IPRO 321
Enhancing the Reliability and Performance of Paper Shredders

Final Report
Fall 2007

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Introduction

IPRO 321: Enhancing the Reliability and Performance of Paper Shredders has been offered at IIT for three consecutive semesters. There has been a great deal of progress made in the Spring 2007 and the Summer 2007 semesters and the Fall 2007 semester is no different.

Through working with Professor Mostovoy and Professor Maurer, the Fall 2007 semester has learned a great deal about the torque that the machine takes to shred paper along with the reliability of the gear train and the source of sound in the paper shredder.

Background

Paper shredders have been used in the office environment for many years. Once sold and used exclusively in offices, paper shredders can now be found in consumer's homes.

Spring semester 2007, President Mr. Seth Lewis of the Manhattan Group came to IIT seeking advice regarding the improvement of his paper shredder. The paper shredders are manufactured in China and sold throughout the world, including the United States. Each year, over a million Royal Brand paper shredders are sold.

Research shows that consumers seek quiet and long lasting paper shredders at the lowest possible price. For the third consecutive semester Mr. Seth Lewis requested that Professor Maurer and the students of IPRO 321 further seek potential methods of improving shredder performance and reliability.

The MMAE lab and machine lab will be used extensively for gear and materials testing. Software resources, sound measuring equipment, and equipment in the EE lab will be used as well.

Potential legal and/or ethical issues will involve patents and idea ownership. Since this is a sponsored IPRO, all discoveries will be property of Mr. Seth Lewis and the Manhattan group. There potentially could be a situation where this IPRO will be unable to provide necessary information to the IPRO office regard work and progress due to ethics.

Purpose

The major problem addressed by this IPRO is to improve performance of a noisy, inefficient, and cost sensitive paper shredder. The Manhattan Group, a mass distributor of household shredders, provided specific goals to accomplish. First of these was to measure the force necessary to cut 6, 8, and 10 sheets of standard 20lb paper. The second objective uses the measurements obtained from the first objective to optimize the gear train and reduce the size of the motor. Finally, acoustical dampeners were to be developed to reduce noise created during the shredding process. These were the three objectives that were given to the team by the sponsor in order to create the most reliable shredder at low cost.

The team used the previous semesters' work to continue down the right path. One example was a previous IPRO suggested to lengthen the worm gear from the motor in order to fully utilize the meshing helical gear. In effort to confirm the effect of this modification, the IPRO group this semester performed further load testing on the shredder. Also, the noise reduction of the paper shredder in a cost efficient manner was the main objective in previous IPROs and will continue to be in following IPROs. It was an essential part of the IPRO project to learn about the previous semesters' accomplishments and continue research on the recommendations of other teams to acquire results.

Many constraints were faced throughout the execution of this semester's IPRO; the major constraints being time and resources. Since the shredder being improved is not yet available in the United States, shredders and replacement parts for testing must be imported from China. This made it difficult to acquire the necessary parts and shredders to complete the necessary testing and

Research Methodology

Torque Measuring Team

The team has worked together to develop a mathematical model that can estimate the torque required to shred several sheets of paper for a given paper shredder.

Experimental data was acquired by measuring the shredder's power consumption (voltage and current) and angular speed. The torque was determined using the relationship:

$$V_{rms} \cdot I_{rms} = \tau \cdot \omega + P_{loss}$$

$$V_{rms} = \text{Input RMS voltage}$$

$$I_{rms} = \text{Input RMS Current}$$

$$\tau = \text{torque}$$

$$\omega = \text{angular speed}$$

$$P_{loss} = \text{power loss due to friction, etc.}$$

This equation is then solved for the torque and it becomes:

$$\tau = \frac{V_{rms} \cdot I_{rms}}{\omega} - \tau_{loss}$$

where all the values are the same as previously stated and τ_{loss} is the measured torque with no load.

