Magnetically Damped Passive Valve

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Overview

"Check valves are the bane of my existence."
– James A. Richard, ER33 Asst. Branch Chief

Passive valves, such as check valves, are a common component in propulsion systems, designed to allow fluid flow in only one direction. Shown in Figure 1, pressure builds, forcing the poppet to compress an internal spring, at which point fluid is able to escape through the valve. Unfortunately, passive valves must be sized for very specific flow, however, in jet propulsion applications, extremely high flow is necessary for takeoff, whereas low flow is typical for the valve's lifetime in space.

During low flow conditions, the poppet begins to chatter, where high frequency differential pressure drops cause the poppet to 'hammer' against the seal seat, causing premature degradation of the components. The goal is to develop a design for a magnetic damping system for passive valves, which will utilize forces produced by magnets within copper tubes according to Lenz's Law to decrease chatter frequency. The application of a magnet inside of a copper tube induces eddy currents in the copper, which (by Faraday and Lenz's Laws) produce a force which opposes the direction of motion. This research intends to establish a mathematical model of design parameters, including magnet strength, copper tube wall thickness, and damping rates necessary. These parameters will then be compared to empirical data gathered in a previous experiment to determine validity. Upon narrowing design parameters, a prototype will be developed using additive manufacturing, and flow tested to evaluate efficiency. Should the design prove to significantly dampen the frequency of passive valve chatter after testing and evaluation, its implementation could be widespread both in jet propulsion sciences and commercial fields, allowing passive valves to function in much wider ranges of flow without relying on traditional damping methods subject to mechanical wear.

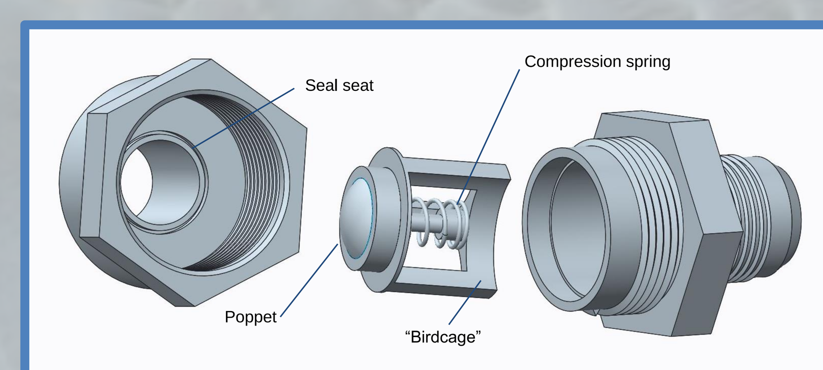


Figure 1: Check valve, a type of passive valve

Data & Mathematical Modeling

James A. Richard and David Eddleman developed an experiment in 2015 to investigate potentially relevant variables for a mathematical model of Lenz forces in a harmonic system. Using "The Pogo Pulser" (described briefly in Figure 2) copper tubes of varying thicknesses and inner geometry were attached to a piston driven by a compressor and motor. Centered within the tube, different magnets were fixed to a stationary load cell to measure the opposing force produced versus piston velocity. Preliminary analysis showed that using an average angular velocity based on the RPM of the motor was insufficient, so the Pogo Pulser setup was re-analyzed using kinematics to produce a more accurate sinusoidal model of instantaneous velocity of the piston. With this new velocity model and a combination of several equations from published journals on magnetic drag forces within a copper tube[1], a more accurate mathematical model was formed as a function of increasing velocity of an oscillating piston:

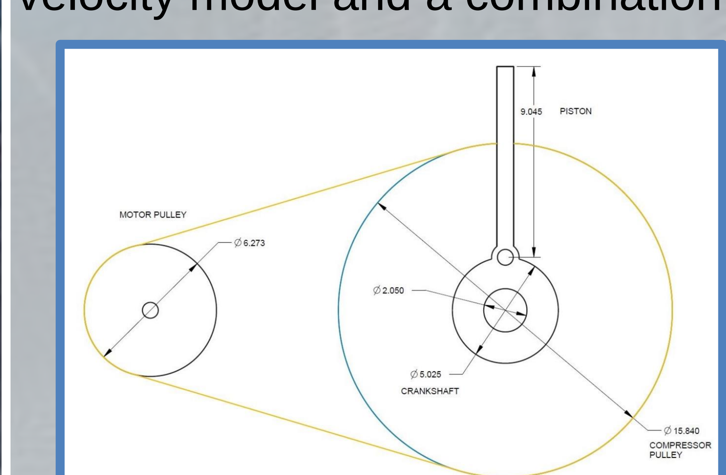


Figure 2: Diagram of the "Pogo Pulser" experimental setup. The piston connected to copper tubes of varying thicknesses (not shown), which oscillated vertically. A load sensor measured force produced on a stationary magnet due to Lenz's Law. The RPM of the motor (featured in Figure 1 above) can be translated to linear velocity of the piston by

