

TACTILE LIMIT CUEING SYSTEMS
FOR ROTORCRAFT
FLIGHT CONTROL

by

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ABSTRACT

The purpose of this research project was to investigate technologies which may be applied to a tactile limit cueing system, and to design, build and test a tactile limit cueing demonstrator based on one of those technologies. The project looked at using the holding torque of a hybrid stepper motor to provide a resistive torque to a control stick. However, there is a ratcheting effect felt when the stepper motor shaft passes through different steps. The project measures this ratcheting effect and considers the viability of this technology as a tactile cueing system for a pilot. The prototype for this system was constructed with a cyclic (control stick) constrained to move in 1-axis. A stepper motor and gearbox was attached to the pivot point of the cyclic to provide the resistive torque. The results confirmed an increase in the holding torque of the stepper motor as the current to its windings increased and also showed that the average torque ripple measured as the motor shaft was actuated, was independent of the current input into the stepper motor.

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INTRODUCTION

Piloting a helicopter requires a high level of multi-tasking. The pilot is responsible for monitoring multiple flight parameters on the panel, maneuvering two control sticks and two foot pedals, whilst looking out the cockpit. To add to that, the pilot must ensure that flight parameters are kept within operating limits to safeguard the functioning of the rotorcraft. With such high demands from the pilot, it is important that adequate cues are given to ease the pilot's workload during flight. It is important that these cues do not distract the pilot from flying the rotorcraft. Generally, cues are given to the pilot when he or she approaches or exceeds a limit. These cues can be visual, aural or tactile.

Tactile Feedback

Tactile feedback is that which involves the sense of touch. It is the most instinctive way of alerting a pilot of an approaching limit without compromising the pilot's focus. This is because the pilot can still have his or her eyes on the surroundings while experiencing a tactile cue.

There are different types of tactile cueing imparted to the control sticks (collective and the cyclic – shown in Figure 1) of the helicopter. One type, the hard stop simply holds the stick in a fixed position when a limit is reached. This is undesirable since control is taken out of the pilot's hands. Another form of tactile cue is the stick shaker: a passive tactile cue that vibrates the stick once a limit is approached. The intensity of stick vibration is adjusted to the level of exceedance or approach of a limit, such that the shaker vibrates with a greater intensity as the limit is exceeded. A third type of tactile

cueing - the soft stop - is a resistive torque added to the control stick as the limit is approached and even exceeded [1]. The magnitude of the torque is increased as the limit is approached, thus making the control stick harder to maneuver. A simple analogy for a soft stop can be seen in an exercise bike. Increasing the difficulty setting on an exercise bike increases the torque that must be overcome to push the pedals through one rotation.



Figure 1 - Cyclic stick of the Helicopter

Similarly, in a helicopter environment, we are trying to increase the ‘setting’ as the pilot approaches a limit, thereby making it harder for the pilot to maneuver the stick. This type of tactile cue is beneficial because it warns the pilot beforehand as a limit is being approached (unlike the hard stop). Also, like the stick shaker, the soft stop increases with the level of exceedance. What sets it apart, however, is that it actively opposes the stick motion, whereas the stick shaker just presents a cue to the pilot without actively actuating the stick.

PRELIMINARY RESEARCH

We are working with Bell Helicopter Textron, Inc. to develop a new system of providing tactile cues to a pilot. Part of the reason that Bell Helicopter was trying to solve

this problem outside of their company is that they wanted fresh eyes on the problem, and they wanted it to be tackled by someone who was not clouded by the ‘helicopter mindset’.

First, we identified the different components of the helicopter where we could impart a tactile cue, and the type of tactile cue that could be imparted, as shown in Table 1.

Table 1 - List of Helicopter Components and Tactile Cues

No.	Component	Type of tactile cue			
		<i>Soft Stop</i>	<i>Vibration</i>	<i>Shaker</i>	<i>Heating</i>
1	Collective	✓	✓	✓	✓
2	Cyclic	✓	✓	✓	✓
3	Pedals	✓	✓		
4	Seat		✓	✓	✓
5	Headset		✓		
6	Vest		✓	✓	✓
7	Gloves		✓		✓

The types of tactile cues that we looked at were soft stop, vibration, shaker and heating. Heating was ruled out due to its inconsistency among different pilots.

Temperature sensitivity varies between pilots; some wear gloves and may have calloused hands thus reducing their sensitivity to temperature. After deliberation with engineers at Bell, we narrowed down the options to a soft stop imparted to a cyclic stick. More

specifically, we looked at building a demonstrator to provide a soft stop to a cyclic stick constrained to a single axis.

In a helicopter, the cyclic stick changes the pitch angle of the rotor blades causing a change in the angle of attack. This leads to a thrust vector in the direction that the rotor blades tilt [2]. For example, if the cyclic is pushed forward, the rotor blades tilt forward and the helicopter has a thrust vector in the forward direction. Typically, the cyclic on a helicopter allows motion in two-axes; however, for this project, a one-axis cyclic system was built for simplicity. This is because the project is not concerned with the functionality of the stick as a cyclic, but with the tactile feel of the stick as a soft stop is initiated. Future developments of the project could look at applying a soft stop to the cyclic in multiple axes.

