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A Liquid-Gas Dynamic System under Vibration

Timothy J. O'Hern, John R. Torczynski, and Jonathan R. Clausen

Engineering Sciences Center

Sandia National Laboratories

Albuquerque, New Mexico, USA

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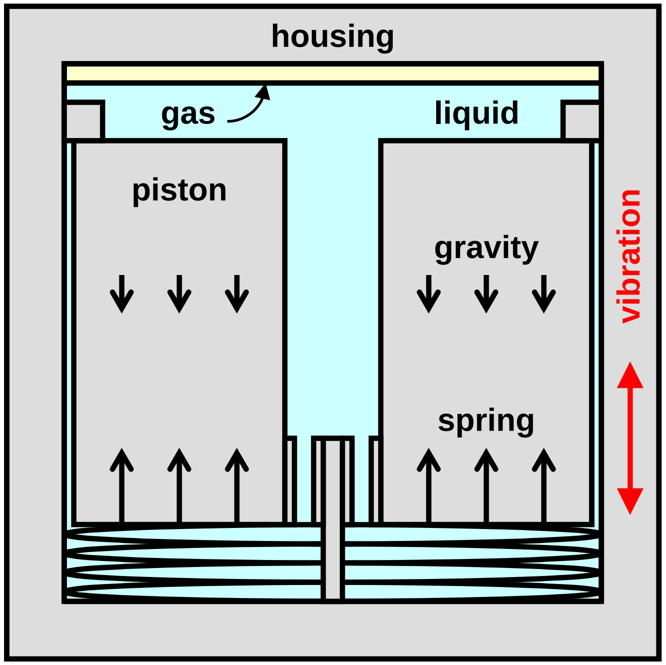
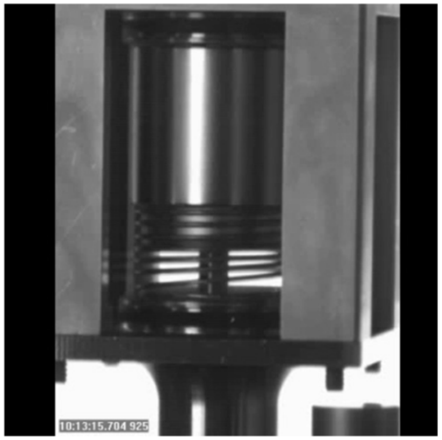
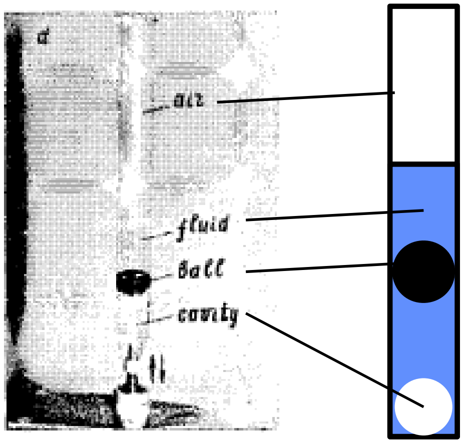
Outline





1. Background/Motivation/Define
2. Experiments
3. Theory
4. Simulations
5. Conclusions and Future Work

Strange Vibration-Induced Dynamics



Chelomey (1984)[1]

- Heavy ball resting at bottom of liquid-filled tube
- Vibrating the tube causes the heavy ball to rise vertically in the tube
- Ball reaches a stable state with air cavity visible at the base of the tube

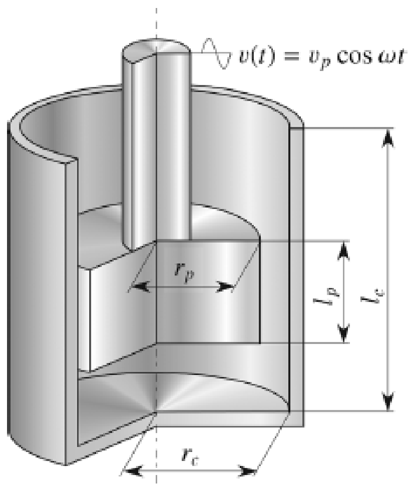


Fig. 3 Cross-sectional view of an oil damper

Asami et al. (2014)[2]

