Conversion of Units – Factor Label Method

Introduction

Units give a common standard that we can compare things to. For example if you were told that a cat is 12 long you wouldn't know how long the cat was unless the term "inches" was used with the number 12. Scientists need to be able to express quantities of weight, distance, time, etc. in common units. Sometimes they need to be able to express things in smaller or larger families of units, like converting between centimeters and meters, and other times they have to be able to convert from English to metric, from inches to meters.

Examples of expressions of "1"

$$\frac{60\text{ sec}}{1\text{ min}} = \frac{1\text{ min}}{60\text{ sec}}$$

$$\frac{16\text{ oz}}{1\text{ lb}} = \frac{1\text{ lb}}{16\text{ oz}}$$

$$\frac{1\text{ in}}{2.54\text{ cm}} = \frac{2.54\text{ cm}}{1\text{ in}}$$

A method of accomplishing conversion of units is known as "Factor Label Method." The fundamental principle at work here is "cancellation of units." This is accomplished by multiplying by an expression equal to a unit that accomplishes a cancellation. In math you've learned that multiplying by 1 doesn't change the value. When converting between units, you will need to find equivalent values like 12 inches being equivalent to one foot. "12 inches equals 1 foot," can be written as two fractions each representing 1: (12 in / 1 ft) and (1 ft / 12 in). Given an expression involving feet, multiplication by only one of the fractions will allow cancellation of feet, yielding an expression in terms of inches.

$$6\,\cancel{\text{ft}}\left(\frac{12\text{ in}}{1\,\cancel{\text{ft}}}\right) = 72\text{ in}$$

Factor-Label Conversion Strategy

The goal of this lesson is learn how to convert one unit of measurement to an equivalent unit of measurement without changing its value. To do this you must multiply the unit by a form of the number one. If you are working with time you know that 60 seconds is equal to 1 minute. This can be expressed as 60 sec/1 minute or 1 minute/60 seconds. See the examples below and then complete the questions at the bottom of the page.

You want to convert from revolutions per second to revolutions per minute.

$$\frac{2.4\text{ rev}}{\text{sec}}\left(\frac{?}{?}\right) = ?\ \frac{\text{rev}}{\text{min}}$$

Choose the conversion ratio that can cancel the units that you don't want, and introduce the ones that you do.

$$\frac{2.4\text{ rev}}{\cancel{\text{sec}}}\left(\frac{60\,\cancel{\text{sec}}}{\text{minute}}\right) = \frac{144\text{ rev}}{\text{min}}$$

In the example below, we are converting inch-ounces into foot-pounds. Note that you can multiply different types of units together to solve the problem.

$$96\,\cancel{\text{inch}}\text{-}\cancel{\text{ounces}}\left(\frac{1\text{ foot}}{12\,\cancel{\text{inches}}}\right)\left(\frac{1\text{ pound}}{16\,\cancel{\text{ounces}}}\right) = \frac{96}{192} = .5\text{ foot-pounds}$$

ANSWER THESE QUESTIONS:

1. If an axle spins at 12 revolutions per second, how many revolutions per minute does it spin?
2. If an axle spins at 58 revolutions per minute, how many revolutions per second does it spin?
3. If a motor can lift 500 inch-ounces, how many foot-pounds can it lift?
4. If a motor can lift 12 foot-pounds, how many inch-ounces can it lift?

motor gearbox design challenge

Design Challenge:
Design, test, and justify the selection of a motor gearbox to control the shoulder joint for an arm for a VEX robot.

Constraints:
1. Use only the gears that come with the VEX starter kit
2. Use a VEX motor module
3. The arm must extend one foot and be able to lift the assigned weight.
4. The gearbox should be designed with a safety factor of two. The motor torque should only reach one half of stall load when picking up the assigned objects.

Investigation challenges for students

LESSON 1:
- Measure the stall torque on the VEX motors in inch-ounces.
- Convert the stall torque from inch-ounces to foot-pounds. Refer to "Conversion of Units – Factor Label Method" handout.