Several tests were performed varying the number of sheets. In addition, the torque data from the torque measuring device team acquired through mechanical means, was also be used as to verify the validity of the method. Following the data taking, for several amounts of sheets the data was fit to an appropriate function. Such a model is expected to estimate the behavior of the torque required to shred different amounts of paper sheets for a given paper shredder. This strategy has high chances of being completed successfully within a month, according to time and supply constraints. The same procedure can be repeated for different shredders and results can be compared.

Gear Train Team

The *Royal* brand shredder given to the group by the Manhattan Group contains a gear ratio and motor size which may not be the most efficient setup for the maximum sheet capacity. As a group we were tasked with determining if there was a more efficient gear train or a different motor size that could be used.

As a team, we discussed the best method of solving the problem at hand. The first step was to research gear types and the pros and cons of each one. Each member of the team was given a different type of gear and it was their responsibility to find any and all information such as efficiency and cost. After the research was done on the gear train, the team had to determine if the current gears were efficient or if there was a better set up. This was done by continually adding more paper to the shredder to determine is any of the gears would be stripped or broken in any way.

Sound Team

The problem presented to the team was to determine where the sound was being produced in the shredder and develop acoustical sound dampeners or tune the shredder to reduce the noise output created during the shredding process by 10 decibels.

The first step in the problem solving process was to familiarize the team with the different methods of sound dampening. The team began researching options such as grommetting, insulation, dampening and sound deflection. After finding the source of the noise, the options were looked into to see if any would be a good solution to the problem.

In order to achieve the objective, the sound team had to determine the amount of sound produced by the paper shredder by measuring both the decibel level and the frequency. First, the team acquired the necessary sound testing equipment and learned the proper use of the equipment and corresponding programs. This first step helped the team determine the best method of problem solving. The team began testing the decibels produced by the shredder in many different situations. The sound produced by the shredder in its entire state both without paper shredding and with paper shredding was measured. This could be used to determine if the force of the paper on the shredder caused more noise or if it dampened the sound.

The team also felt that in order to get a good idea of what a quiet shredder needs, another brand of shredder needed to be purchased. The team went to an office supplies store and bought the quietest shredder that the store contained. The same sound tests were run on this quiet shredder as were run on the *Royal* brand shredder and the results were compared.

The final research step was to begin dismantling the shredders and measuring the sound produced by the components. The motor was detached from the gears and shredder head and the sound was measured to determine if most of the sound was being produced by the motor. Then one by one the gears were added to the motor and the sound was measured to determine if there was a specific gear that was producing most of the noise. The results were placed into graphs to show the difference in decibels for each situation.

Finally, after all the measurements were taken, the team began putting the research from the beginning of the year into practice. The team placed insulation around the motor, the gear train and the shredding head to determine if insulating any of these systems would decrease the noise. All of the data that was taken analyzed the frequency and the decibels in order to determine if either could be lowered to decrease the entire noise of the shredder.

Torque Measuring Machine Team

One of the most important variables in determining the characteristics of the paper shredder is the torque requirements as a function of the number of pieces of paper in the shredder knife head. The team worked with Professor Mostovoy on creating a machine that could mechanically determine the amount of torque required to shred different amounts of paper. It was determined that building a separate drive system for the shredder head with torque measuring capability would be the best option. It would allow a determination of torque as a function of the number of sheets of paper and a measurement of the torque when severe overloads cause failure. In recent tests without the torque system in place it was determined that feeding 13 pieces of paper resulted in the failure of one of the metals gears. We intend to reproduce this failure using the separate drive system so that a direct measurement of approximate torque at failure could be determined. Additionally, this system could be used with other shredder heads in order to determine if a particular shredder design is more efficient in terms of power requirements.

