the integrals for expansion and contraction (the area of a loop on the graph) is the heat in joules generated per cycle in the material. The most common examples of this behavior involve rubber and similar polymers. For instance, tires become warm when driven on the road. The heat is not generated by friction, but is due to hysteresis in the rubber as it flexes (becomes momentarily flat on the road). The drag due to this conversion of kinetic energy to heat is described as rolling resistance.

Demonstrations

1 Extension/contraction cycles for rubber bands

A basketball is suspended from a force probe on a rubber bungee made by linking rubber bans as shown in the inset.

Fig 1 – a basketball hangs from a force probe (not shown) on a rubber-band bungee above a motion detector.

A force-extension graph for the rubber bands and a velocity-time graph for the ball are plotted at the same time. The red lines show the hysteresis loops on the force extension plot and the inset shows the damping of the motion.

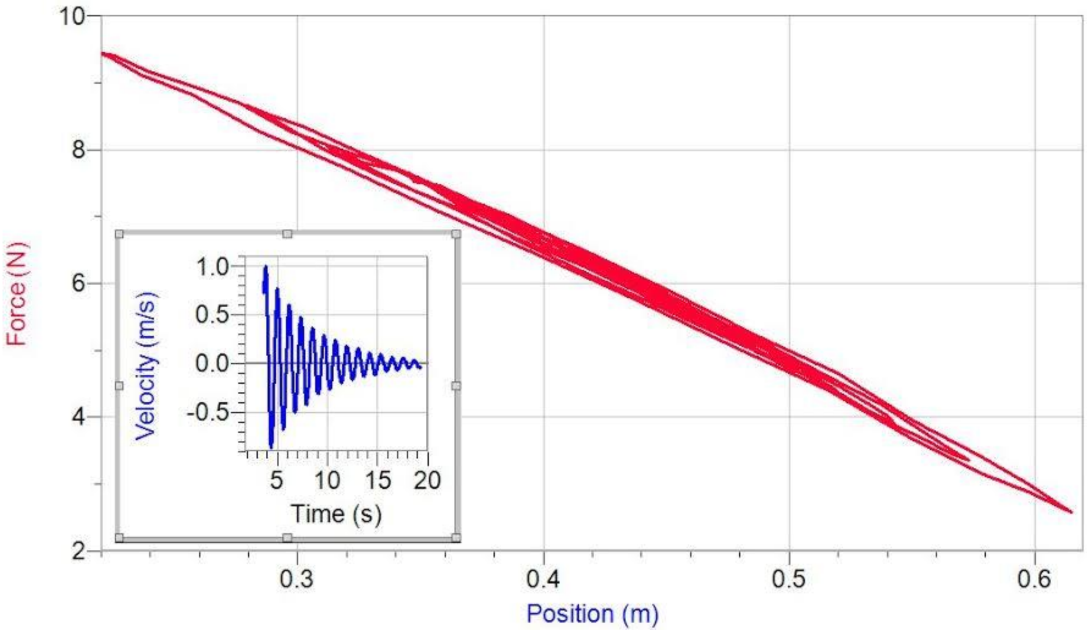

Fig 2 – loops on the force/extension plot and the velocity of the ball.

Successive loops may be separated by copying data points to new manual columns or by striking through unwanted data. The result for the first four loops are compiled in figure 3 below.

