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Water Jet Cutting Head Actuator

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Water Jet Cutting Head Actuator

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Ben Heckert
Micah Steiner

Project Advisor: Dr. Shao Wang
WARDJet
Tallmadge, Ohio
Executive Summary:

As manufacturing progresses further and further into the current age of technology and innovation, different needs must be met to keep up with strict quality standards and customer demand. Some such technology is the waterjet cutting machine. Waterjet machines in comparison to laser cutting or other forms of material shaping are able to provide a cleaner, more efficient cut on a wide variety of materials with many benefits. The cutting heads of waterjet machines are able to be placed on multi-axis mounts and can be rotated to cut around three-dimensional objects, or can cut intricate two-dimensional patterns in wood, metal, foam, polymer, and glass, among most other types of material.

In an effort to increase efficiency and productivity, WARDJet was seeking a better actuation method for the cutting head on their waterjets. Current actuation methods were, for the most part, purely mechanical, relying on compressed air, springs, and water pressure to open and close the valve to 60,000 psi of water. Increasing the speed of the on/off cycle times of the waterjet would allow for faster movements of the cutting head from one cut to the next, increasing the overall amount of products cut in a day, week, and year. This obviously points to increased sales, increased profit, and increased customer satisfaction when implemented.

Initially, the scope of our project was set to design a smaller, faster actuator that could be manufactured for a reasonable price. For the best results to meet our deadline, the scope of our project was reduced to simply showing we could reduce the actuation time. Further modifications could be made once it was decided there would be significant time savings that would justify the time and money invested into the development of this concept. Initially, we needed to know what sort of time standard we would be working against with this study. To start, we completed several time trials to determine the actual lag between pressing the “on” button to when the waterjet exited the nozzle and conversely, pressing the “off” button to when the waterjet is shut off. This gave us a reference time to determine how much we should try and skim from the response time in order to have a more effective cutting head actuator. We needed to redesign the section of the actuator where our lag was occurring.

We chose to continue with the designing of our actuator with electric motors on the basis of the speed with which they can act, and the minimal time delay that exists from when they receive a signal to when they act. Ultimately, our design used a similar setup to the existing actuator, but replaced the compressed air components with a solenoid as the method to facilitate a quicker actuation. Calculations needed to be made to find the necessary force to overcome the fail-safe springs that would be used to hold the valve closed in case of a power outage. A housing was also designed to connect the nozzle to the actuator such that it could operate efficiently without interference.
Acknowledgments:

A special thanks to the entire WARDJet team for accommodating our student senior design team and allowing us to work alongside them in their offices and for making our work as easy as possible. We received much help from WARDJet, specifically Ben Adams and a few of the other project engineers at WARDJet.
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1. Introduction

Team Members:
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Ben Heckert, Mechanical Engineering
Micah Steiner, Mechanical Engineering

Project:
WARDJet Waterjet Cutting Head Actuator

Sponsor:
WARDJet

1.1 Background
WARDJet is a Tallmadge based company that manufactures waterjets for all types of consumers, from commercial and industrial giants all the way down to hobbyists and garage mechanics. From their website:

“WARDJet offers over 20 different models of waterjets from small ballscrew driven waterjets to linear motion units with high accuracy that cut at 7,000 inches per minute. No matter what your waterjet need, we have a system that will work for you. WARDJet is also known for building custom engineered systems to meet unique needs.

WARDJet takes a different approach to much of what we do. In fact, up until 2003 we were one of the largest capacity waterjet job shops in the USA when the company elected to switch gears and focus on building new waterjets for the industry. In the years following, WARDJet has gained a strong worldwide presence with many machines exported annually. WARDJet also builds a number of products to improve waterjet cutting and reduce consumable costs, including the patented WARD Pro, a waterjet abrasive recycling system.

Richard Ward is the founder and president of WARDJet, which has been operating in the waterjet cutting industry since 1995. Born and raised in Zimbabwe, Richard Ward attended the University of Cape Town and began his career as a Civil Engineer. In 1991, he had the opportunity to come to the USA on a 2 year contract to manage a company so he moved his wife and two young children across the globe with only a suitcase each. After the contract was completed, Richard started his first company in his garage—one mile from where the present 220,000 square foot facility WARDJet operates.