The system this team devised is shown below

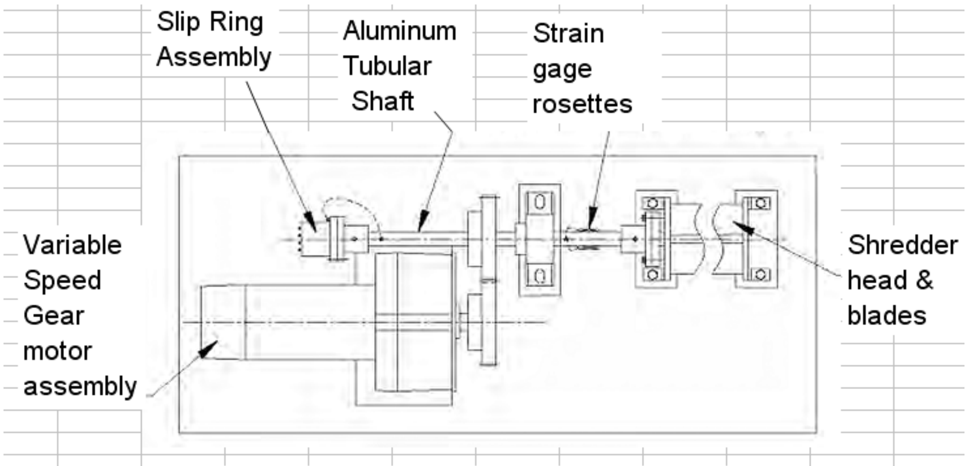


Fig. 1. Alternative torque measuring drive assembly

The system consists of a variable speed DC motor/reducer assembly that permits the speed of the head to match the measured speed of the actual shredder during normal operation. The mechanical assembly consists of bearings and an attachment to the shredder head metal drive gear. This drive gear is connected to a pair of smaller gears that drives the shredder rollers in opposite directions. The torque measuring system uses an aluminum tube (0.5 inch ID with a 0.25 inch bore) and two strain gage rosettes mounted on the outside of the tube at 45° to the axis of the tube in the maximum normal stress direction. When connected in a Wheatstone bridge, this arrangement magnifies the actual strain by a factor of four.

Calculations of the maximum strain to be measured with this tube were calculated based on an estimate of the torque at about 200 in-lbs. A good "rule-of-thumb" for strain gage usage keeps the maximum strain at under 1000-μ-ε. In this way, the strains are well below yield and there is some room for slight overloads (about 50%). To calculate the maximum torque for 1000 μ-ε we use the following equations.

$$\tau = \frac{M_t \frac{d}{2}}{I_p}; I_p = \pi d^3 t; \tau = \frac{2M_t}{\pi d^2 t}$$

$$\tau = G\gamma; \gamma = \frac{\tau}{G} = \frac{2M_t}{\pi d^2 t G}$$

$$M_t = \frac{\gamma \pi d^2 t G}{2}$$

In these equations M_t is the applied torque, d is the outer diameter of the tube, t is the wall thickness of the tube, I_p is the polar moment of inertia, γ is the shear strain and G is the shear modulus.

Thus, for a ½ inch diameter tube with a ¼ inch bore loaded to a shear strain, γ, of 1000μ-ε the maximum torque is 184 inch-lbs. While this is the capacity of the system, it does not address the calibrations relating strain to applied torque. The gages, hooked up as a Wheatstone bridge, are terminated at a slip ring assembly that permits the tube to rotate while still taking readings from the slip ring. The bridge is hooked up electrically to a strain gage conditioner module which provides activation voltage to the bridge and output terminals to either a voltmeter or a PC hookup for data collection during the time paper is passing through the shredder.

A torque calibration system was specifically designed for this apparatus. It consists of an equal length arm which attaches to the torque tube by clamping. There is a balanced weight pan at exactly 6 inches from the center line of the tube and this is loaded progressively, noting the voltage output from the gages at each load. Once the load vs. output relationship is determined to be linear and the value of the slope of the voltage output vs. applied torque from the strain gage conditioner is determined, a shunt resistor is activated which gives a pseudo torque. The value of this pseudo torque is then used for further calibration at a later time without the need to repeat the actual application of test torques.

Assignments

The team decided to break into three groups and each group took one of the objectives. Then there was a subteam of the sound group that worked on the torque measuring device with Prof. Mostovoy.