Typical flight parameters that are monitored during flight are the engine torque, rotor speed and exhaust gas temperature [3]. However, this project is not concerned with the specific parameters being exceeded but with how the system reacts as a parameter is exceeded.

Traditionally, soft stops have been implemented using mechanical springs [4]. This method, although effective, initiates a soft stop at a predetermined position and supplies a set amount of resistive force which cannot be changed once the springs are installed. Another method of providing a soft stop to the control stick is by using a magnetic particle clutch [5] – a clutch whose resistive torque is a function of current and slips less as a higher resistive torque is required. Another method uses stepper motors coupled with spring cartridges to provide a resistive torque to the stick [3]. This project

looks at exploiting the holding torque characteristic of the stepper motor to provide a resistive torque to a cyclic.

Our preliminary research looked at technologies from the automotive, gaming and medical industry. Instead of trying to reinvent the wheel, we looked at ways of importing existing technologies into the aviation industry. For the gaming industry, we looked at rumble motors or vibration motors used on modern consoles [5] to give the user a tactile feel during suspenseful moments of a game. We also looked at modern suspension systems used in the automotive industry.

Magneto-Rheological Fluid (MR Fluid)

Modern automotive suspension systems use a smart fluid called magneto-rheological fluid (or MR fluid) whose viscosity is a function of a magnetic field applied to it [6]. It consists of micrometer-sized iron particles in a carrier fluid such as oil. Applying a magnetic field through the liquid causes the iron particles to line up, thus increasing the viscosity of the fluid [6]. Considerations were made to use MR fluid to provide a resistive torque, or *soft stop*, to the control stick as a pilot approached or exceeded a limit.

The world's leading manufacturer of MR-fluid based products, LORD Corporation, has a Tactile Feedback Device (TFD) that provides a resistive torque of up to 12 Nm using MR fluid as the damper [7]. This device is designed for steer-by-wire systems in vehicles to provide a force feedback to the driver. Figure 2 shows the 12 Nm TFD. This device is originally used in steer-by-wire cars where the vehicle functions through electrical or electro-mechanical signals instead of the traditional mechanical linkages. With these systems, it is important that the driver gets a sense for his or her control of the car while

steering it. This is where the steer-by-wire device comes into play as it provides a resistive torque that artificially emulates a sense of moving the car, i.e. the steering wheel feels harder to push as the driver turns it. This is done by varying the current to the device which accordingly makes the MR-fluid more rigid and increases the resistive torque of the device [7].

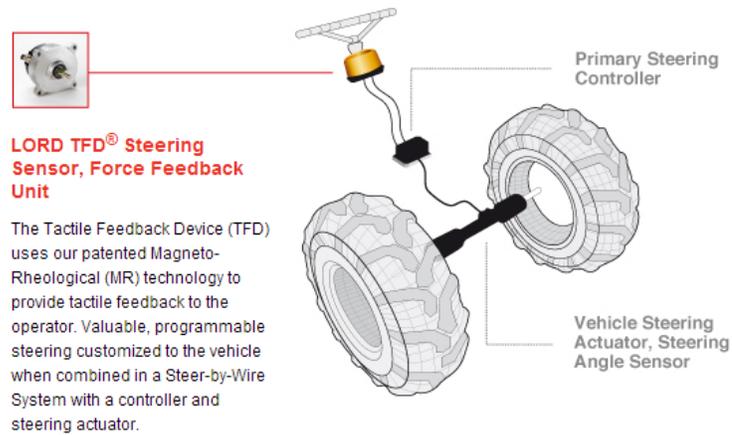


Figure 2 - LORD Steer-by-wire device

Source: [http://www.lord.com/products-and-solutions/magneto-rheological-\(mr\)/the-system.xml](http://www.lord.com/products-and-solutions/magneto-rheological-(mr)/the-system.xml)

Our original design concept used the MR Tactile Feedback Device connected at the pivot point of the cyclic to provide a programmable resistive torque as the user maneuvers the stick. In Figure 3, the component in yellow represents the MR Tactile Feedback Device. In this case, it provides a resistive torque to the cyclic stick based on the magnitude of the current applied to it.

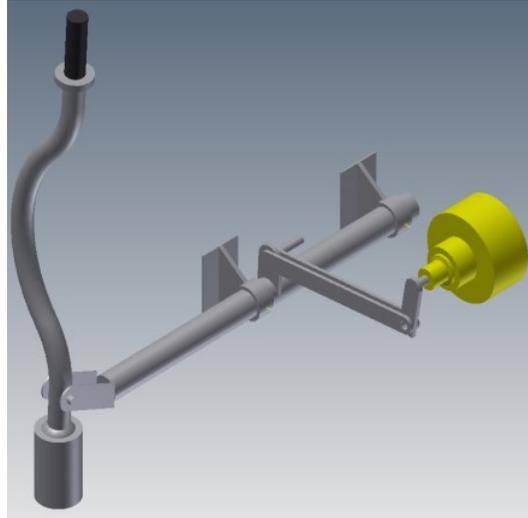


Figure 3 - Cyclic Assembly with MR-TFD

Stepper Motors

Stepper motors are widely used in positioning applications due to the accuracy at which the rotor can move to a particular step. They consist of a fixed stator and a movable rotor which may be magnetized depending on the type of stepper motor. The stator has windings that are energized in a particular sequence to change the magnetic field [8]. A change in magnetic field induces movement in the rotor. We proposed using the holding torque provided by the stepper motor to provide a resistive torque to the pilot. There are three different types of stepper motors [9]:

- Variable Reluctance (VR) – uses gear teeth in the rotor to rotate the shaft.
- Permanent Magnet (PM) – uses a permanent magnet in the rotor to rotate the shaft.
- Hybrid – combines the qualities of both VR and PM stepper motors by using a permanent magnet as well as gear teeth in the rotor leading to a higher torque motor with greater step resolution.