WARDJet builds quality waterjet cutting systems that have earned the respect of thousands of people, companies and customers all over the world.”

(WARDJet)

With the reputation that WARDJet has established in the waterjet industry, first as a job shop and now as a manufacturer of waterjets, they have set themselves up for success.

Part of that success relies on the fact that they are always trying to better themselves and their company through innovation, simplification, and being quality focused. Each of these push the engineers who design and build the waterjet machines to create the best systems possible for their customers. From this desire, the thought to create a faster actuation system began.
When a waterjet is in use, you can hear the water jet turn on from across the manufacturing floor, even with other machines running. Water, pressurized to 60,000 psi, bursts from the nozzle of the waterjet cutting head. To hold back that kind of force, a simple valve could be sufficient, but it would need to be sizeable and would most likely be too slow. However, to penetrate the material being cut, an initial high pressure is required, and for that to occur, a special system is necessary to open and close the valve quickly. The current method of actuation makes use of compressed air and springs to control the on/off function of the jet. The normal state of the valve is “always closed” by function of the springs, so in case there is a failure, the valve will not open and 60,000 psi of water will not be released from the nozzle. When the water jet is turned on, the actuator goes to work. A signal from the on board computer is relayed to the compressed air valve and it opens to enter a chamber in the actuator, which compresses the springs that are holding the valve closed, allowing the water pressure to push the valve open and flow out the nozzle.

While utilizing the compressed air is quick and efficient enough for most water jetting, there are some cases that could allow faster cutting. Knowing how long of a delay that exists is important for determining movement timing when making cuts like this, as well as knowing what the baseline timing is. To measure that time was a bit tricky. We brainstormed several ideas; the first being to use a light gate and a signal on the switch to record the time at which the button was pressed, to when the light gate was broken by the water stream. That proved difficult, as the light gate we had required a bigger diameter stream to register that it had been broken. While that would have been the most accurate method, spending a large amount of time waiting on parts and getting them to interface would have been wasted time when another method could be utilized to attain an estimate. The second idea we proposed was to use a high frame rate video camera and a signal light to measure the delay. A small LED bulb was wired into the on/off switch, so that when it was turned on, the LED would illuminate showing us the starting time for our delay. We could then count the frames, going one at a time, until we saw the stream of water leave the nozzle and get an estimate that way (see Figures 1 and 2 in Appendix C for waterjet setup with LED). This ended up being the method that we used; using a GoPro action video camera on the highest frames per second (fps) setting we recorded the start and stop time several times. We found that the average time it took the water jet to appear after turning the machine on was about 40 milliseconds (10 frames at 240fps), and the time to turn off was around 100 milliseconds (25 frames at 240fps).

While a delay of that length may seem inconsequential, it can ruin product pieces being water jetted if the cutting head begins a lead-in or lead-out before the water jet has completely stopped, causing stray cuts or unfinished parts.
1.2 Design Brief
WARDJet was a guest to the University of Akron’s senior seminar class in the Fall 2016 semester where they presented several senior design project ideas. One of those ideas was their desire for a faster actuating cutting head to implement into the production of their waterjets.

Waterjet machines are very useful in today’s fast-paced, quality driven production environment. With the ability to cut a variety of materials quickly, cleanly, without many of the side effects that come with alternative methods, waterjets are a sought after tool. For example, a company that produces a metal shell for a small laptop computer could use the waterjet machine to precisely cut the shape of the shell, and then quickly switch programs and settings to cut out the foam shapes that nest the product when it is shipped. However, when cutting the foam, careful timing must be observed so that the waterjet does not move too quickly from the current cut to the next cut. The on/off timing, though still important, is not as crucial when cutting hard, durable materials like steel; but when cutting more pliable materials like foam and plastic, the valve must be fully closed to prevent the partially closed valve jet to cut the softer material outside the designated path. Because the cutting head must sit idle for a fraction of a second at the beginning and end of each cut, reducing that fraction means an opportunity for time savings and therefore cost savings when mass producing a product.

