Magnetic Damping with Phased Mass Approach

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Overview

The dynamic vibration absorber was invented in 1909 by Hermann Frahm (US Patent #989958), and since then it has been successfully used to suppress wind-induced vibration and seismic response in buildings. Since then, many damping mechanisms have evolved to include a secondary mass and spring to provide counter inertia to vibrations. Later, the 'tuned mass damper' (TMD) was developed, where the secondary spring-mass system *also* has its down damper to dissipate energy from the system.

Robert Berry, Jeff Lindner, and the EV team here at Marshall has developed an entirely new approach to damping vibrations. Rather than 'bleeding energy' from the system from the damping constant, they found that introducing a compressible degree of freedom fundamentally changed the system by passively disrupting & altering the dynamics, dubbed "the phase mass approach." This is mathematically complicated, and involves complex modes and imaginary components in harmonic systems—however, in practice, it's fairly simple: a device was introduced which provided a *constant resistance*, altering the *phase* rather than providing a counter force.

With this controlled phase lag, the dynamics of the system were fundamentally altered, which effectively dampened the vibrations in their system by (in some cases) 35 times more than expected. This lead to the development and patent of the VARR (Variable-Aperture Reciprocating Reed) Valve, which controls fluid flow back and forth between two chambers. The VARR's self-compensating orifice effectively eliminated the differential pressure, and thus, the vibrations nearly ceased. The team is working to create oil and magnetic elements that behave within the system as the VARR does.

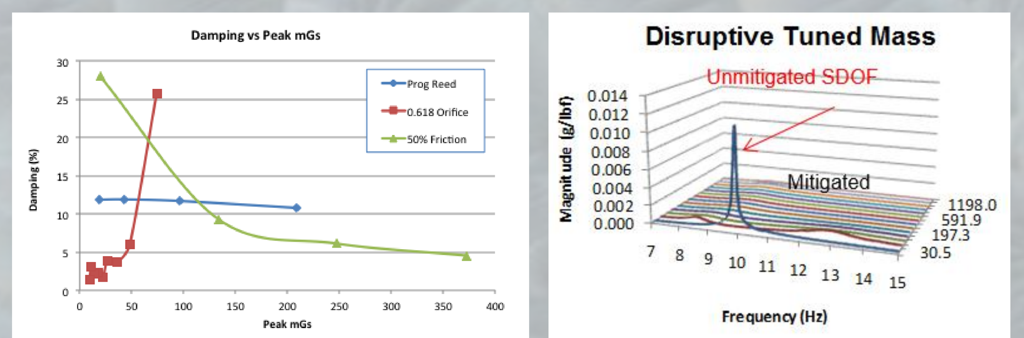

Figure 1: Variable orifice reed valve performance vs. standard orifices. Due to the reed valve's self-compensating nature, it produces a constant damping force which disrupts the system very similarly to a disruptive tuned mass, but with fantastic results. On the right you can see the reduction of amplitude compared to the unmitigated single degree of freedom mode.

By creating a magnetic element which produces constant force throughout the duration of a 2-pi cycle, the same damping effects should be expected.

Theory & Mathematical Modeling

James A. Richard and David Eddleman in ER33 developed an experiment in 2015 to investigate potentially relevant variables for a mathematical model of Lenz forces in an oscillating system. Using a unique experimental setup, 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[1] on magnetic drag forces within a copper tube, a more accurate mathematical model was formed as a function of increasing velocity of an oscillating piston:

$$F = \frac{15\pi^2\sigma\mu^2(b^3 - a^3)}{64a^3b^3} * v$$

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 v is the velocity, which changes constantly throughout the duration of the 2-pi cycle.

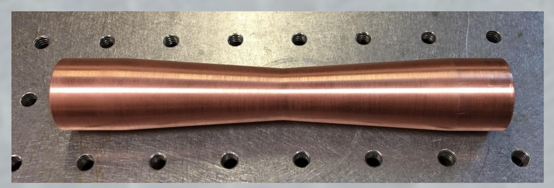

Figure 3: Copper tube profiled to increase resistance at the ends (v=0) and decrease resistance in the center (v max).

Expanding on this experiment this fall, tubes of variable thicknesses were developed to linearize the forces throughout the stroke. At the oscillation turnarounds, velocity is 0, and the maximum velocity occurs in the middle of the tube. To linearize the drag forces, the resistance at turnaround must be increased, and the resistance in the center of the stroke must be decreased. The best way to do this would be to increase copper tube thickness at the ends and decrease it in the center, pushing the magnetic drag to a constant.