$$v_p = -r\omega\left(\sin\theta + \frac{sin2\theta}{2\frac{l}{r}}\right)$$

$$F = \frac{15\pi^2\sigma\mu^2(b^3-a^3)}{64a^3b^3}\left[-r\omega\left(\sin\theta + \frac{\sin 2\theta}{2n}\right)\right]$$

where σ is the conductivity of Cu-101; μ is the magnetic dipole moment; a and b are the inner and outer diameters of the tube, respectively; and the expression in brackets models the tube's linear velocity detailed in Figure 2.

Due to the complex nature of magnets, the magnetic dipole moment μ is an approximation based on parameters from K&J Magnetics, our supplier. Though this equation maps to the data gathered, it produces results a force ~2x higher than experimental data (see Figures 4 and 5). This variation is currently being investigated, and is suspected to be caused by millimeters of error in the experimental setup.

[1] *Donoso, G., C L Ladera, and P. Martin. "Magnet Fall inside a Conductive Pipe: Motion and the Role of the Pipe Wall Thickness." European Journal of Physics 30.4 (2009): n. pag. Web. 13 June 2016.*

Irvine, Benjamin, Matthew Kemnetz, Asim Gangopadhyaya, and Thomas Ruubel. "Magnet Traveling through a Conducting Pipe: A Variation on the Analytical Approach." Am. J. Phys. American Journal of Physics 82.4 (2014): 273-79. Web. 18 July 2016.

Research & Design

According to Faraday's Law of Magnetic Induction, the induced electromotive force (EMF) of a closed circuit is proportional to the time rate of change of enclosed magnetic flux—as anticipated, the data (and model) both show a direct relation between force, velocity, and copper tube wall thickness, as well as magnetic strength. This model indicates that thicker tubes, stronger magnets, and tighter clearances will produce the strongest opposing force.

Based on these findings, a design has been developed for a magnetically damped check valve to be additively manufactured after the creation of this poster. To simplify analysis, this magnetically damped passive valve will be flow tested to intentionally chatter in low flow conditions. The frequency of chatter will be audio recorded, and then compared to the frequency of chatter (if any) after adding the new magnetic damping component. This design utilizes modularity to easily test axial and diametric magnets, as well as different magnet configurations. This will maximize efficiency in future testing without rebuilding the prototype valve. Figure 3a shows a magnetic field strength diagram of one prototype magnet from K&J Magnetics, a RX038DCB-N52, which is bored in the center to fit a #6 screw. Due to the "doughnut shape," flux lines are shown to be more concentrated along the magnet's exterior. This is essential for inducing the necessary damping force to combat valve chatter. Figure 3b shows the effect of ferromagnetic plating on flux lines, which could also be added to the tubing interior to maximize flux (and consequently, force).

Should this design prove to be successful, it will be submitted for a patent for use in both scientific and commercial applications, effectively eliminating valve sizing expenses and drastically increasing flow variability in passive valves.

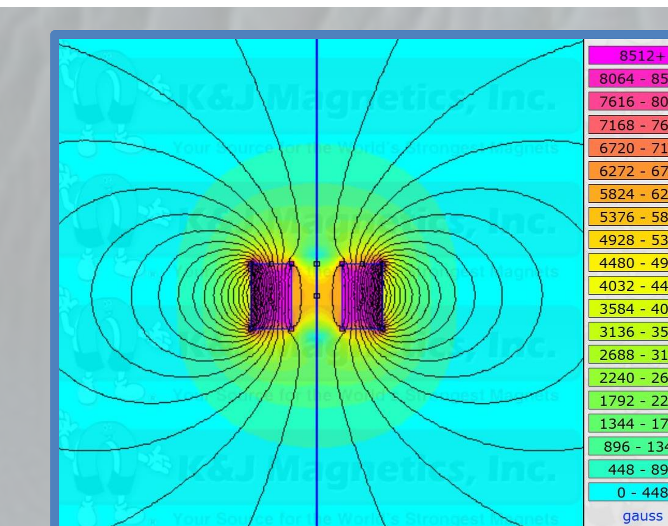


Figure 3a: Magnetic field strengths as a function of distance, RX038DCB-N52, axially magnetized, (K&J Magnetics). The copper tube's intersection with flux lines induces eddy currents in the tube wall, producing a force opposing the magnet's motion.