LESSON 2:
- Measure the RPM of the motor

ADDTIONAL LESSONS:
- Calculate gear ratios that will enable the VEX robot motor with the student-designed gearbox to pickup a one-pound, two-pound, and three-pound weight extended one foot from the pivot point. Then design and build a solution that will allow the robot to lift the weight.
- Calculate the RPM of the newly designed shoulder joint given the RPM of the motor and mechanical advantage needed to move the assigned weight. Test the rotational speed of motion of the shoulder joint with and without a load and document your findings.
- Calculate the speed the object will move at the end of the arm with and without a load and test it.
- Design and build a solution that will allow the inventor to lift the weight.
- Write a report that details the results of the investigation.

Refer to the Motion Resources "Terminology" page to find definitions of terms you're not familiar with.

Concepts Covered:

- **Assembly**
  - *Set up gear spacing for the whole gear box before adding the bearings and locking down the axles*
  - *Use angled segments to construct the arm*
  - *Connect the arm to your gear box at the middle of the arm segment to avoid the arm's weight from contributing to the load*
- **Measurement**
- **Calculating gear ratios**
- **Calculating compound gear ratios**
- **Calculating lever arm loads**
- **Conversion of units using the factor label method**

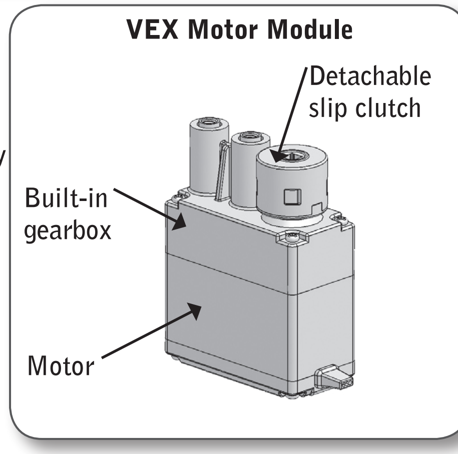
motor gearbox design challenge

LESSON 1: Measuring stall torque for motors

Introduction

The main characteristics of the DC motors that make up the VEX motor modules are: high speed, low torque, reversible, and they apply continuous motion. The VEX motor modules have a built-in gearbox attached to the motor. When the load on a typical DC motor increases, the response of the motor is to draw more current which will eventually cause damage. There is a proportional relationship between motor load, current drawn, heat, and torque. As the load on a DC motor increases the motor will:

- Draw more current
- Decrease motor RPM
- Increase rotational torque
  (This can cause permanent damage to the gearbox)
- Increase motor temperature.
  (This can cause permanent damage if condition is held)



All serious robot designers should test robot motors to define stall torque and then design their robots to decrease the probability of motor damage. *Motor damage can be reduced by designing drive systems with proper gear boxes to keep the motors from repeatedly approaching stall torque conditions.* Design robot gearboxes with a safety factor of 2.

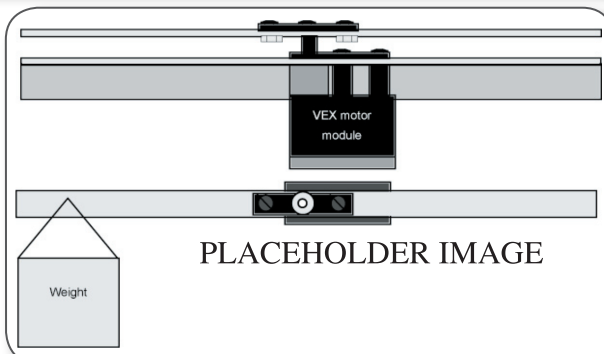
Each VEX motor comes with a detachable slip clutch. Your job is to measure the stall torque for the motor.

Investigation Steps

Safety glasses should be worn for this activity.

Have your instructor check your setup before you power the motors.