Other proposed setups included solid copper profiles oscillating through the center of a Halbach array, though throughout one stroke the copper volume *and* tolerance would be changing parametrically.

[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 & Data

To kickoff research, several magnets were probed with a Gauss meter to understand the magnetic field of different shapes & sizes of magnets. As a function of distance from the surface of the magnet, the magnetic field exponentially decreases, losing roughly 30% of its strength in the first millimeter, and 50% of its strength in the second. This clearly indicated that tolerance is a key player missing from the original mathematical model.

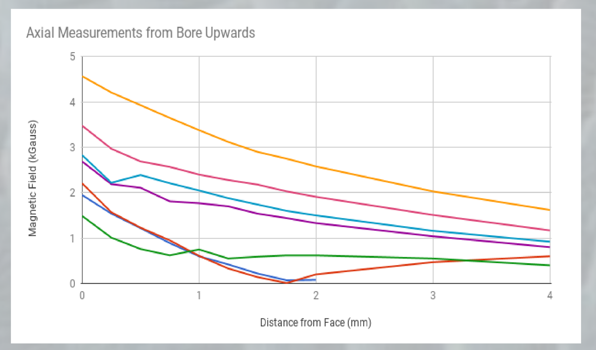

Figure 4: Magnetic field strength as a function of distance from the surface of several magnets. Note: Measurements taken from the poles outward on all magnets except one denoted in green; the green lines corresponds to the adjacent side on a diametric magnet, which remains relatively constant.

In an arrangement utilizing external magnets, this factor can be leveraged—however for the purposes of our experiments, the tolerance of the profiled tube inner diameter must be both tight and consistent.

To test the mathematical model, an experimental setup was devised to oscillate different magnetic arrangements inside a copper tube of constant thickness. This experiment showed that magnetic drag is directly proportional to velocity as predicted, and also that magnetic arrangements of reversed polarities increased magnetic drag forces roughly by a factor of 3, as shown in the figures below.

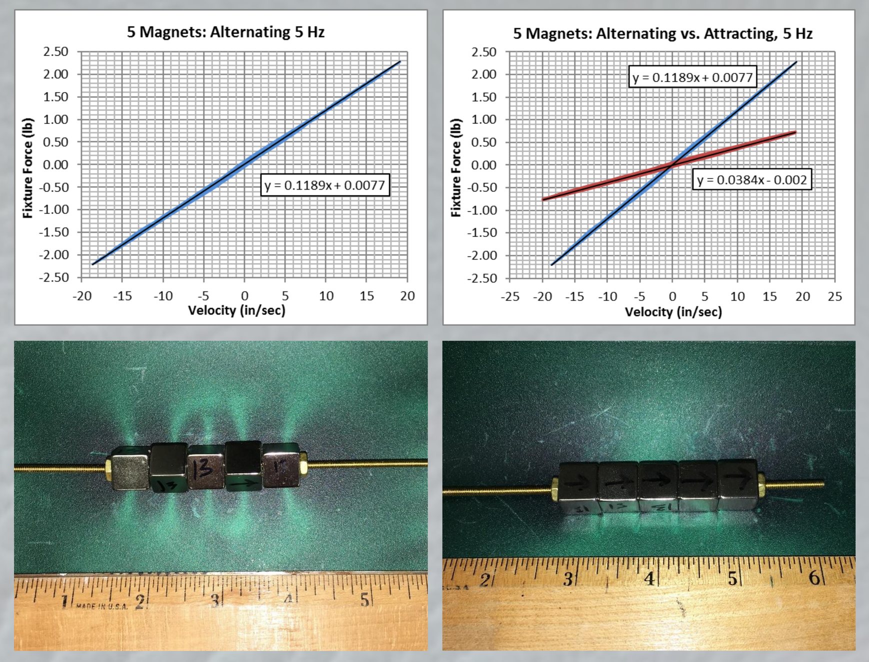

Figure 5: (Top Left) Force versus velocity of the arrangement shown bottom left. (Top Right) Blue line shows same alternating arrangement; red line corresponds to the attracting arrangement shown bottom right.

Not only does the alternating arrangement produce more drag force, but adding magnets in this arrangement linearly increases force, and the magnetic field shape resulting can be controlled in a way which reduces need for magnetic shielding around future components.

Further testing is currently being conducted on the profiled copper tubes, utilizing several different shapes to increase forces at the ends of the tubes and decrease forces in the center, ideally linearizing the system. Preliminary results of this experiment should be available by the time this poster is presented.