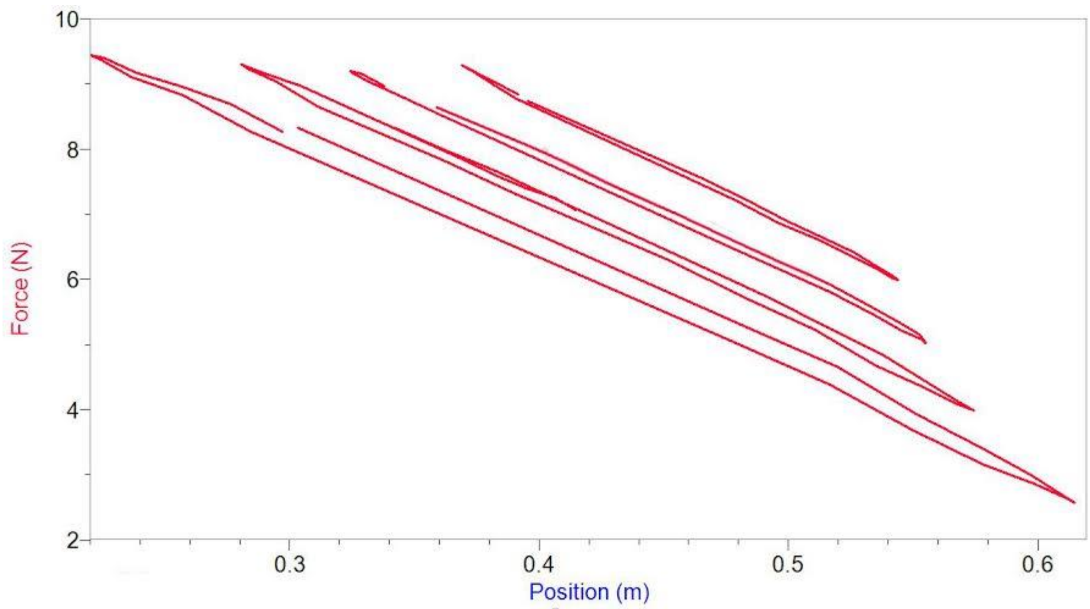

Fig 3 – the first four loops on the force/extension plot.

Calculating the kinetic energy of the ball that has a mass of 0.61 kg as a function of time gives the plot below.

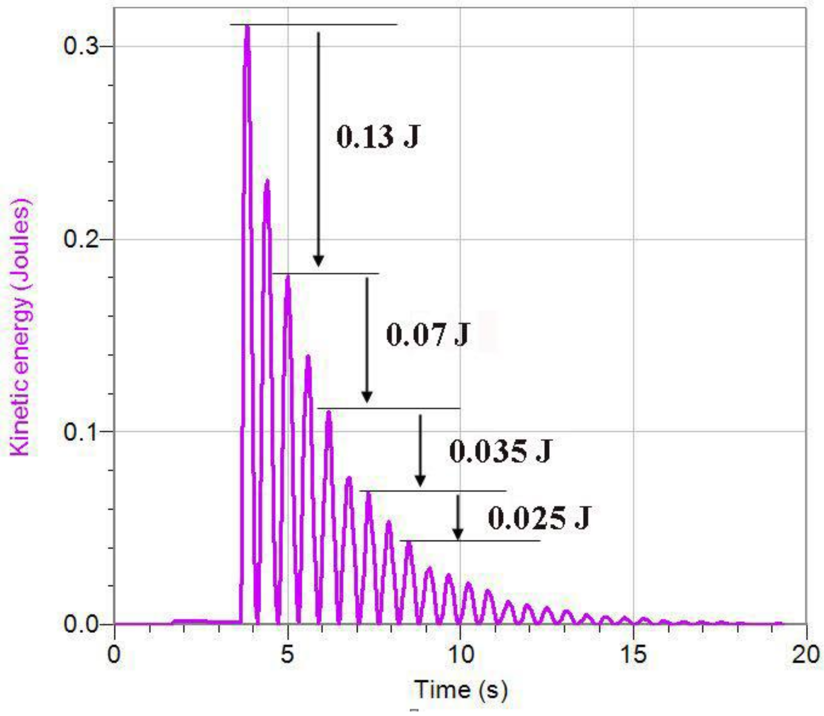

Fig 4 – the kinetic energy of the oscillating ball as a function of time.

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The energy loss per cycle is shown in figure 4 for the first four cycles.

The integration function of Logger pro could be used to find the area of each loop in figure 3 but the function must be applied carefully with the subtraction of an unwanted rectangle. A more convenient demonstration is provided by rotating the loops with a calculated column auto-scaling the new graphs and counting squares.