The current style actuator being used by WARDJet and most other waterjet manufacturers works for customer needs. However, as previously stated there is an opportunity for WARDJet to gain a competitive advantage over their competitors with a time-saving cutting head actuator. With that advantage, WARDJet could get a leg up in the industry.

Ideally, the new cutting head actuator design would be better in every way, but realistically can only be improved in certain ways with the time given. The new design ultimately needs to prove that a reduction in the time required to open the valve to allow flow and conversely, to close the valve, is possible. Preferences for the new actuator prototype are that it should be roughly the same size or smaller, the cost should be reasonable, and the performance should not suffer.

2. Conceptual Design
WARDJet’s objective for this project was to minimize the cycle time of the actuating head on their waterjet cutting machines. It was clear that this was our main priority and our design should be based around improving actuation speed. This objective was even to the point of ignoring other factors if necessary, such as size and feasibility, if it meant the actuation speed would be optimized. Given the scope of the project, our top objectives
were very clear: the first priority was increasing actuation speed while maintaining a fail-safe mechanism, while our secondary priorities were small packaging and reduced cost. Our objectives for our project were illustrated and laid out using an objective tree that can be seen in Figure 3 of Appendix C.

In order to fully understand the functions of the current actuator head used at WARDJet, our team had to learn about its design. With the actuator head and manual our team received, we read about and disassembled the part in order to better our knowledge of its functionality. A functional decomposition diagram was created to display the actuator’s basic functions, most of which our new design would have to account for. This diagram can be viewed in Figure 4 of Appendix C. The basic design of the actuator currently used by WARDJet is based around four main components: compressed air, needle valve, high pressure water, and compression springs. Air is pumped into a compartment in the actuator, which causes the springs to compress and begin the process. With the springs compressed the high pressure from the water is enough force to push the needle off of the seat, and the high pressure water can pass through the small hole, which is the water jet. To stop the water jet, the air pressure is removed from the compartment, the springs decompress, and the needle is forced back into the seat which blocks the water from passing through the hole, thus cutting off the water jet. One important feature of the current actuator design we discovered was that the needle used to block and open the hole for the water jet was not solidly attached to any other part of the solenoid. The needle is inside a seal where it slides up and down to move on and off the seat. The water pressure moves the needle off the seat, and the springs expand to drop the needle back on the seat. However, the needle is hanging free besides the seal and needle bearing that it slides up and down through. This was important as we discussed potential design features to improve speed; perhaps an attached needle could improve actuation speed.

At this stage in the process we were still gathering as much information as possible about the design of the current actuator. In order to optimize the on/off cycle time, we needed to know what duration the cycle time was. This data was obtained by testing the actuator on one of the waterjet cutting machines at WARDJet. After brainstorming different ways to accomplish this, our team decided that the most feasible idea was to hook up an LED light to the machine that would light up when the waterjet is turned on. Then, by using a high speed camera we could observe the difference between the light turning on and the water stream exiting the nozzle in order to obtain our time readings. The best option for a high speed camera at WARDJet was a GoPro with 240 frames per second. This would not be as accurate of a reading as we initially hoped because we would only see frames of about every .004 seconds, which would give an uncertainty of plus/minus .0079 sec if the light comes on at the beginning of one frame and the waterjet comes out at the end of another frame. However, because this was the option most easily accomplished, we decided to continue with it and consider the results at the end if we needed to increase the
accuracy of measurement. This method worked, and we obtained the average time measured in our testing for the waterjet to turn both on and off. Surprisingly, from our results we saw that the time it takes to turn the water jet off was much higher than the time to turn it on. This is a vital piece of information as our team considered ways to shorten the wasted time while operating their waterjet cutting machine. Since the time to turn the water jet off was longer, we could focus on ways to shorten the turning off process in order to optimize our design.

