Crawler Power Tests and Analysis

- Where does the crawler power go?
- How can we choose an ideal motor speed and transmission ratio for efficiency?
- How can we measure force, power, speed to determine what we want to know?

The basic flow of power is shown in Fig. 1.

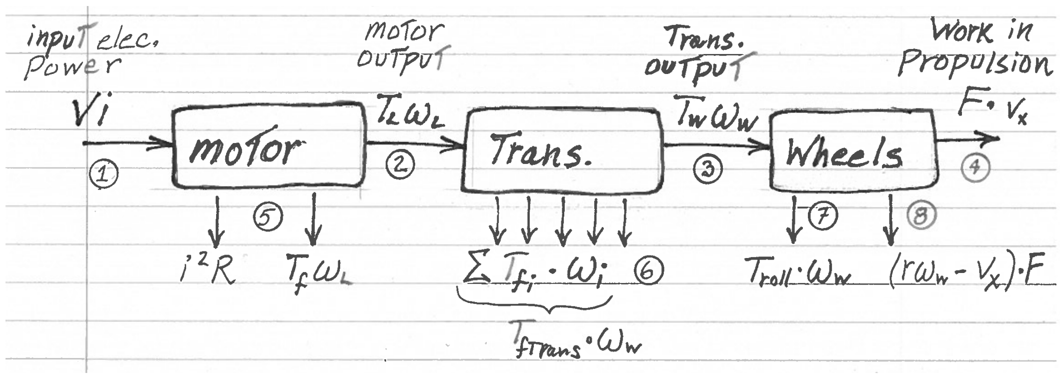

Figure 1: Schematic of power flow in a motorized crawler. Circled numbers match notes in text.

The general case

1. Input power is just Vi. A power supply and ammeter are set up to measure voltage across the motor and current through the motor.

2. Using the procedure from Assignment 4, we measure i_s and i_{nl} and ω_{nl} at several different voltages and use these measurements and the Week 3 motor equations to determine the torque constant, k, resistance, R, and friction torque, T_f that describe the motor. Knowing these, we can compute the output torque T_L (with T_f subtracted) and velocity ω_L of the motor for any voltage. And we can see if we are near the current and speed (i_η, ω_η) associated with maximum efficiency.

3. The input to the transmission is $T_L\omega_L$ and the output is $T_w\omega_w$ where the total speed ratio of the transmission is $N = \omega_L/\omega_w$. Due to power loss, $T_w < NT_L$.

4. The input to the wheels is the torque and speed applied to the drive axle(s). The "useful work" is the work required to propel the vehicle along the track. In terms of power, $P_{out} = Fv_x$. In theory, F is the force required for propulsion if there were no rolling resistance.

5. Motor power is lost partly due to the coil resistance and partly due to the friction torque. (See Week 3 motor notes.)

6. Power is lost at each transmission stage due to gears and bearings (Lego "bearings" are just shafts spinning in holes, so they're not especially efficient). It is convenient to lump the losses together as $T_{ftrans}\omega_w$. Note that the friction forces will tend to be proportional to the total forces and loads. So $T_{ftrans}\omega_w$ will tend to be a constant percentage of $T_w\omega_w$.

7. Rolling resistance is probably significant with high-traction tires.

8. A second source of lost energy is slippage. Unlike gears, the wheels slip so $v_x < r_w \omega_w$.

9. The system efficiency is $\eta = \eta_{motor}\eta_{trans}\eta_{wheels}$ and it should not be surprising if the total efficiency is $< 15\%$.

The special case for our Lego motors in 2014

As it happens, this year's Lego motors have their own little gearbox incorporated inside the motor unit. The situation is as shown in Fig. 2. We can measure V, i and ω_L directly. Given the known N:1 speed ratio, we have $\omega_m = N\omega_L$.

1. We solve for R as usual, using $V - i_s R = 0$ at stall, and plotting points at a few voltages, as in Assignment 4.

2. When the motor is spinning, $V - iR - kN\omega_L = 0$. Thus, by measuring V, i and ω_L, and knowing R from the measurements above, we can solve for k. We can do this at no-load, trying several voltages for a good estimate.