Detent torque

Detent torque (or cogging torque) is the maximum torque that can be applied to the shaft of a de-energized motor without causing the motor to rotate [8]. This torque is due to the residual flux in the permanent magnet (if a hybrid or permanent magnet stepper motor is used). Physically, they are the bumps experienced as the rotor is manually actuated when the windings are not energized.

For a Tactile Limit Cueing (TLC) application, this detent torque would generally be considered undesirable. When the pilot is flying within the flight envelope and a soft stop is not required, the detent torque will manifest itself in the stick motion even though the motor is not powered, leading to non-smooth motion of the stick. However, in this experiment, this detent torque will be measured with different gearboxes and considerations will be made for its use as a tactile cue.

Holding Torque

Holding torque is defined as the maximum torque which an energized motor can withstand without causing any rotary movement [8]. This is achieved by inputting a constant DC current to the stepper motor. By energizing a single phase with constant magnitude (DC power), a net magnetic field is created that causes the rotor to be repelled between steps. This repulsion provides the resistive torque (or soft stop) that the pilot experiences either due to exceedance or approach of a limit. The holding torque is defined as the maximum torque that the rotor reaches before it moves into the next step [8].

Research into stepper motor literature did not yield any results of how the holding torque of the stepper motor varies as the rotor is manually moved between steps. A simple experiment was set up to assess this. The main goal of the experiment was to see how the holding torque varied as the rotor was manually moved between steps. The *peak-to-peak force ripple*, defined as the variation in force between steps, was measured and analyzed.

The magnitude of this force ripple would determine how smooth the soft stop would feel to the pilot. Ideally, the soft stop motion should not be ‘jerky’ as the pilot pushes against the holding force through different steps.

A smaller hybrid stepper motor with a holding torque of 1.52 ft-lb was used for this experiment. A beam was extended perpendicularly out of the rotor and a load cell was fixed on to the end of this beam, as seen in Figure 4. The beam was manually rotated about the rotor by pushing on the load cell with a finger.

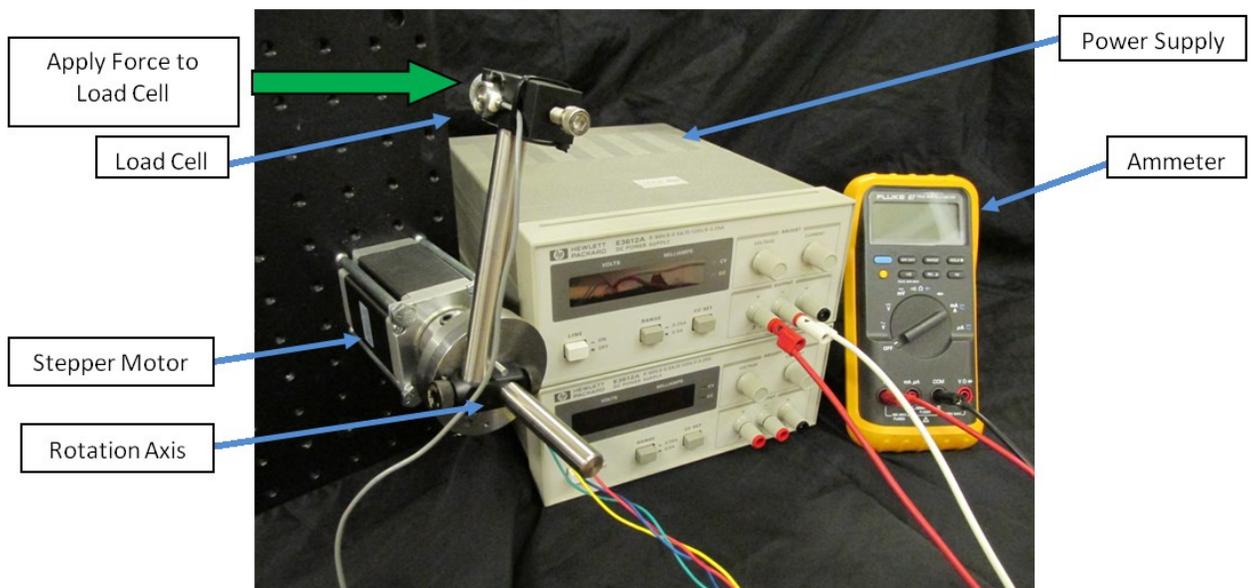


Figure 4 - Experimental Setup to determine torque ripple

The force on the beam was measured 60 times per second using Smart Sensor Indicator data logging software. Force was measured for unenergized conditions (cogging torque) as well as energized conditions by supplying current to the motor in 50mA increments from 0 mA to 500 mA. The current values provided by the power supply were confirmed by connecting an ammeter in series with the power supply and stepper motor.