1. Gather investigation instructions, tools, and parts.
2. Build the test bed pictured at the right.
3. Add small amounts of weight to the basket at the end of the lever arm until the motor will not lift.
4. Measure the weight.
5. Record your data.
6. Repeat the experiment three times to confirm your results.
7. Convert weight to torque of the motor.
8. Average your results and record your data.
9. Convert the result of your test from inch-ounces into foot-pounds.
10. Write a summary of the investigation.



motor gearbox design challenge

LESSON 2: Measure the RPM of the Motor

Introduction

In this investigation inventors will build a gearbox and use the gearbox to measure the RPM of the motor turning free.

The gearbox axles on the gearbox above have a 1-1, 3-1, 15-1, and a 75-1 mechanical advantage.

Investigation Steps

Safety glasses should be worn for this activity.
Have your instructor check your setup before you power the motor.

1. Connect a large wheel (or gear) to the axle with the 75-1 mechanical advantage.
2. Mark the top of the wheel so that it is easy to see.
3. Power the drive motor on the gearbox for 10 seconds
4. Count the number of revolutions the wheel turned in 10 seconds
5. Calculate the number of times the drive motor turned by multiplying the number of revolutions by 75.
6. Repeat the experiment three more times.
7. Average the results of the three tests.
8. Convert revolutions per second to revolutions per minute.
9. Predict the revolutions per minute for 3-1 and 15-1.

Information for Teachers:

All possible gear ratios available with the VEX gears contained in the starter kit

Available Gears:
12-tooth gears x 4
36-tooth gears x 4
60-tooth gears x 4

Two-Gear Combinations:
- 12-tooth gear to 36-tooth gear is 1:3
- 12-tooth gear to 60-tooth gear is 1:5
- 36-tooth gear to 60-tooth gear is 3:5

Four-Gear Combinations
(two compound gears):
- Any multiple of the above ratios
- 1:9, 1:15, 3:15 (1:5), 1:25, 3:25, 9:25

Six-Gear Combinations:
- Any multiple of the three 2 gear ratios
- 1:27, 1:45, 3:45 (1:15), 1:75, 3:75 (1:25), 1:125, 3:125, 9:125, 27:125

Eight-Gear Combinations:
1:81, 1:135, 3:135 (1:45), 1:225, 3:225 (1:75), 9:225 (1:25), 1:375, 3:375 (1:125), 9:375 (3:125), 27:375 (9:125), 1:625, 3:625, 9:625, 27:625, 81:625

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CONTENT ON THIS PAGE IS STILL UNDER DEVELOPMENT

Terminology

Clutch – A detachable piece normally mounted to the Vex motors that prevents them from entering the potentially damaging stall or back-driving conditions.

Compound Gear – A system of gears involving several pairs of gears, some of which share axles with each other. When calculating gear ratio, this whole system of gears behaves as if it were a single gear pair with a gear ratio that might not otherwise be achievable.

Compound Gear Ratio – The overall equivalent gear ratio produced by a group of gears in a compound gear configuration. This can often be quite high or quite low, due to the multiplicative nature of gear ratios in a compound gear system.

Gear – Essentially, gears are spinning discs with teeth that prevent them from slipping past each other. Gears are frequently used to transfer rotational motion from one piece to another, and to provide mechanical advantage while doing so. The number of teeth on a gear (assuming the same spacing between teeth on both gears, so their teeth mesh properly) is directly proportional to the gear disc's circumference, thus the number of teeth can easily be used to calculate the gear ratios of gear trains.

Gear Ratio – The mechanical advantage, or "force multiplier" generated by a group of 2 or more gears turning together. For simple non-compound gear trains, this can be calculated as the number of teeth on the driven gear divided by the number of teeth on the driving gear.

Gear Train – In general, a group of gears that turn together to transmit motion from one point to another on the robot, often providing mechanical advantage along the way.

Idler Gear – A gear in a gear train that is neither the driven nor the driving gear, and does not share an axle with another gear in the train (i.e. does not form a compound gear). Each idler gear in the train reverses the direction of spin once, but never affects the gear ratio.

Stall Torque – A condition where a motor encounters so much resistance that it cannot turn. It is damaging for the motor to be in this condition. This condition can be avoided through the use of a clutch, which will disengage the motor when too much resistance is encountered.