3. The torque balance is: $N(ki - T_{fm}) - T_{fg} = T_L$

4. At no load, $T_L = 0$ so $Nki_{nl} = T_{fg} + NT_{fm}$. We can lump the right hand side together as $T_{fL} \equiv T_g + NT_{fm}$ where $T_{fL}\omega_L$ represents the total mechanical power loss in the motor with its gearbox. We can't really tell how much of this comes from T_{fg} versus T_{fm} and it doesn't matter because they are always together.

5. At this point, we can compute things like peak power and peak efficiency in the usual way, using V, R, k and T_{fL}. As before, $i_s = V/R$ and now $i_{nl} = T_{fL}/(Nk)$.

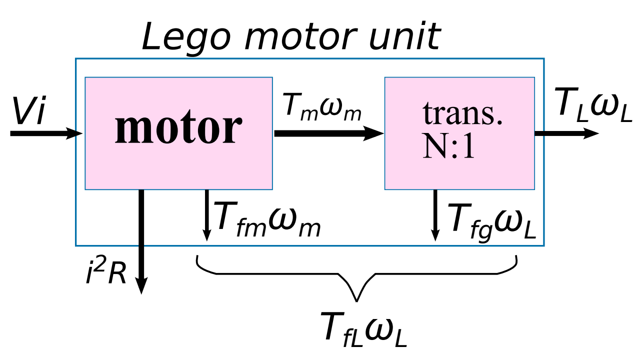

Figure 2: Schematic of Lego motor unit, showing the quantities for the motor and the small gearbox inside.

Testing Tips

1. Watch on the power supply whether the "current limit" light comes on – this means that the power supply cannot deliver as much current as desired at the desired voltage. Probably you are too close to stalling.

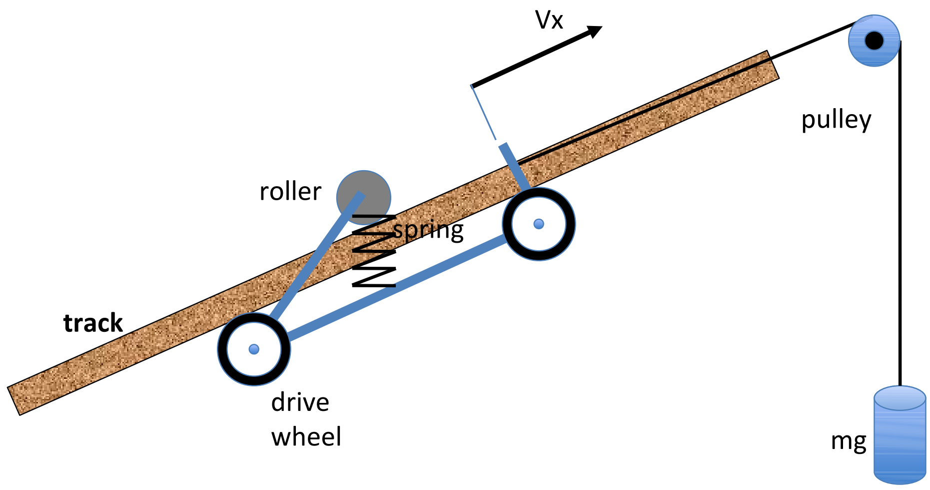

Figure 3: Measuring F and v_x on the track

2. You can measure v_x using the stopwatch function on your cell phone to get the time required to travel 1m in the channel.

3. Getting an estimate of F is a bit trickier (Fig. 3). Using a pulley and weights, you can estimate $F_{total} = F + F_{roll}$ where $F_{roll} = T_{roll}/r_w$. Add or remove sand from the container until the string just pulls your vehicle along, without accelerating. Use the digital scale to find out what the weight is. A subtle point, however, is that the force required to *pull* a vehicle through the channel may be slightly different (probably lower) than the force required to *drive* it.

4. Once you've measured v_x, since you also know ω_L and ω_w from your motor information and speed ratio, you can estimate $v_{slip} = r_w\omega_w - v_x$.

Design Tips

1. Larger wheels will have a proportionately smaller rolling friction and slippage, especially over bumps.

2. Precise, well-braced Lego construction will go a long way to increasing efficiency and reliability of the transmission. If shafts are overloaded and bending, they will also have a lot more friction.

3. A little lubrication helps, but be careful you don't get carried away and make all your Legos unsnap. WD40 is not a good lubricant; it's a solvent and only lasts a short while. Vaseline is good (but watch for getting dirt in it). Graphite (e.g., as used for locks) is a pretty good lubricant and less likely to trap dirt. Excess lubricants tend to un-snap Legos.