The force measurements gathered for each 50mA current increment were plotted against time. An example plot for a current of 400 mA is shown. This data set was chosen as it showed a more consistent peak-to-peak force over time. The plot displayed an average force ripple of 0.38 lb and an average resistive force of 0.60 lb, as seen in Figure 5 below.

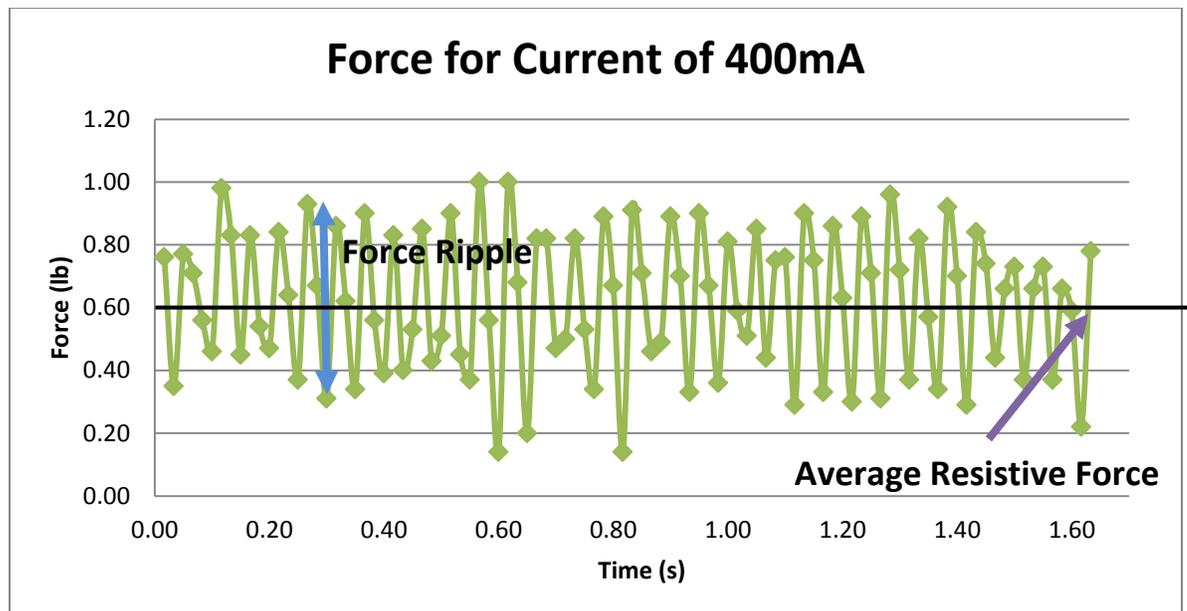


Figure 5 - Force Ripple for Current of 400 mA

This experiment confirmed that as the current supplied to the windings of a stepper motor increases, the average resistive force also increases, as shown in Figure 6 below. Because the force increases with an increase in current, a stepper motor would be capable of increasing the resistance of the cyclic as a pilot reaches a limit.

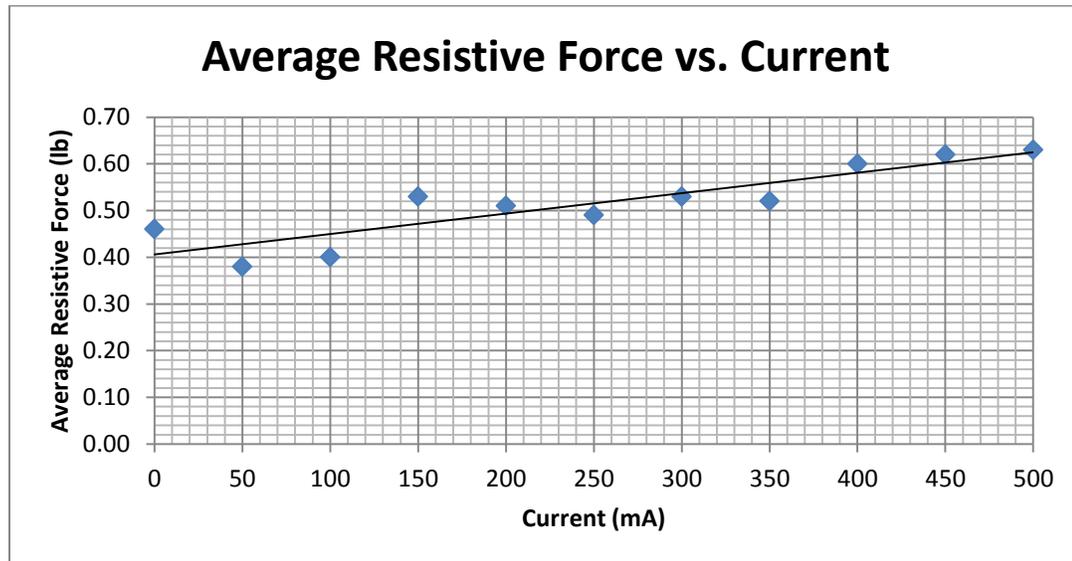


Figure 6 - Resistive Force vs. Current Supplied to the Windings

The experiment also helped to characterize the force ripple, which we defined as the average peak to peak fluctuation of the resistive force as the motor is moved from step to step. As current supplied to the windings increased, the force ripple showed an increasing trend, as shown in Figure 7 below. This states that as the current is increased, the force ripple would cause the pilot to feel an increased “bumpiness” or “jerkiness” of the cyclic.