Torque Measurement Team	**Gear Train Team**	**Sound Reduction Team**
Yuxiong Huang	Brandee Toyama	Stephen Flicek
Vesna Pesik	Justin Choriki	Richard King
Nil Valls	Tyler Inouye	Angad Nagwan
	Garrett Nielson	Leslie Obst

Sound Reduction Subteam (Torque Apparatus)
Plamen Morinov
Kyle Swaidner

Each team member had their own specific tasks assigned to them to ensure that everyone did their part in the project and to split up large assignments to get all the necessary tasks completed.

Torque Measurement Team

Team Member	Tasks
Nil Valls	1. Electrical Setup 2. Supplies 3. Measurements 4. Data Analysis
Yuxion Huang	1. Supplies 2. Measurements 3. Paperwork
Vesna Pesik	1. Electrical Setup 2. Measurements 3. Documentation

Gear Train Team

Team Member	Tasks
Garrett Nielson	1. Reseach Materials 2. Research Heat Effects on Gears 3.Running Tests On Shredder 4. Documenting Results and Procedures
Tyler Inouye	1.Research Materials 2. Research Heat Effects on Gears 3. Running Tests on Shredder
Justin Choriki	1. Researching Gear Ratios 2. Researching Reliability and Cost of Different Gear Types 3.Running Tests on Shredder
Brandee Toyama	1. Researching Worm Gears 2.Running Tests on Shredder 3. Assisting with Deliverables

Sound Reduction Team

Team Member	Tasks
Angad Nagwan	1.Acquiring Information from Office Depot 2. Purchasing another Shredder for Comparison 3. Working with Torque Measurement Device Team 4. Assisting with Deliverables
Richard King	1. Researching Insulation 2. Researching Sound Deflection 3.Running Sound Tests 4.Testing Methods of Sound Reduction
Stephen Flicek	1. Acquiring Essential Lab Equipment 2. Researching Insulation 3. Working with Torque Measurement Device Team 4. Assisting with Deliverables
Leslie Obst	1. Researching Insulation 2. Running Sound Tests 3. Testing Methods of Sound Reduction 4. Putting Together IPRO Deliverables 5. IPRO Scribe/Liaison

Torque Measurement Device Sub-team

Team Member	Task
Plamen Marinov	1. Working with Prof. Mostovoy on the Device Design 2. Drawing Schematics 3.Writing up Results 4. Testing with Device
Kyle Swaidner	1. Working with Prof. Mostovoy on the Device Design 2. Writing up Results 3.Testing with the Device 4.Assisting with Sound Testing

Obstacles

One of the obstacles that affected the entire team was that this product is not yet available for sale anywhere. It's still in the design stages. This means that if we needed another shredder for testing or if a part on the shredder broke it wasn't readily available to the team. A request would have to be put in to the sponsor to ship the necessary items from China. This put a damper on the progress of the experimentation.

Torque Testing Team

In the first couple of weeks of the IPRO, the team wasn't sure how to measure the torque. It wasn't until after consulting Dr. Mostovoy, that it was decided to use the conservation of energy. Therefore, the team wasn't able to get started right away because a measurement method needed to be determined.

Once the method was determined, the measurements were not able to be completed because the proper instruments were not available to the team. They once again turned to Dr. Mostovoy and he quickly aquired the tachometer that was needed.

Also, during the measurements, the team found that no matter how the electrical circuit was set up, the ammeter and voltmeter would not work. After careful examination, they found that a wire on the PCB was disconnected and soldered properly to make it work.

After the data was taken, it couldn't be compared to the mechanical method because the torque measuring machine was not completed. The team had to wait until the device was finished and the mechanical data was taken to see if there was any correlation.

Gear Train Team

One of the biggest obstacles that the gear team had to overcome was the lack of knowledge of gears that the team members possessed. The team had to take some time research the different kinds to understand how the current gear train was built and determine the best solution to the inefficiency of the gears.

Also, the team spent a lot of time waiting on the progress of the other groups. There weren't enough shredders for each team to test so this group was forced to wait for a shredder from one of the other teams. The team also had to wait on the data from the torque team to determine if the motor could be changed or if there needed to be a different gear configuration to handle the torque.