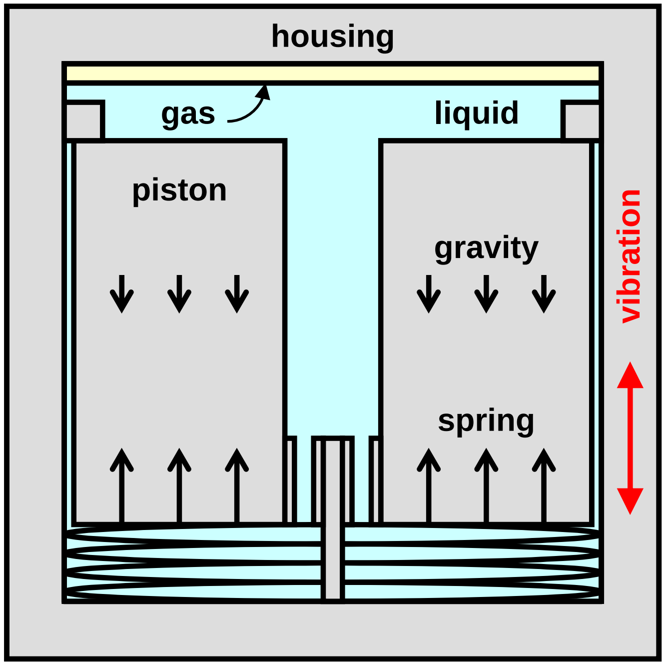
- Numerically and experimentally studied flow field around moving piston in damper
- Measured flow field above and below driven, oscillating piston
- No gas was present

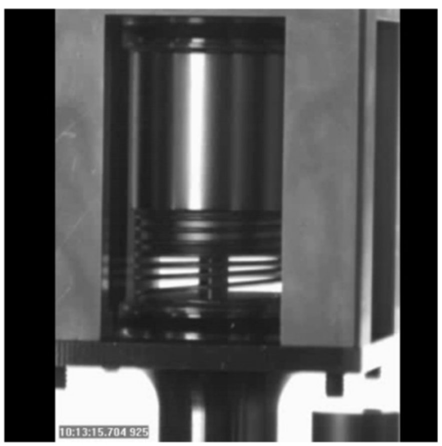
1. Chelomey, V., (1984), “Paradoxes in Mechanics Caused by Vibrations,” Acta Astronaut., 11(5), pp. 269–273.

2. Asami, Honda, and Ueyama, (2014), “Numerical Analysis of the Internal Flow in an Annular Flow Channel Type Oil Damper,” J. Fluids Engineering, 136.

Strange Vibration-Induced Dynamics

Sandia National Laboratories



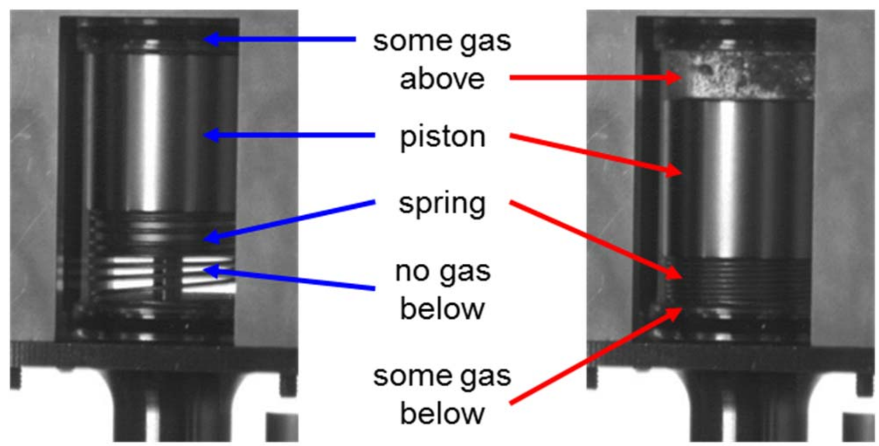


Spring-mass-dashpot system

- Piston moves vertically in housing
- Spring supports it against gravity
- Viscous liquid provides damping
- Small amount of gas is present