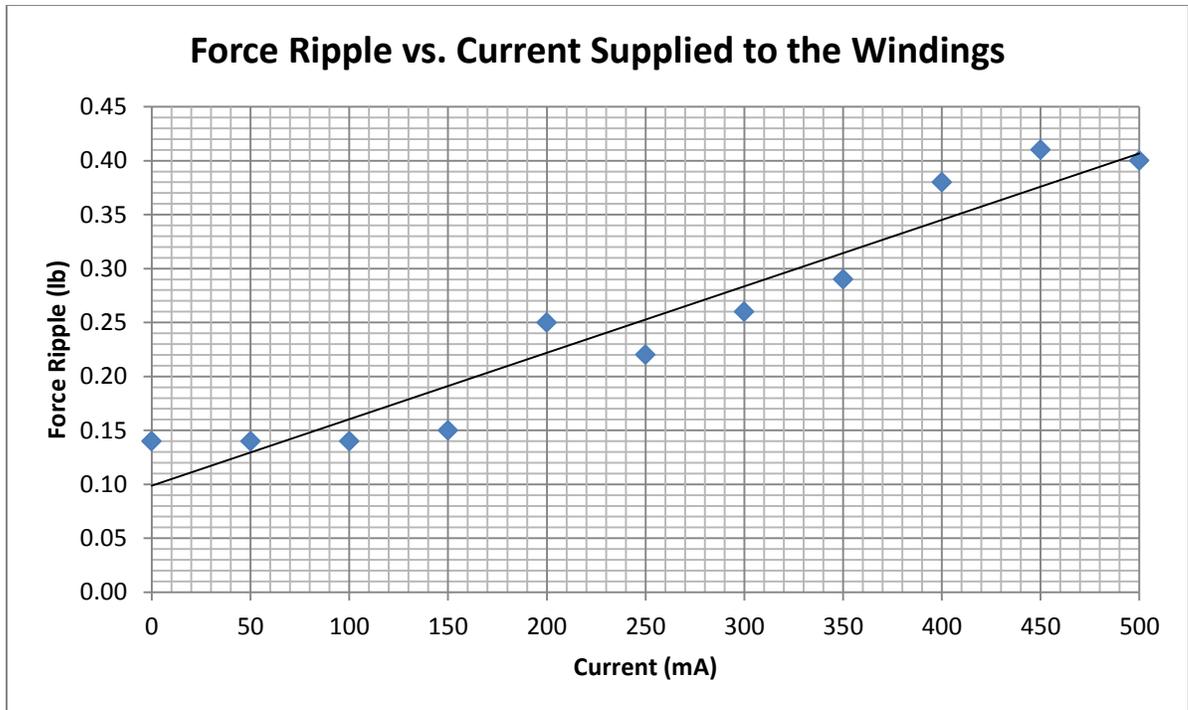


Figure 7 - Force Ripple vs. Current Supplied to the Windings

EXPERIMENTAL SYSTEM DESIGN

A more robust experimental setup was required to take torque measurements at torques more comparable to that experienced by a cyclic. After our research, a hybrid stepper motor was chosen due to its high positional accuracy and high-torque capabilities. The variable reluctance stepper motor (which does not have any detent torque) cannot be purchased off-the-shelf and is considered obsolete in the stepper world industry. Table 2 below shows a comparison of the three stepper motor types.

Table 2 - Comparison of different stepper motors

	<i>Variable Reluctance</i>	<i>Permanent Magnet</i>	<i>Hybrid</i>
Detent Torque	No	Yes	Yes
Cost	Low	Low	High
Availability	Unavailable (considered obsolete)	Commercial Off-the-shelf	Commercial Off-the-shelf

Stepper motors of various sizes were considered with different gearbox ratios to achieve a holding torque of 30 ft-lb (this value was obtained by assuming a 3 foot stick being actuated by 10 pounds in the forward and aft direction).