Sound Reduction Team

The first barrier that the sound team had to overcome was that the team wasn't really familiar with the shredder and the ways that the sound can be reduced. The team needed to research sound reduction options. Then the IPRO needed the proper tools to open the shredder to study what parts may be causing all the sound.

The next obstacle that the team needed to be overcome was obtaining the proper test equipment and learning how to use it. After discussing the tools that the team needed with IIT staff, they were able to obtain the necessary equipment to measure the sound coming from the shredder. Then the team had to spend a class period learning how to set up the equipment and how to properly use it. It took some time, but the team was able to overcome the obstacle.

Torque Measuring Device Team

The first obstacle was that detailed design specifications and drawings had to be created in order to have parts custom made in the IIT machine shop. After brainstorming and consultations with professors from the department, these detailed drawings were made and given to the machine shop.

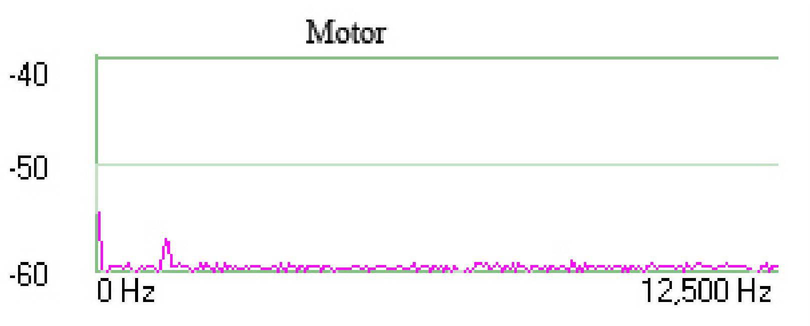
Next, prefabricated parts from various vendors had to be found, matched with other parts, and purchased. After close examine of the design, the required parts were selected and orders were placed with several different vendors.

Finally, one remaining obstacle was to conclude construction of the apparatus. It took some time for the machine shop to finish with the fabrication and assembly of the components, and then the strain gauges had to be installed and then calibrated. This finalized the construction stage and allowed the testing stage to begin.

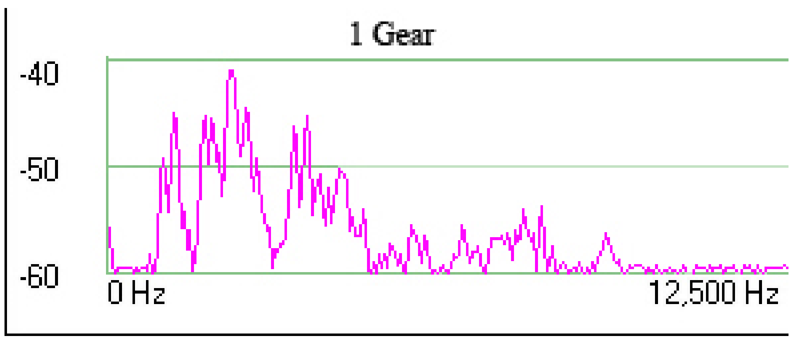
Results

The team needed to collaborate and bring all the parts together in order to determine the results.

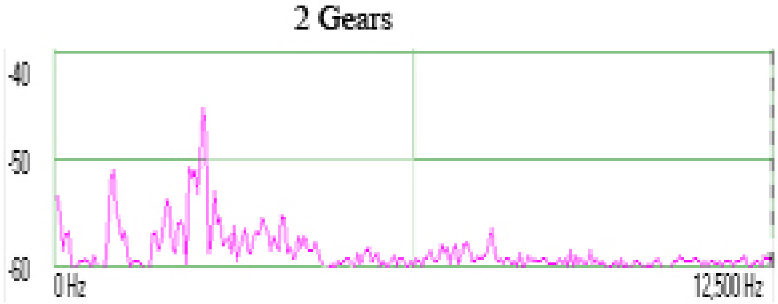
After a great deal of testing, the team was finally able to determine that the majority of the sound coming from the shredder was coming from the first gear in the gear train. The motor was isolated and the number of decibels was measured. The graph below shows the value of the decibels shows the decibels produced by the motor alone.