Using the knowledge and information gathered from testing and studying the current actuator used, we began brainstorming and conceptualizing ideas for a better design. All different types of actuators were considered: pneumatic (currently used), mechanical, electric, and hydraulic. Some simple sketches of our preliminary electric motor designs are shown in Appendix B, Figure 1. Changes to the internal design of the actuating head were also considered as ways to improve cycle time were thought through. Specifically, our team looked at the manner in which the needle was utilized and the design of the springs. We organized and illustrated our potential ideas into a morphological chart which can be seen in Figure 5 of Appendix C.

During our brainstorming and research on actuators, we came across a design that was very intriguing and had some potential for being utilized in our project. Launchpoint Technologies, an engineering design group in California, had some technology on their website that caught our attention. Under the transportation section on their site, we found valves for a car engine that were electromechanically powered. Typically, engine valves are powered pneumatically or with cams and springs, but these have limitations. Launchpoint looked into using solenoids to power these valves with hopes of exceeding these limitations. These valves were each individually powered with a solenoid, along with an energy storage spring mechanism. This idea seemed to have potential for what we were attempting to do, so we contacted Launchpoint to ask about this technology. They sent us a study concerning their design, done as a graduate-level design project, which we used to help understand how they utilized solenoids for their actuating purposes.

With the information we obtained from Launchpoint, along with the rest of the research we conducted, our conclusion was to proceed with designing an electromechanical actuator powered by a push-pull solenoid for actuating our redesigned product.

3. Embodiment Design

3.1 Actuator Components

1. Actuator Assembly – The whole assembly of our actuator ended up being similar in mechanisms to the actuator currently in use: springs are still used to hold the needle valve closed when no flow is desired or as a failsafe in case of a
malfunction; a solenoid is used instead of compressed air to compress the springs and allow the water to flow, and the nozzle remains unchanged so our version of the actuator can be adapted to work with the current nozzle. The improvement of our design lies in the replacement of compressed air with an electronically actuated solenoid.

2. Solenoid – This is the main functioning component to our redesign of the actuator. After sitting down and learning about the current actuator with the engineers from WARDJet, we discussed ways that we could potentially improve the current design. To improve response time, we decided the best way to do that would be to incorporate electric components, as the reaction time of these components is unmatched. Small electric motors were discussed, but upon further research, we determined that larger, stronger motors would be required to hold the needle valve closed with the upward force that the pressurized water was applying to the needle. To avoid a complete redesign of the entire assembly, we continued our research and settled on using a linear push-pull solenoid to act as our actuator. The solenoid replaces the function of the compressed air in the previous design and compresses the springs to allow the water to flow.

3. Solenoid Housing – The housing serves the basic function of containing the solenoid and protecting it from the environment of the waterjet cutting area. The housing cap also provides the springs a surface to act on and keep the valve closed. If implemented into production, a gasket or seal would be integrated into the design of the housing to fully protect it from all the water. This would also contain the threaded adapter to connect to the waterjet nozzle (3-1). Reference Appendix

4. Springs – These would act as the mechanism that forces the needle valve closed during normal operation as well as in the case of a failure and will hold it closed as a failsafe in the case of the failure of another component.
5. **Needle Valve** – This valve is the type of valve that was selected for the current design of the actuator as a simple, efficient way to stop the flow of high pressure water. The needle is free-floating in the assembly and once the actuator compresses the springs, is then pushed up by the pressurized water, opening the valve and allowing flow.

6. **Nozzle** – This component is reused from the previous design. Here, the flow, once through the needle valve, is mixed with a very fine abrasive that aids in cutting materials, then flows through the rest of the nozzle and out as the cutting jet we see.

### 3.2 Design Steps

Once our team made the decision to move forward with the solenoid as the main component of our actuator, we needed to determine what kind of solenoid was necessary for our purposes. From our calculations (reference Chapter 4: Detail Design), our team found that we would need a solenoid capable of applying at least 800N of force, as well with a minimum stroke of at least one millimeter. We decided that it would be a better use of our time, efforts, and resources to order a fully functioning solenoid, as opposed to designing our own. Time was spent looking around at different solenoid options available for purchase, and we found that our specific needs for force and displacement were not very common among solenoids. The displacement of one millimeter was not a problem, as that is a relatively small displacement for a solenoid’s stroke; however, the force of at least 800N was a requirement that made it difficult to find a suitable solenoid.