Based on availability, lead time and ease of communication with the manufacturer, we decided to purchase the Lin Engineering stepper motor to test with a 28:1 gearbox. The system consisted of the following main components:

- Test stepper motor and gearbox (Lin Engineering Stepper Motor)
- Torque sensor
- Drive motor and gearbox
- Drive motor controller and power supply (not shown)
- Breadboard
- Constant DC Power Supply (not shown)

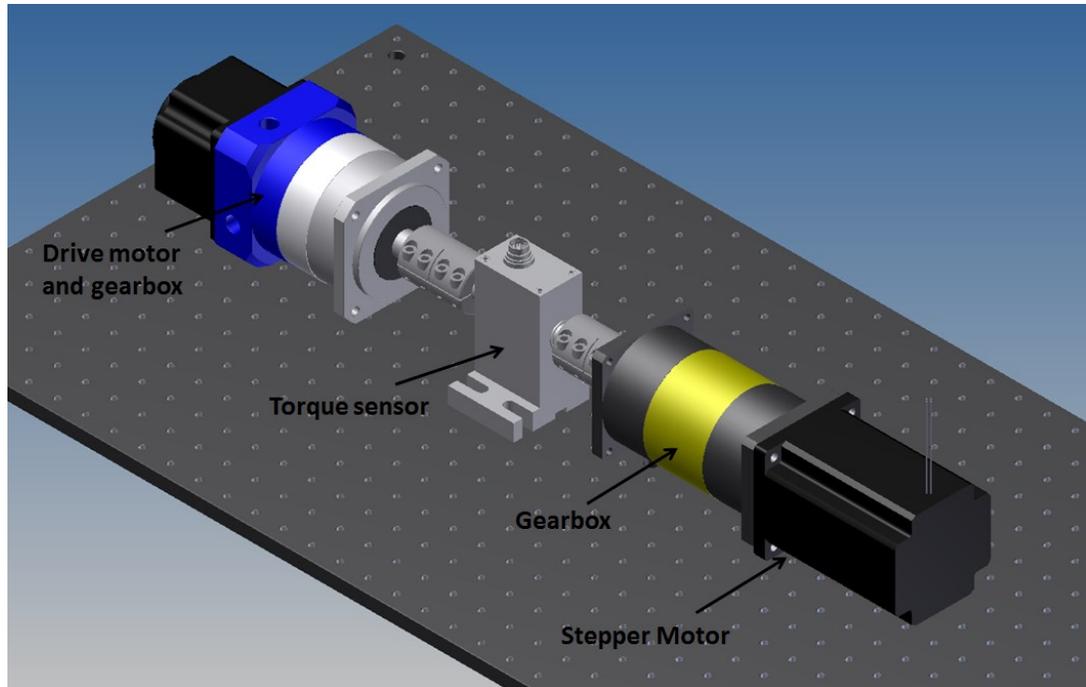


Figure 8 - Experimental Setup in Autodesk Inventor

Other components such as riser blocks and couplers were used to vertically align the components so their shafts were at the same height from the breadboard, and were properly attached to each other.

In this system, the torque was measured using a Futek torque sensor. The sensor measures torque using metal-foil strain gages that measure the differential torsion between the two shafts of the sensor [10]. An external brushless DC motor was used to drive the shaft, essentially behaving as a pilot actuating the stick. This motor allows for constant speed rotations of the shafts for varying loads, thus allowing for consistent and comparable experimental data.

Figure 9 shows the system after assembly.

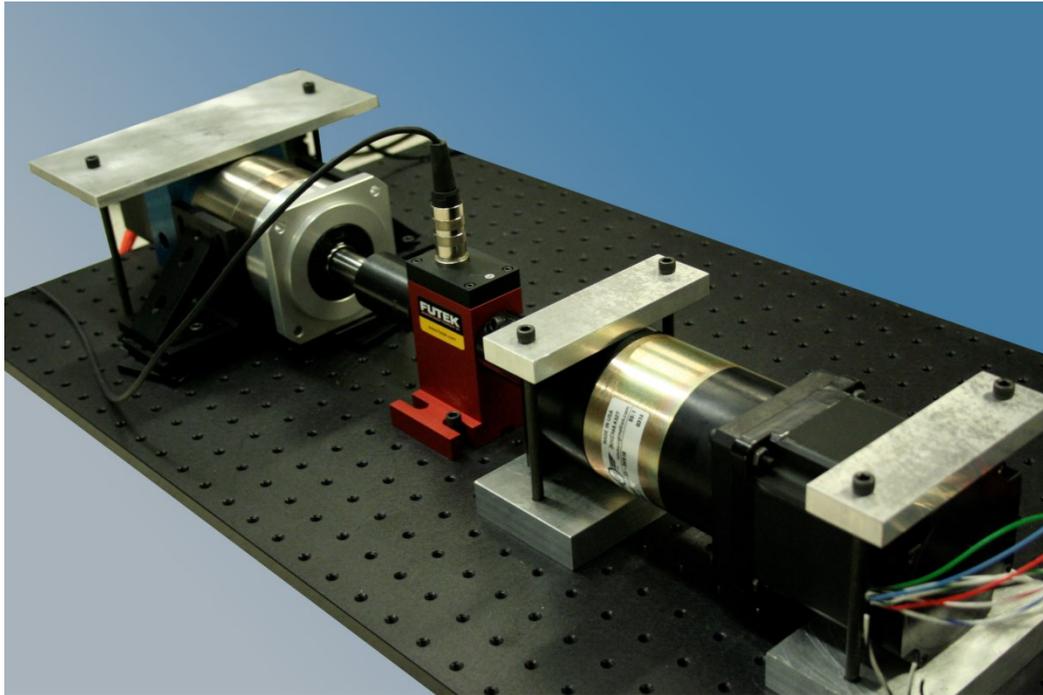


Figure 9 - Experimental Setup

EXPERIMENTAL PROCEDURE

A constant voltage was applied to one phase of the stepper motor windings creating a holding torque at the stationary stepper motor shaft. The drive motor was then powered using the Brushless DC Motor controller that allows for control of various parameters of the drive motor such as direction, speed and maximum current settings [11]. This causes the drive motor to actuate the shaft against the resistive torque of the stepper motor.