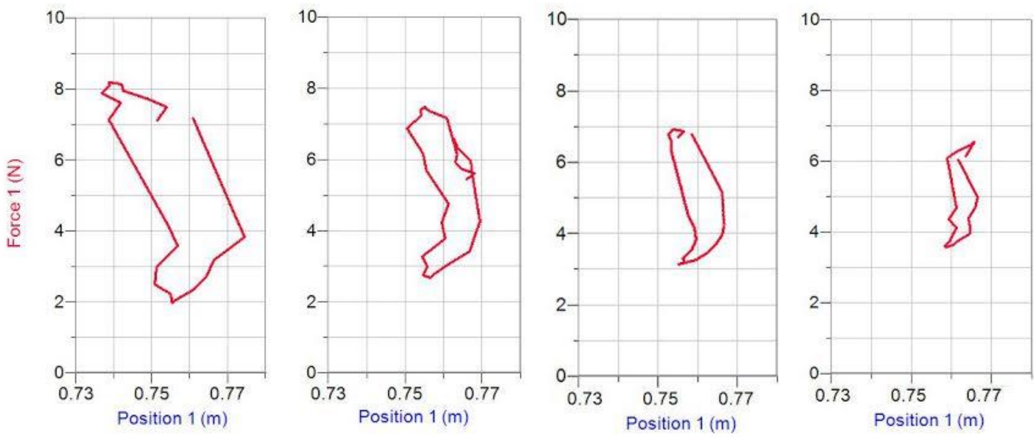

Fig 5 – the areas of the loops can be estimated in joules.

Note: the loops in figure 5 are irregular because the ball may not have been oscillation exactly vertically and the data rate for position detection is limited to less than 20 data points per second. The area estimates are at the limit of the accuracy of the Vernier detection equipment.

(If more position data points had been available my preferred method for demonstration would have been to print figure 5 … cut out the loops and weigh the paper, but no advantage over counting squares would be obtained in this case by this method.)

The approximate loop areas are … 0.10 J … 0.08 J … 0.035 J and … 0.025 J. Comparing these estimates of energy conversion to heat with the kinetic energy loss per cycle (figure 4) … 0.13 J … 0.07 J … 0.035 J and …0.025 J shows that the two sets of values are the same to a first approximation.

Projects

1 Design modified apparatus and/or data collection methods to improve the accuracy of similar measurements.

2 Design experiments to determine the small (but perhaps significant) contribution to damping made by air resistance when using a large standard basketball in this application.

2 Compression/relaxation cycles for rubber balls

The 0.80 kg metal bar with four 200 gram weights at the end in figure 6 is pivoted (under an overhang) at the left hand end. It rests on a rubber ball. A motion detector is above the right hand end of the bar as shown.

Fig 6 – a weighted metal lever rests on a rubber ball.

The rubber ball in figure 6 rests on a force plate improvised with three force probes (figure 7 below).

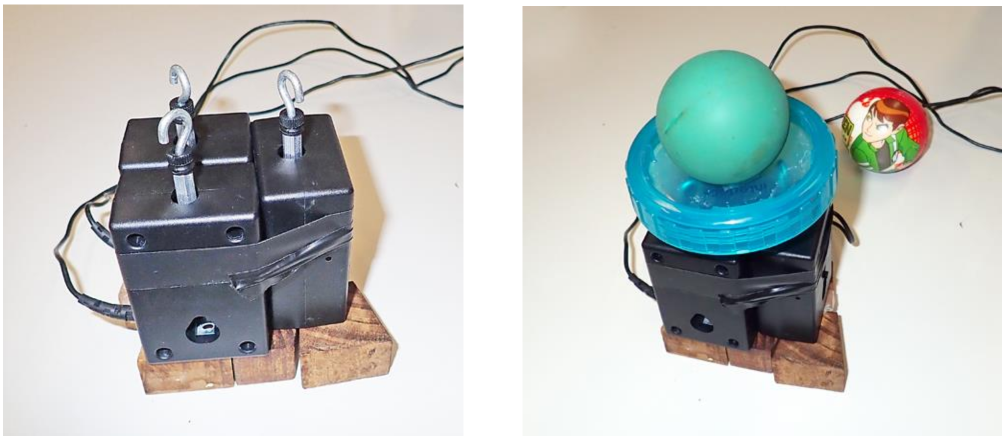

Fig 7 – three force probes on the left and the force plate on the right.

The bar in figure 6 is set in oscillation. A force/displacement plot and a velocity-time plot are shown below for a racquet ball.