Housing is vibrated vertically

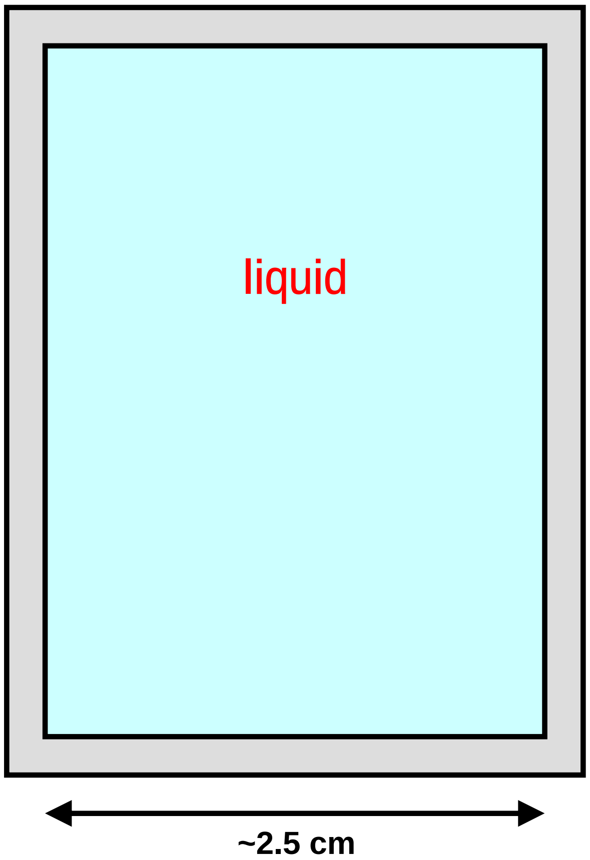
- Gas moves down below piston
- Piston moves down against spring



Vibration off
Spring supports piston

Vibration on
Piston compresses spring

Fill a Housing with a Liquid



Cross-section of cylindrical liquid-filled housing

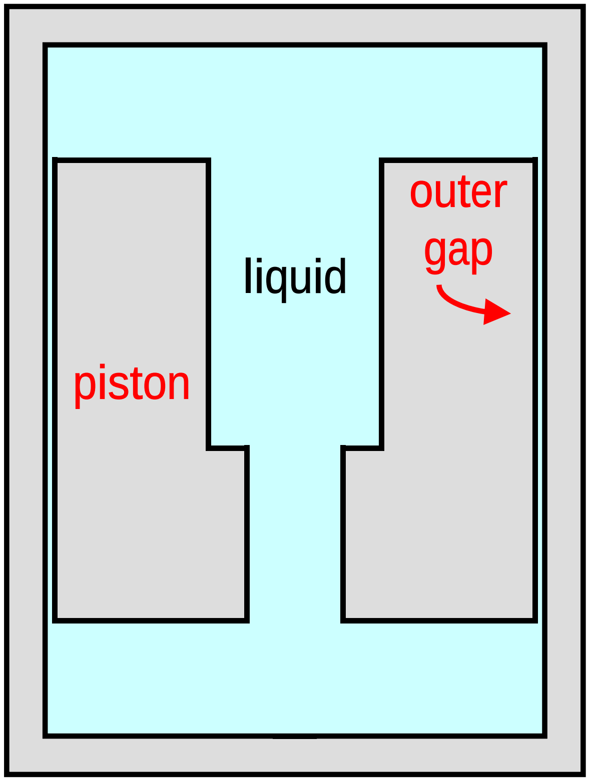
Make a cylindrical housing

- **Stainless steel, completely rigid (thick acrylic for experiments)**
- **ID ~ 2.5 cm, height ~5 cm**

Fill it with incompressible liquid

- **Typically PDMS silicone oil**
- **Density ~ water density**
- **Viscosity ~20x water viscosity**