The torque sensor measures this differential torque and outputs this data to the computer via a USB connection. The software used – SENSIT – was provided by Futtek Advanced Sensor Technology and directly interfaces with the torque sensor. Thus, we

obtained a curve expressing the relationship between the current input to the stepper motor and the average holding torque experienced.

The independent axis represents time (sample number) and the dependent axis represents torque in Newton meters. This test was conducted for currents varying in 10 mA increments. An example plot of the data for an input current of 380 mA is shown in Figure 10. Comparing this data to our previous experiment with the smaller stepper motor, we see a more consistent torque ripple due to the steady actuation of the shaft by the drive motor.

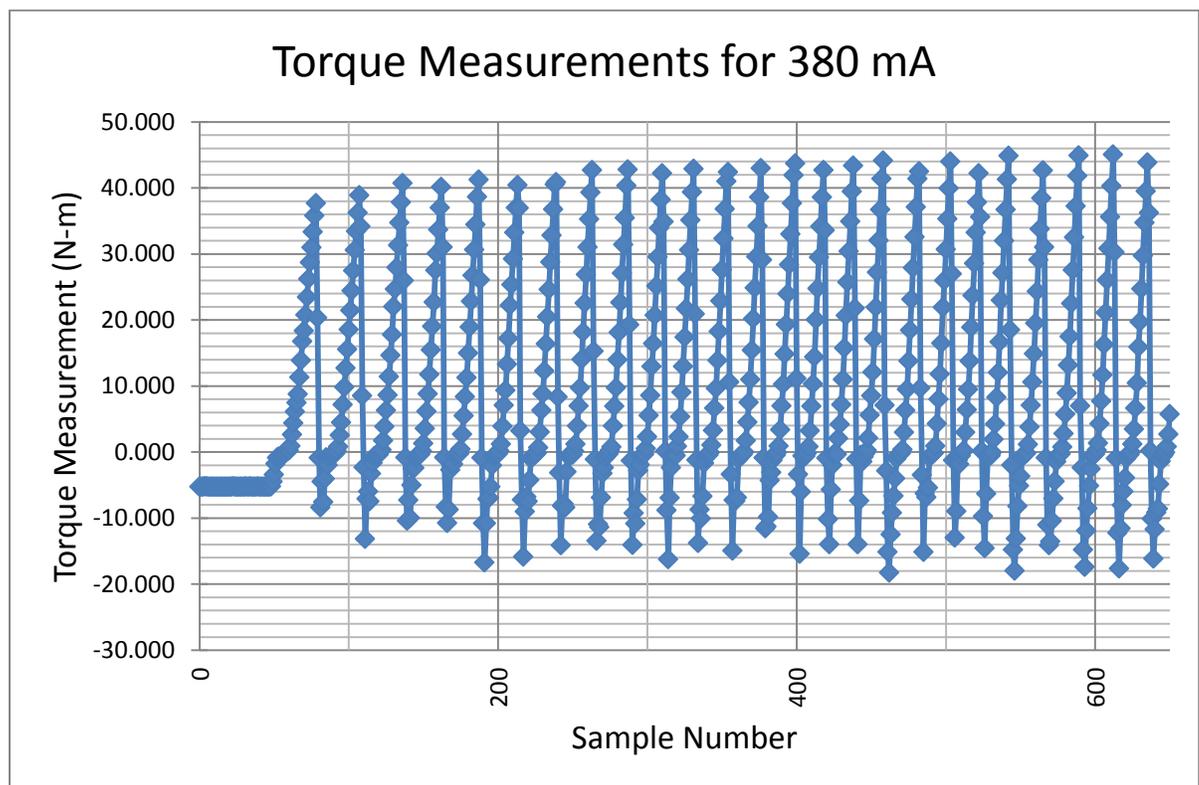


Figure 10 - Torque measurements for 380 mA

The results allowed us to plot a calibration curve for the 28:1 gearbox between current and average holding torque. This allows us to calculate the required input current to yield a particular holding torque as seen in Figure 11.