With assistance from WARDJet, our searching eventually led us to a company based in the United Kingdom called Geeplus Inc., who specializes in designing and supplying advanced actuation devices. From reading through data sheets for products listed on their website, we found several push-pull solenoids that appeared strong enough to meet our requirements. We located contact information for a United States representative of Geeplus, and decided to call and ask about their products. The representative was able to answer our questions about the solenoids we were considering, and how to theoretically utilize their product for our project’s purposes. In discussions with the representative, we were able to choose a solenoid model that Geeplus had in stock to use in our prototype: model 870F, solenoid whose data sheet can be seen in Appendix D. Discussions with the
Geeplus representative continued throughout our design process, as we discerned the best way to complete the design of our actuator.

The next phase was to determine how to successfully incorporate the solenoid into our actuating head. Our team engaged in discussions on ways to change or modify the current design of the actuator, in areas the solenoid would not account for. This was mainly the springs, and the needle and seat. We brainstormed different ideas that would replace these components of the actuator head, such as one large spring instead of six smaller springs, replacing the springs with Belleville washers, or even ideas without the springs component. We also discussed potentially fixing the top end of the needle to the actuator piston rod, instead of having it move freely in its seal and needle bearing. We determined the springs were necessary for safety purposes; if the power goes out the springs will still hold the needle onto the seat, even if the solenoid is not working. Therefore, we eventually decided to use the same components for the current actuator in conjunction with the solenoid for our new design.

After the internal functions and components for our actuating head were determined, our team began to create the housing for our design. This was completed by creating three dimensional models in Solidworks using the parameters of our solenoid and springs.

4. Detail Design

In order to know what type of solenoid was necessary for our actuator, we needed to calculate several forces. First, since the force from the water at 60,000psi is the only force lifting the needle up off of the seat, it was necessary to find what that upward force was. The 60,000 psi from the water was acting on the tip of the needle, which is a conical section slanted at 60 degrees and with a length of 0.06 inches. The diameter of the needle was 0.706 inches. When the needle is in the seat and the waterjet is shut off, there is a section of the cone below the seat that the 60,000psi water is not acting on. Subtracting the area of the cone below the seat from the entire cone surface area, we were able to calculate the upward force acting on the needle from the water at 60,000psi when the waterjet is shut off. The value we got for this upward force was about 174 pounds, or 774.3N, and can be seen in Appendix A. Using this upward force, it was known that the force from our six springs had to be greater than 174 pounds in order to hold the needle on the seat and keep the waterjet off. We then were able to calculate the types of springs and the spring constants necessary to hold the needle onto the seat, which can be seen in Appendix A.

See Appendix A for calculations of water pressure on needle and necessary spring force to hold needle in place.
See Appendix B for basic component drawings.
See Appendix D for solenoid data sheet
The prototype design we decided on was an electrical alternative to the original pneumatic actuator. The decision to use an electromagnetic solenoid actuation system was largely aimed at removing the bottleneck in the response time that was due to the time required for the pressurized air to overcome the spring force in order to move the piston and open the needle valve. The response time of electromagnetic solenoids is much faster than that of pneumatic actuators; the solenoid chosen for our design is capable of executing a 2 millimeter stroke within a range of 20 - 40 milliseconds. There are also ways to change the voltage given to power the solenoid, which can optimize the delay. WARDJet has outstanding electrical engineering capabilities, and the engineers there were confident of optimizing the solenoids response time by experimenting with different voltages. The stroke required for the cutting head application is only 1 millimeter, and the current design with the pneumatic actuator had an average “on time” of approximately 50 milliseconds and an average “off time” of approximately 120 milliseconds. Therefore, it is easy to see that our new design with an electromagnetic solenoid will yield a decrease in actuation speed of 20% or more over the current design. The effect of a 10 millisecond decrease in response time may not seem like much in itself; however, that increase in speed would allow WARDJet to handle and process orders with substantially higher volumes in a timely manner.