Put a Piston Inside the Housing



Cross-section of cylindrical liquid-filled housing and piston

Piston is basically cylindrical

- Stainless steel, ~8x liquid density

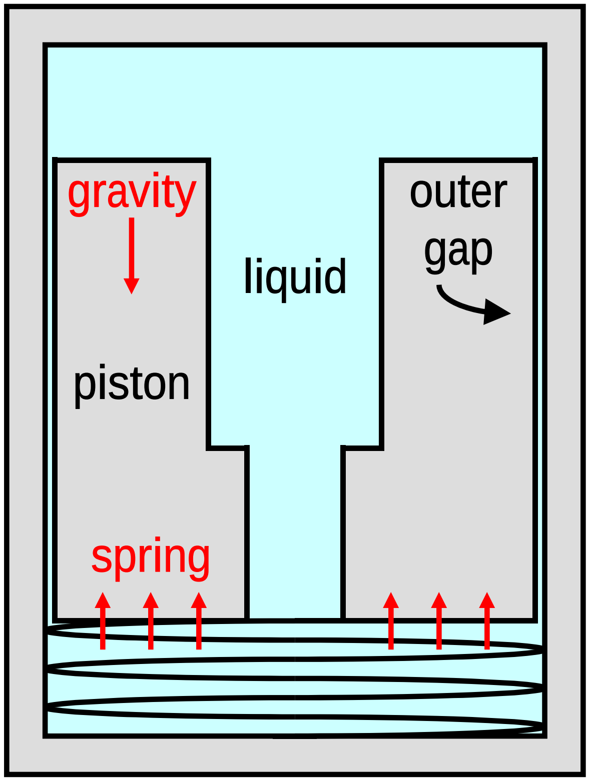
Piston and housing define outer gap

- Outer gap is ~10^{-3} piston diameter
- Piston can move only vertically

Piston has hole along axis

- Diameter varies with position

Support the Piston with a Spring



Cross-section of cylindrical liquid-filled housing, piston, and spring

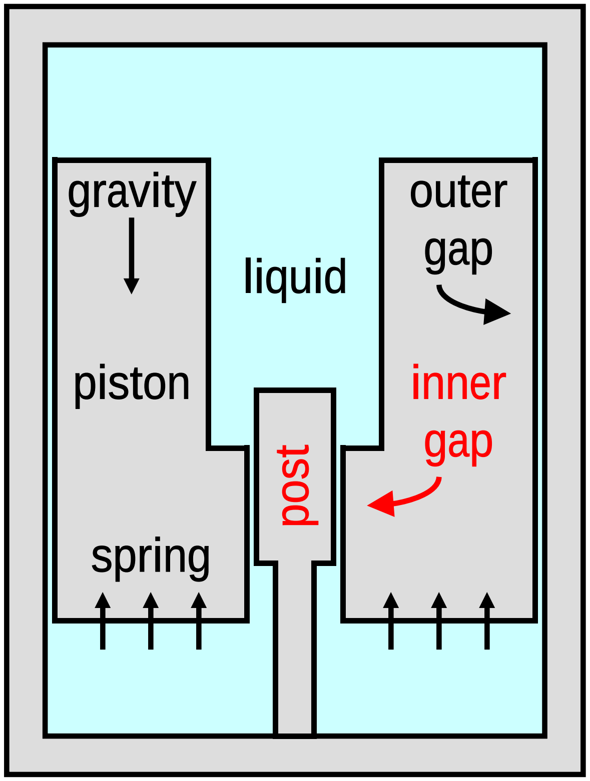
Piston wants to sink to bottom

- Gravity pulls down on everything
- Buoyancy is much less than weight

Support it from below with a spring

- Helical coil of very narrow wire
- Only its force shown in later figures

Add a Post to Specify the Damping



Cross-section of cylindrical liquid-filled housing, piston, spring force, and post