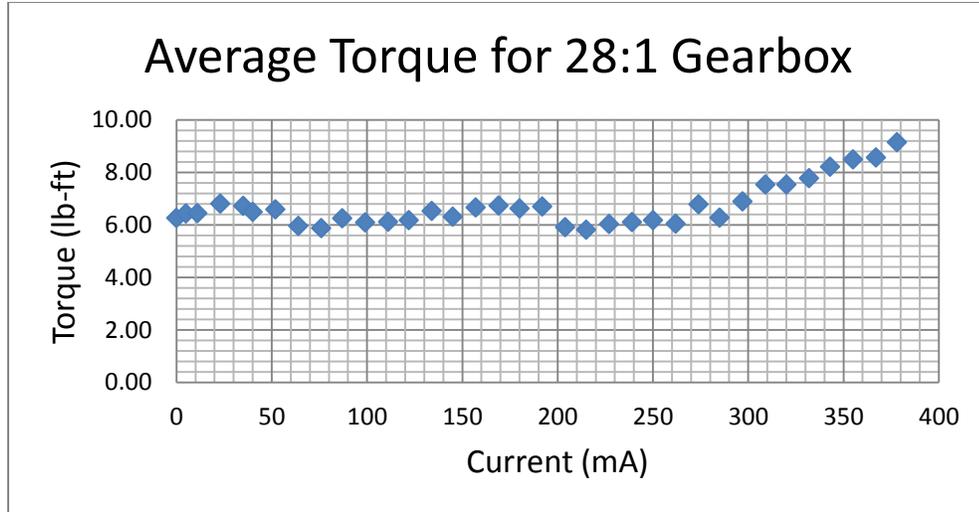


Figure 11 - Average torque vs. Current

As expected, figure 11 above shows a linear trend between the input current and the average holding torque of the stepper motor. However, this trend is more prominent only after 200 mA. A plot was also made for the average torque ripple to identify any trends for a changing current, as seen in Figure 12.

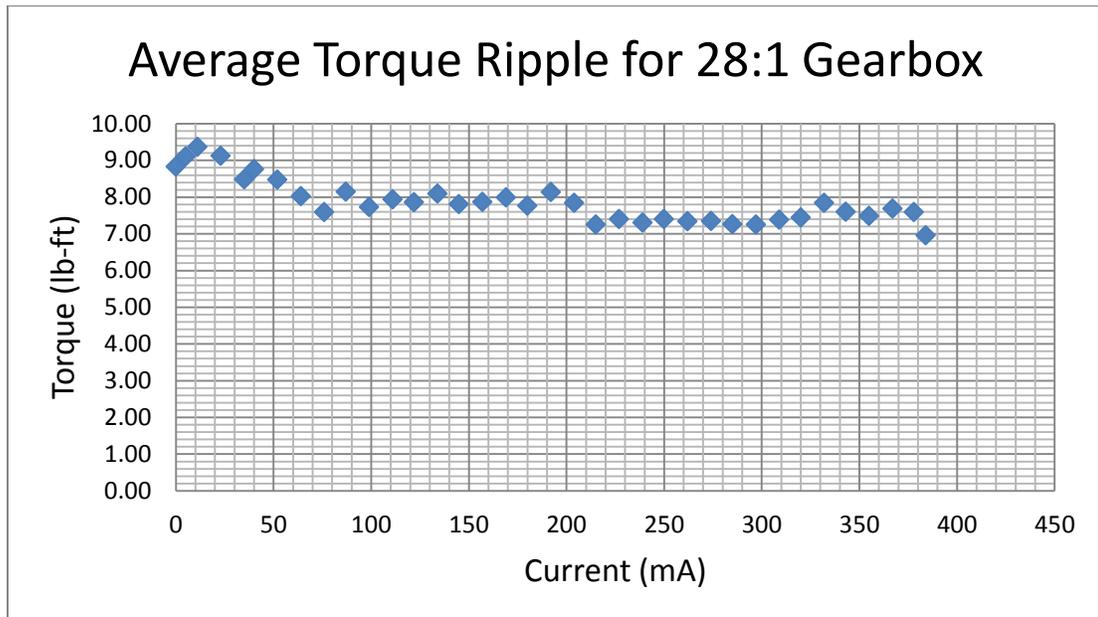


Figure 12 - Average torque ripple

Figure 12 above shows no relation between the current and the average torque ripple of the stepper motor, unlike our previously measured data from the smaller stepper motor experiment. This plot tells us that as the current increases, the average torque ripple or ‘bumpiness’ stays the same but the overall holding torque itself increases.

CONCLUSIONS AND FUTURE DEVELOPMENTS

The soft stop provided by the stepper motor is not smooth due to its inherent bumpiness; however, this bumpiness can be used as a tactile cue to the pilot with a holding torque that increases in magnitude as the input current is increased. As mentioned before, this project can be scaled up to provide a tactile cue in two axes. The next step in this process will be to characterize other gearboxes and to study the effect of gearbox ratios on the average torque ripple.

Cyclic System Design

We wanted to provide Bell Helicopter with a system that was more representative of a helicopter cockpit. We were especially interested in designing one that would allow qualitative feedback to be made on the viability of our tactile cue. For this reason, we designed a cyclic stick constrained to the pitch axis that would be coupled to the stepper motor providing the resistive torque. Figure 13 below shows this setup.



Figure 13 - Cyclic System

Tracking a peak

For future developments, the following setup is proposed to provide a smooth soft stop by tracking a single peak on the torque versus current plot: For a given current, there is a maximum torque that the stick will reach before the stick breaks into a new step. By measuring the present torque value of the system and comparing it to the maximum torque value for that corresponding current, the system can calculate how close the user is to reaching the maximum torque. When this difference is small enough, the current supplied to the windings is increased thus increasing the maximum torque value. This prevents the user from breaking out of a step, thus leading to a smooth soft stop.

In this system, the current supplied to the windings was increased as the user broke out of a step. This increased the repulsion between the two steps thus increasing the resistive torque and preventing the rotor from breaking out of a step.

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