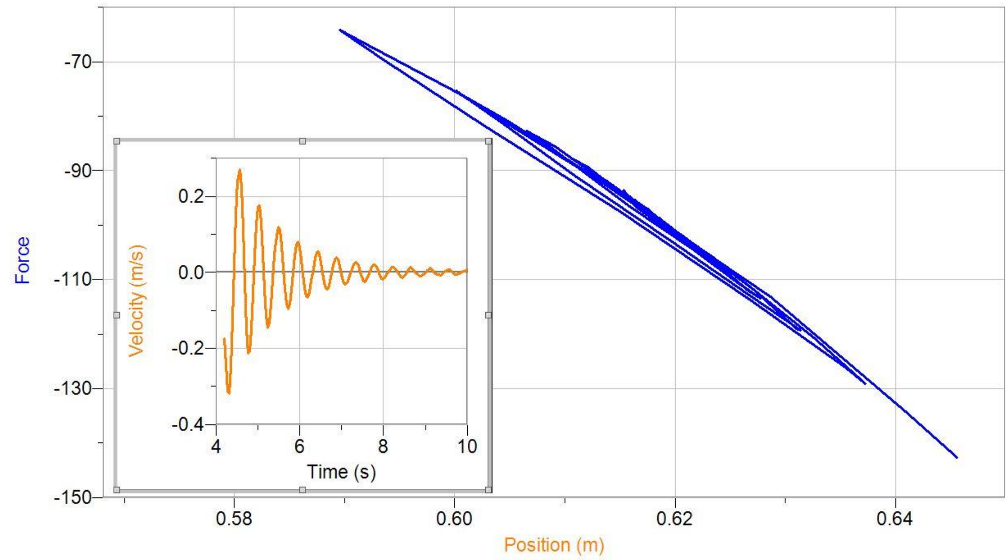

Fig 8 – the oscillation of the bar when resting on a racquet ball.

Note: the energy of motion on this case must be calculated as half the moment of inertia of the bar multiplied by the angular velocity squared. The moment of inertia can be approximated as that of a uniform 0.80 kg bar pivoted about one end with an added mass of 0.80 kg.

It is left as an exercise to take measurements from figure 6 and make an estimate of the moment of inertia. The length of the bar is 120 cm.

The racquet ball is replaced with a soft solid rubber ball. The damping of the motion is increased (figure 9).

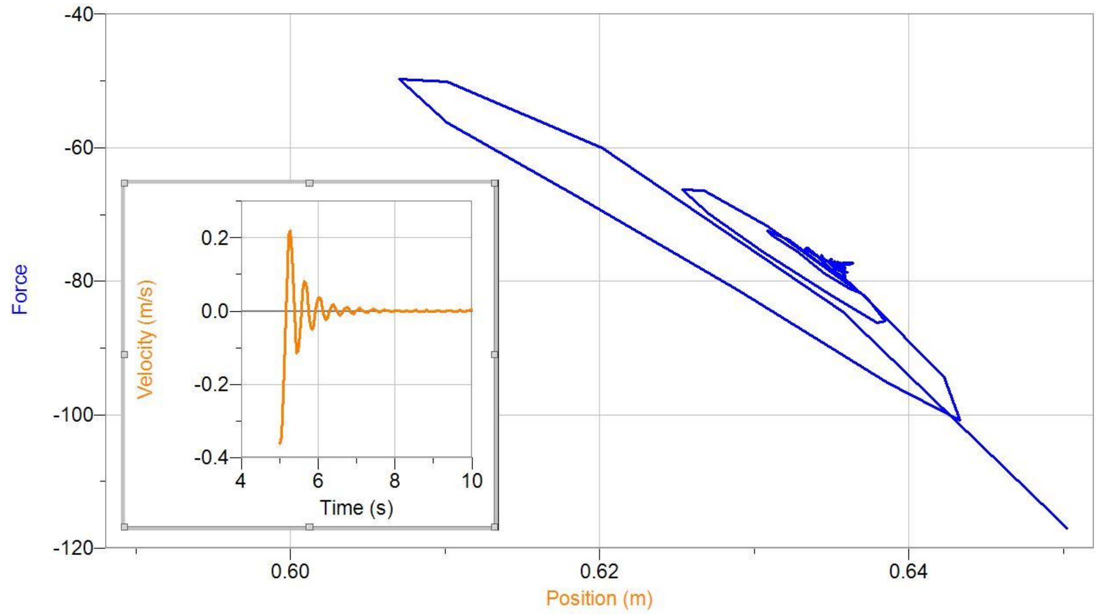

Fig 9 – the oscillation of the bar when resting on a soft solid rubber ball.

Figure 9 should be compared carefully with figure 8.

Note the similar initial velocities in both insets which implies similar initial angular kinetic energies. Note the greatly increased damping in the inset of figure 9 and both the larger area of the initial loop and the greater percentage reduction in area of the subsequent loops. These observations are consistent with the damping being provided by hysteresis in the balls.