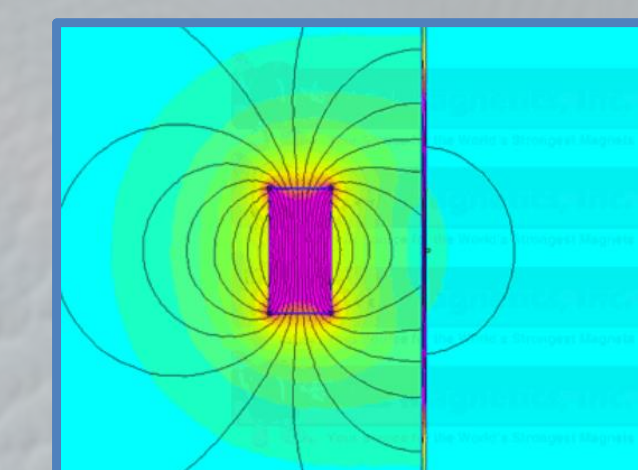
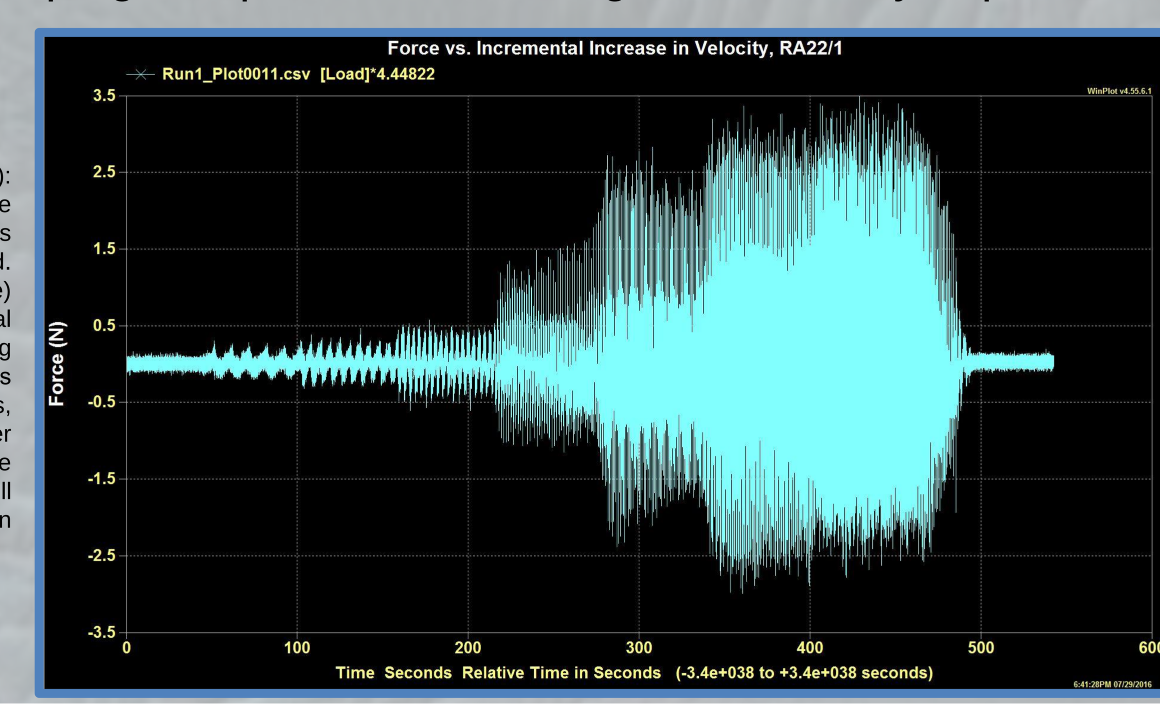
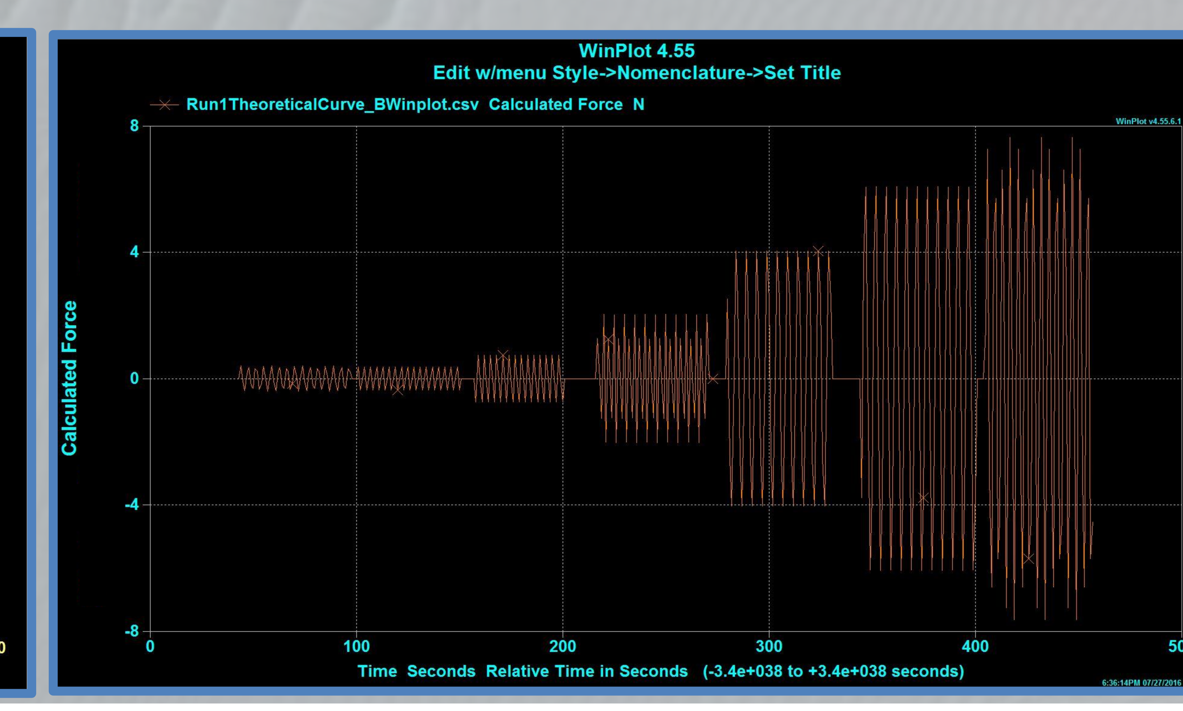