4. Rubber bands do not make good belt drives. They slip too much and the work done in stretching and unstretching as they go around the small pulley greatly reduces the efficiency.

More...

Additional tips and notes are collected and updated as we discover new things for 2014 at

- http://bdml.stanford.edu/Main/CrawlersProject2014.

Power Loss Assessment

From Fig. 1, the power out of the transmission is $T_w \omega_w$. It goes into 3 activities:

- "useful work": $f_x v_x$, where $f_x = mgsin(\theta)$ – This is the work required to go up the slope.
- rolling loss: $T_{roll}\omega_{roll}$ – These are rolling losses (significant with soft tires).
- slippage: $v_{slip}F_{slip}$, where $v_{slip} = r_w\omega_w - v_x$ and v_x is the measured forward velocity.

What are T_{roll} and F_{slip}?

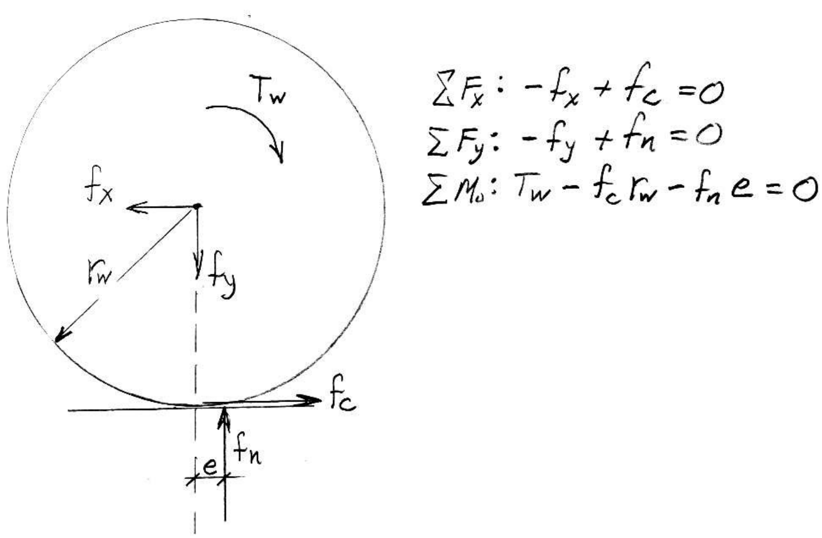

Figure 4: Wheel free body diagram. In our example, $f_x = mgsin(\theta)$.

A standard way to define rolling resistance is with the diagram in Fig. 4. Due to rolling resistance, the centroid of the pressure distribution under the wheel is not at the centerline, but is slightly ahead of it, by an amount e (for *eccentricity*). So $T_{roll} = f_n e$. The power loss associated with this rolling resistance $P_{roll} = T_{roll}\omega_w$ because the wheel is instantaneously rotating with angular velocity ω_w about the contact. Now, if we define F_{roll} as the equivalent force needed to pull a cart along a horizontal surface when the only resistance is due to rolling, then by definition: $F_{roll} = T_{roll}/r_w$ and $v_{roll} = r_w\omega_w$.

Meanwhile, the slippage power loss is given by $f_c v_{slip} = f_x(r_w\omega_w - v_x)$.

The total losses are therefore: $P = F_{roll}r_w\omega_w + f_x(r_w\omega_w - v_x)$.

However, when we do the pulley test (Fig. 3) we define things a bit differently. We say that the "rolling resistance" is the force required to drag the vehicle along the channel (with $mgsin(\theta)$ subracted). The rolling power loss is therefore $P_{roll} = F_{roll}v_x$. Then we say that the slippage loss is $P_{slip} = (r_w\omega_w - v_x)F_{slip}$ where $F_{slip} = f_x + F_{roll}$. The total power loss is therefore $P =$

$F_{roll}v_x + (f_x + F_{roll})(r_w\omega_w - v_x)$ or, $P = f_x(r_w\omega_w - v_x) + F_{roll}r_w\omega_w$, which is the same result as above. So we are using a slightly different definition of $F_{roll}v_{roll}$ and compensating with a correspondingly slightly different definition of F_{slip}.