This next graph shows the decibels produced after the first gear was placed back on the motor.



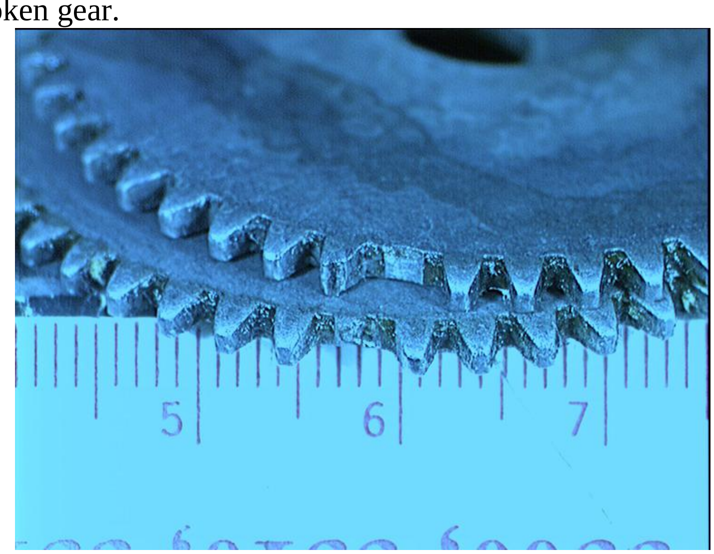
Finally, this last sound graph shows the decibels produced by adding the second gear onto the first gear and the motor.



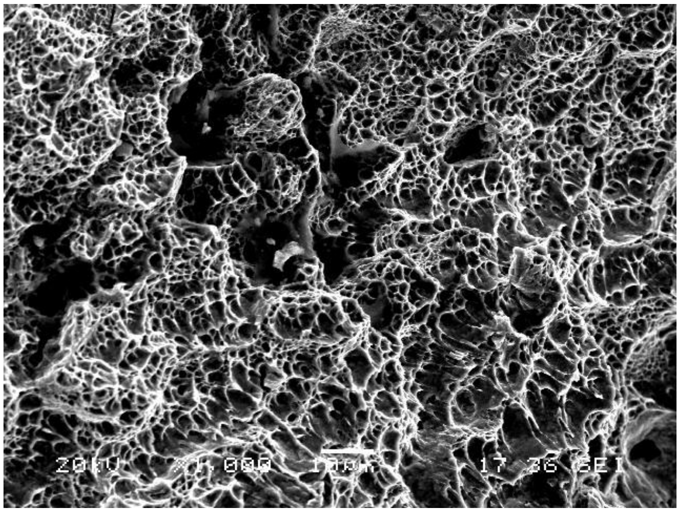
By look at the first sound graph, it can be seen that the motor doesn't produce much sound when it runs on without the gears. However, when the first gear is attached the sound jumps by at least 15 decibels. This means that a majority of the noise is coming from the first gear. However, the team continued to add more gears and test the decibels to see if each gear added more noise. Then by looking at the last graph it can be seen that the number of decibels actually drops when the second gear is added. The team determined that this was because the first gear rattles when it is alone and the second gear helps steady it.

The team performed a number of tests on one of the shredders by continually putting a larger number of papers into the shredder. However, it was expected that the motor was supposed to stall before the gears broke and that this would happen at only a few sheets of paper exceeding the maximum amount of 6 sheets. When the test was done the team was able to put 16 sheets of paper through the machine before it failed. This means that over 2x the number of sheets were able to be shred before the machine failed. Also, the motor didn't stall and it caused one of the gears to break. This showed that the motor wouldn't stall which was the original assumption.

Also, it was expected that the if a gear broke, that it was going to be the plastic gear breaking. However, when the gear broke, it was one of the metal ones. The picture below shows the broken gear.



It was greatly unexpected for the metal gear to break and therefore the team began to research why this may have happened. The break was magnified to 10 microns to determine if there were impurities in the material. The picture below shows the break in the gear magnified.