Figure 3b: The vertical line represents a steel (or ferromagnetic) plate, attracting flux lines. Future work may include plating the interior walls of the copper tube with ferromagnetic materials, potentially increasing eddy currents and maximizing force without increasing magnet strength. (Source: K&J Magnetics, *Shielding Materials*)

Figure 4 (Left, blue): Graph of Force Vs. Time as angular velocity is incrementally increased. Figure 5 (Right, orange) shows the theoretical model of the forcing function given this test's magnet specifications, dimensions, and copper tube dimensions. The missing factor of 2 will need to be explored in future work.





Future Work & Acknowledgements

- The factor missing from the theoretical model likely results from magnets not being centered on the load cell, causing inaccuracy in magnetic dipole moment calculations. Future tests could prove beneficial with extreme care taken to center the magnets within the tube to prevent random errors.
- Future testing with axially and diametrically magnetized components is recommended. Research indicates that spherical magnets may not only be stronger due to increased flux density, but easier to use in calculations of their magnetic dipole strength due to their geometry. Some published works do perform these calculations in detail with cylindrical magnets, but require a deeper understanding of partial differential equations.
- Utilizing the organized data, future work can still be done to investigate the differences in forces that could be caused by variations in inner-diameter geometry and length of the copper tubes—ideally using a software package such as FEMM.
- The new design still requires detailed force and flow analyses to ensure normal functionality.

It has been my heartfelt honor to work with Jim Richard and David Eddleman this summer, who have not only taught me more about the engineering process, but about the insight, passion, and ingenuity that NASA values.

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