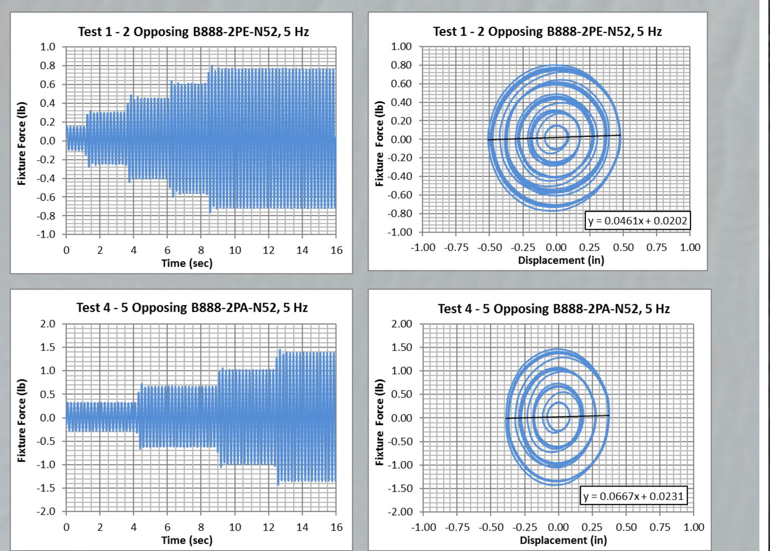

Figure 6 (above): Test 1 involved 2 opposing magnets in a constant-thickness tube; test 4 involved 5 magnets. The behavior of the system is nearly perfectly linear, though the "tilt" of the ellipse is likely caused by fringe effects of the magnets interacting with the tube.

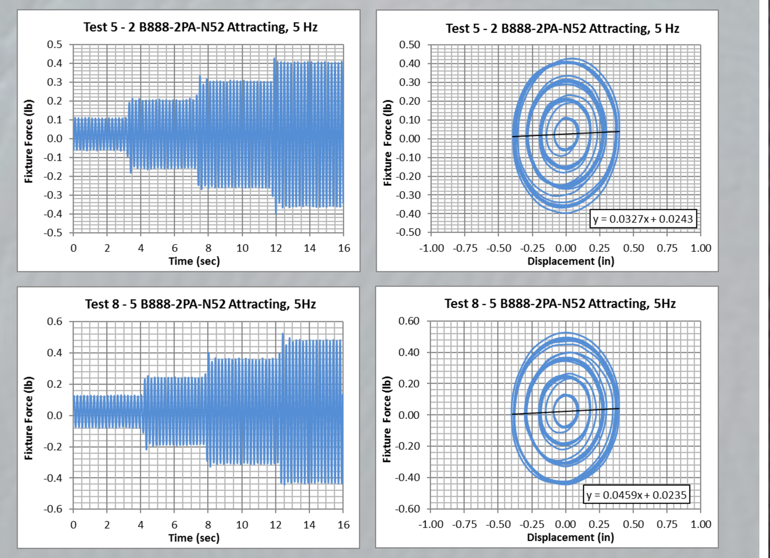

Figure 7 (above): Test 5 involved 2 attracting magnets in a constant-thickness tube; test 8 involved 5 magnets. Due to the magnetic field concentration differences between attracting and opposing magnets (details in Figure 5) the forces output are only 30%-50% of their opposition counterparts. Also, in adding magnets, the field is increased with a diminishing return.

Future Work & Acknowledgements

- This research will be continued from a "telework-study" position when I return to Oregon, where I will assist in onboarding new interns, providing recommendations, and assisting with electromagnetic principles.
- Future testing with axially and diametrically magnetized components is recommended, though a holster for opposing arrays would be necessary to prevent quantum torqueing of the magnets on the piston.
- Creation of a Halbach array with concentrated magnetic field inside of a magnet ring was difficult without more specialized tooling. In creating this array, solid rods can be oscillated concentrically, which allows for the leveraging of tolerance as well as electromagnetic parameters previously discussed.
- Other potential variables can be leveraged through utilizing magnets in attraction or repulsion to linearize the system.
- Rotational components using a "C-shaped" Halbach array could prove useful in passively disrupting the system.

It has been my heartfelt honor to work with Robert Berry and Jeff Lindner this fall, who have not only taught me more about the engineering process, but about the insight, passion, and ingenuity that NASA values.

I would also like to thank Samantha Frederick, Frederick "Fritz" Gant, and Adam Martin for their guidance and support as we sought to unravel the mysteries of magnetism in mechanical applications.

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