NOTES:

The **torque of a motor** is the rotary force produced on its output shaft. When a motor is stalled it is producing the maximum amount of torque that it can produce. Hence the torque rating is usually taken when the motor has stalled and is called the stall torque.

The **power of a motor** is the product of its speed and torque. The power output is greatest somewhere between the unloaded speed (maximum speed, no torque) and the stalled state (maximum torque, no speed).

Motors that draw more current will deliver more power. Also, a given motor draws more current as it delivers more output torque. Thus current ratings are often given when the motor is stalled. At this point it is drawing the maximal amount of current.

DC motors are widely used in robotics for their small size and high energy output. They are inexpensive, small, and powerful.

Typical DC motors operate on as few as 1.5 volts on up to 100 volts.

Roboticists often use motors that operate on 6, 12, or 24 volts.

DC motors run at speeds from several thousand to ten thousand RPM.

A low voltage (e.g., 12 volt or less) DC motor may draw from 100 milliamps to several amps at stall, depending on its design.

When the motor is loaded to the point of stalling, maximum current is drawn. The internal gearbox may be damaged and the motor can be ruined.

Thinking in Terms of Behaviors

Behaviors

Robot programmers break down every action a robot makes into simple tasks called behaviors. Robot programs are built one behavior at a time. A behavior is anything your robot does: turning on a single motor is a behavior, moving forward is a behavior, tracking a line is a behavior, navigating a maze is a behavior. There are three types of behaviors: basic behaviors, simple behaviors, and complex behaviors. New programmers will find it much easier to make their robots "behave" when they learn to think in these terms.

Basic Behaviors

Basic behaviors are the most fundamental decisions a programmer makes for his/her robot. Examples would include turning on a single motor, or checking a single sensor port. Basic behaviors are combined to form simple behaviors.

Simple Behaviors

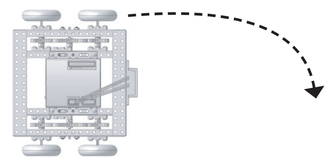
Simple behaviors are small, combinations of basic behaviors that allow your robot to perform a simple, yet significant task, like moving forward for a certain amount of time. These are perhaps the most useful behaviors to think about, because they are big enough that you can describe useful actions with them, but small enough that you can program them easily by combining basic behaviors.

Complex Behaviors

These are behaviors at the highest levels, such as navigating an entire maze. Though they may seem complicated, one nice property of complex behaviors is that they are always composed of smaller behaviors. This means that if you observe a complex behavior, you can always break it down into smaller and smaller behaviors until you eventually reach something you recognize.

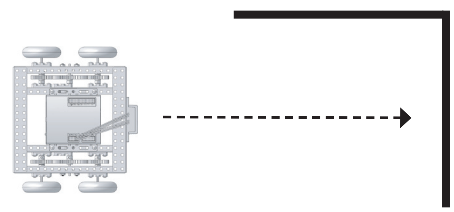
The Basic Behavior...

Turn on left motor in forward direction



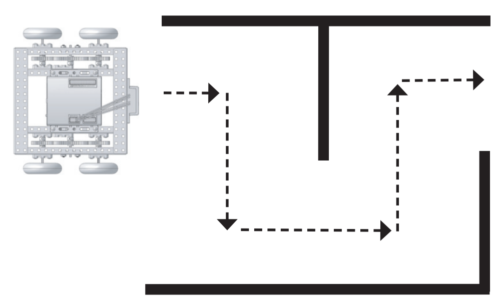
...is used in the Simple Behavior

Move forward until Bumper Switch Sensor is pushed



...which is used in the Complex Behavior

maze navigation



HELPFUL HINTS:

1. Begin by breaking the programming challenge into simple behaviors.
2. Divide the simple behaviors into basic behaviors; these will be the building blocks you will use to build the robot program.
3. Test each simple behavior as you build it.
4. Add a wait state, sound, or some other signal between simple behaviors. This will allow you to verify that the program worked to that point.
5. Test. Test. Test. The key to building a reliable program is to test it under a variety of conditions.