This picture shows the material to be very porous because of the sintering process it underwent. All these tiny holes make the material very brittle. This explains why the gear broke when it underwent too much force.

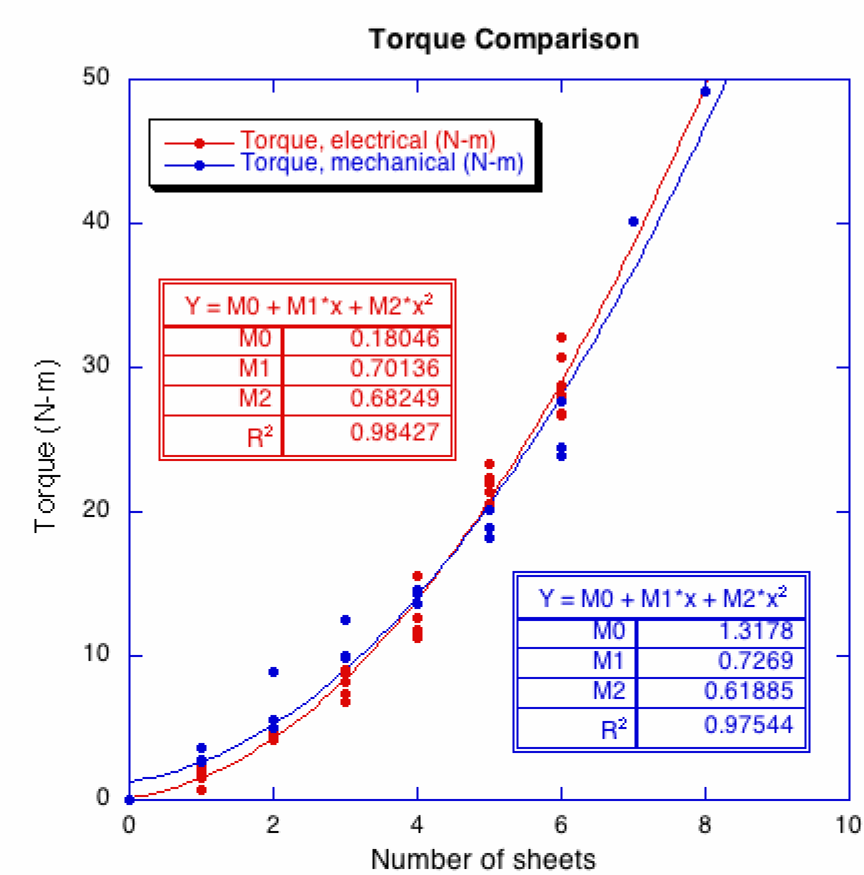
Finally, the results of the electrical and mechanical methods of measuring torque were graphed to determine the correlation. The data from the electrical method of determining torque can be seen in the table below.

V_{rms} (V)	I_{rms} (A)	ω (rps)	# of sheets	Overall τ (N·m)	Effective τ (N·m)
127.70	466.00	1.6700	0.0000	5.6713	0.0000
127.70	576.00	1.4100	1.0000	8.3026	2.6313
127.60	639.00	1.3800	1.0000	9.4035	3.7322
127.60	740.00	1.2600	2.0000	11.927	6.2557
127.60	743.00	1.2700	2.0000	11.881	6.2098
127.50	898.00	1.0300	3.0000	17.692	12.020
127.50	905.00	1.0400	3.0000	17.658	11.987
127.50	1111.0	0.9700	4.0000	23.242	17.571
127.50	1081.0	0.9900	4.0000	22.157	16.486
127.50	1231.0	0.8600	5.0000	29.046	23.375
127.50	1215.0	0.8800	5.0000	28.017	22.346
127.50	1510.0	0.8000	6.0000	38.302	32.630
127.50	1405.0	0.8000	6.0000	35.638	29.967

In comparison, the data taken from the mechanical method of measuring torque (using the torque measuring device created) is shown in the table below.