It is left as an exercise to make estimates of the loop areas in joules in figure 9 and to estimate of the angular kinetic energy loss over each of the first two cycles using the moment of inertia of the bar and values of the angular velocities.

3 Rolling resistance

Fig 10 – two black rubber balls rest on a flat metal track.

The balls in figure 10 are made from different rubbers: one with low hysteresis that bounces to about 70% of its initial height when dropped on tiles, and the other that bounces very little if at all. The details are on the web. Search for *Sad and Happy balls.* If the track is inclined slightly and the balls are released from rest at the same time the happy ball (with low hysteresis) reaches the bottom well before the sad ball (with high hysteresis).

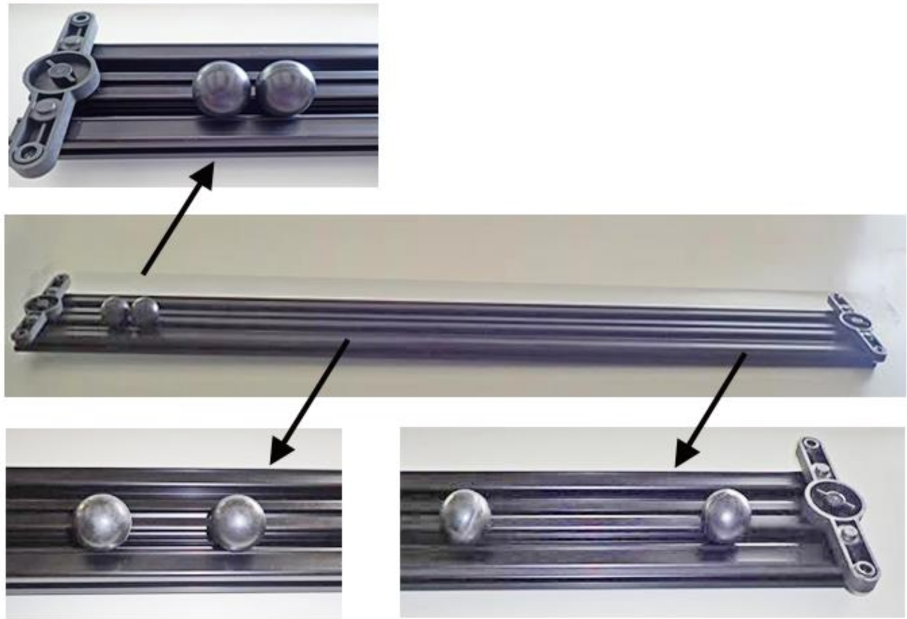

Fig 11 – the sad ball rolls more slowly.

Rolling resistance is greater for the high hysteresis ball. The same effect is seen for the two balls used in demonstration 2 above.

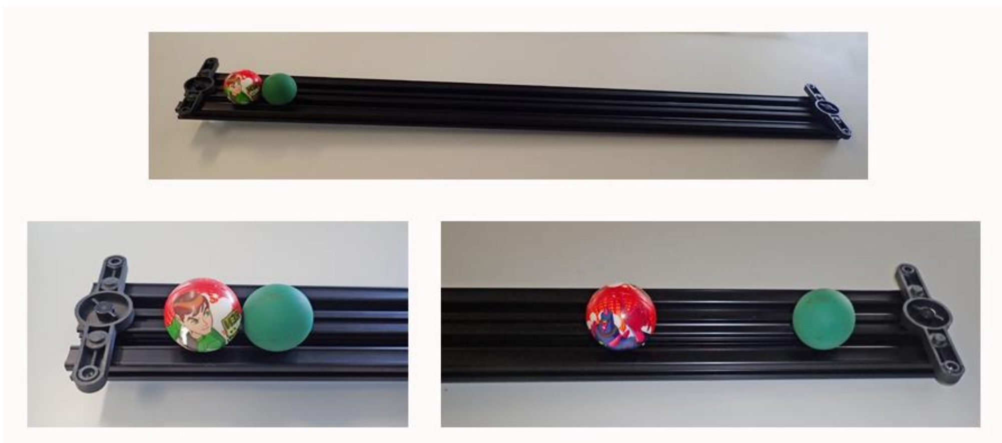

Fig 12 – rolling resistance is again greater for the high hysteresis ball.

Note that in this case the effect of hysteresis is large enough to mask the effect of mass distribution. The racquet ball is hollow and would roll more slowly than the solid ball if both were made from the same rubber. For more on rolling resistance see Rolling Resistance [pdf].