Another potential advantage of the proposed design is the size. It is common for waterjet cutting machines to have a gantry arrangement. The gantry format is relatively simple and easy to build and implement both services that WARDJet offers. For these machines, the speed of the actuator is the primary objective and the size of the actuator takes a back seat. However, some more complex and advanced machines operate on a 6-axis arrangement for more intricate cutting capabilities. For the 6-axis waterjet machines, the size becomes a much more crucial factor. Our prototype design that maintained the six-spring arrangement will not provide any significant improvement in the overall size of the actuator. However, a potential adjustment that has been discussed for a final design is the use of belleville washers, which are much smaller than traditional coil springs. This adjustment would make the size of the solenoid itself the limiting factor in the overall actuator size rather than the space required for the spring pack, which would in turn yield a significant size reduction over the current pneumatic actuator.

Using an electromagnetic actuator system is a novel concept in the waterjet industry. Many waterjet companies use a similar pneumatic concept to the current design that WARDJet uses. This is likely due to the commonality of compressed air in factory and manufacturing environments and relatively low operating costs associated with using a pneumatic system, the main cost is the cost of operating the air compressor. In reality, the
fact that pneumatic systems are used by the majority of waterjet companies is evidence to the fact that the performance of a pneumatic actuator, in terms of response time, really is not bad; it gets the job done. A response time of 50 milliseconds is more than adequate for most processes. However, if the objective is to be able to take on high volume orders, then cutting head response time is the most obvious area of optimization. That is why the search for a new design was launched. Initial research showed that solenoid actuators have been used in some systems that require incredibly high speed, such as intake and exhaust valves in a Formula One engine. These applications typically do not require as much in the way of holding force, but it was enough to focus our search on solenoids. The only obstacle then was finding a solenoid that could produce relatively high holding force while also maintaining a fast response time.

6. Conclusions

Working on this real world engineering project alongside engineers at WARDJet was a great experience, and provided us with a better understanding of how the engineering design process evolves in real life situations. We talked to several companies on the phone, asking about their technology and how we could apply it to our problem. We also utilized 3-dimensional modeling, 3D printing, and used basic calculations from our engineering textbooks to find forces and spring rates. Unfortunately we were not able to test our prototype, as of yet, due to some unforeseen circumstances. The timeline our team had set did plan for enough time to have it tested by this point; however some unexpected complications arose during the making of our prototype which halted its progress. The setup we used on one of the WARDJet waterjet cutting machines to test the current version of the actuator, is still presently arranged for testing. Once the prototype is fully created, WARDJet can very easily test its performance to see if our design has increased the speed of the actuating head’s cycle time. We believe results will show an increase of at least 20% of actuation speed, with potential for more. Our team is confident that testing results will show an increase in actuation speed, and the main objective for our project will be met.
References:

Appendicies

Appendix A.

Figure 1: Water pressure force calculations
Figure 2: Spring calculations

Springs: Steel Compression Spring (2% plated Music Wire)
1.5" long, .025" OD, .120" wire (3 pack = $85.80)

For 870

S = 108 * 9657 k354 (McMaster)
S = 39,000 psi

For 874

Springs: 1.25" long, .750" OD, .135" wire
(9657 k342) (McMaster)
Appendix B.

Figure 1: Early idea actuation sketches
Figure 2: Actuator rough sketch

Figure 3: Actuator housing drawing
Figure 4: Housing cap drawing
Appendix C.

Figure 1: Frame capture from time delay measurement. Notice: LED illuminated, no water stream

Figure 2: Frame capture from time delay measurement. Notice: LED illuminated and water stream
Figure 3: Objective Tree

Objective Tree

Water Jet Actuating Head

Quantitative
- Actuating Speed 0.3
- Size 0.03
- Cost 0.07

Qualitative
- Safety 0.4
- Quality 0.1
- Usability 0.1

Figure 4: Functional Decomposition Diagram
**Figure 5:** Morphological Chart

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<th>Springs/Safety</th>
<th>Power Source</th>
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**Figure 6:** Green: Spring retainer/Housing cap  
Blue: Solenoid housing  
Red: Nozzle attachment
Appendix D.

Figure 1: Geeplus 870 Solenoid Data sheet