Sheets	Average Torque (in-lb)				AVG
0	4.5	3	3.5	4.25	3.8125
1	11.8	7.7	13.4	12	11.225
2	20.4	24.3	29.5	28.3	25.625
3	44.5	39.1	42	42.8	42.1
4	56	53.7	50.4	50.5	52.65
5	83	74.9	76	66.5	75.1
6	101	96.5	101	97	98.875
7	122	123	128	118	122.75
8	161	150	151	150	153

Then the results were placed on a graph together to see how closely they correlate.



This graph shows that both the mechanical and electrical torque measuring methods were relatively accurate. The equation of the lines that were found can be used to determine the value of the torque for any number of sheets.

Recommendations

The group came up with a list of recommendations for Mr. Seth Lewis, president of the Manhattan Group:

- From the broken gear and the electron microscope images we have of it we can see that the gear was made using a sintering process and this process was not done up to the level that it should have been resulting in a weak set of gears. The gear came out more porous and brittle desired. Therefore, the process of sintering the gears should be changed to create more reliable materials.
- A gear was broken while shredding 16 sheets of paper because the motor didn't stall even though this was two times the rated number of sheets. This means that motor could be downsized so that it stalls instead of breaking gears.
- Also, a slower motor with increased torque would be recommended. This will reduce maximum shredding speed at low load, but will provide more consistent speed across all loads. Reducing the motor speed will also decrease the noise level of the shredder.
- It was also determined that the maximum load rating of the shredder should not be increased. Increasing this value by just 2 sheets of paper would require an increase in drive torque of 60%, and a doubling of total input power. These increased power loads would significantly reduce the shredder lifespan.

The team also came up with a list of recommendations for future teams that work on this IPRO in order to continue progress on the work that has been started.

- Obtain competing shredder models. Pull the shredding heads out and place them in the new torque measurement device. This will find the torque curve for each shredder. The machine was created to be able to do this so different shredders can be compared.
- Also test the motors for power output. This will allow them to compare the different types of shredding heads in terms of efficiency and security level. Reverse engineering will then allow improvements to the development model.
- Measure more varied load, including 10+sheets, CD's, manila envelopes, etc. This will allow better sizing of components, and determine maximum load ratings for the shredder.

References

- Mr. Seth Lewis –*President of Manhattan Group*
- Professor Maurer – *Faculty advisor for IPRO 321*
- Professor Sheldon Mostovoy –*MMAE Professor at Illinois Institute of Technology*
- Opeyemi Babatola –*IPRO 321 student Summer 2007*
- Luke Cho –*IPRO 321 student Summer 2007*
- Russel Janota –*Director of MMAE Labs*
- Aero Gear – *Gear company*

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President of The Manhattan Group
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MMAE Professor at Illinois Institute of Technology
Professor Mostovoy made himself readily available to answer the teams questions and provide us with his expertise. He played a huge role in the design and building of the torque measuring device created this semester.

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Faculty Advisor for IPRO 321
Professor Maurer guided the team through the entire semester. He answered all necessary questions to get us started on the project and to ensure that the team stayed on schedule. He also worked with Mr. Lewis to ensure that he stayed updated on the progress and worked to get the shredders needed for the project.

Russel Janota
Director of MMAE Labs
He worked with the team to ensure that we had all the necessary equipment to perform the desired tests. He also assisted in the preparation of the torque measuring device to ensure that it was built correctly.

Machine Shop
Illinois Institute of Technology
The team would like to acknowledge the machine shop for all the work that they put into the torque measurement device. The team designed and created schematics of the machine and the machine shop took time to ensure that it was built to the correct specifications.

IPRO Department
Illinois Institute of Technology
We would like to thank the IPRO office for working to give us this wonderful opportunity. It was good experience to work as a team on a specific problem in order to please the sponsor.

Luke Cho and Yemi Babatola
IPRO 321 Students from Summer 2007
We would like to thank these two students for taking their time to guide the team based on the work they had previously done. The assisted in providing the team with the information that they had found previously and in continuing the work that was already started.