Post is fixed firmly to housing

- **Diameter also varies with position**

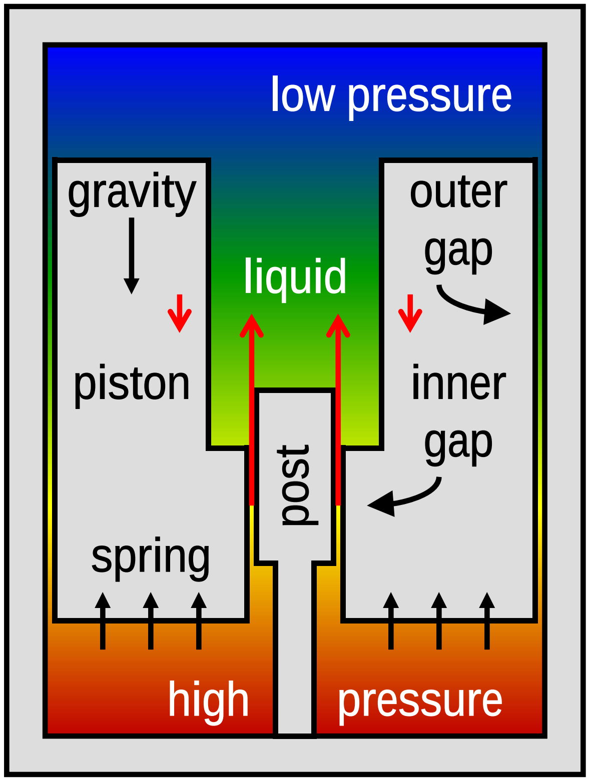
Piston and post define inner gap

- **Inner gap ~4x as wide as outer gap**
- **Inner gap flow resistance ~10^{-2} that of outer gap**

Damping depends on piston position

- **Damping proportional to gap length**
- **Gap shortens (reducing resistance) as piston moves down**

Try to Move the Piston



Poiseuille flow in gaps

Piston and liquid motions are coupled

- **Suppose piston moves down**
- **Liquid flows up through inner gap**

Resistance to piston motion is large

- **Inner gap has small cross section**
- **Liquid velocity in gap is very large**
- **Opposing pressure is large**

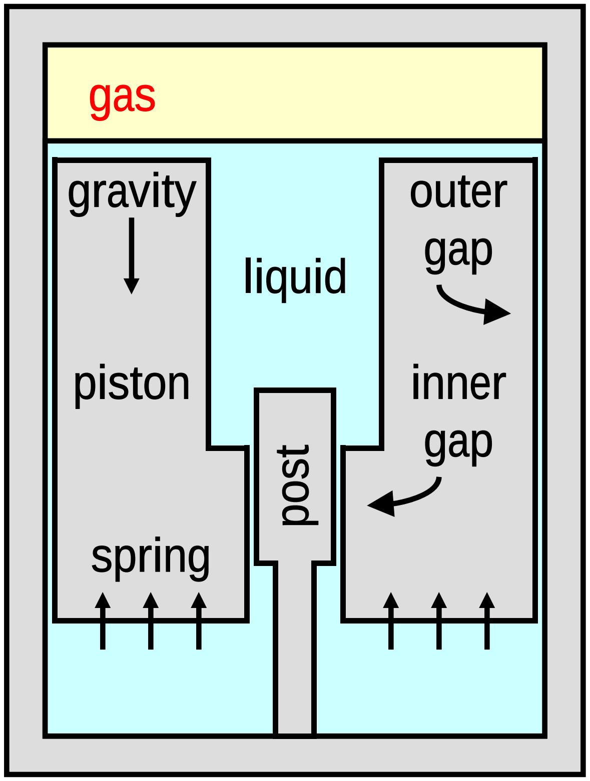
Liquid-filled system is overdamped

- **Acting as intended: a dashpot**

Piston-spring "resonance" irrelevant

$$\omega = \sqrt{\frac{K_{\text{spring}}}{M_{\text{piston}}}}$$ is highly overdamped

Now Add Some Gas



Air, nitrogen, or argon is typically used

- Gas is filtered, humidity controlled

Gas prevents housing from bursting

- Oil has large thermal expansion
- Steel has small thermal expansion

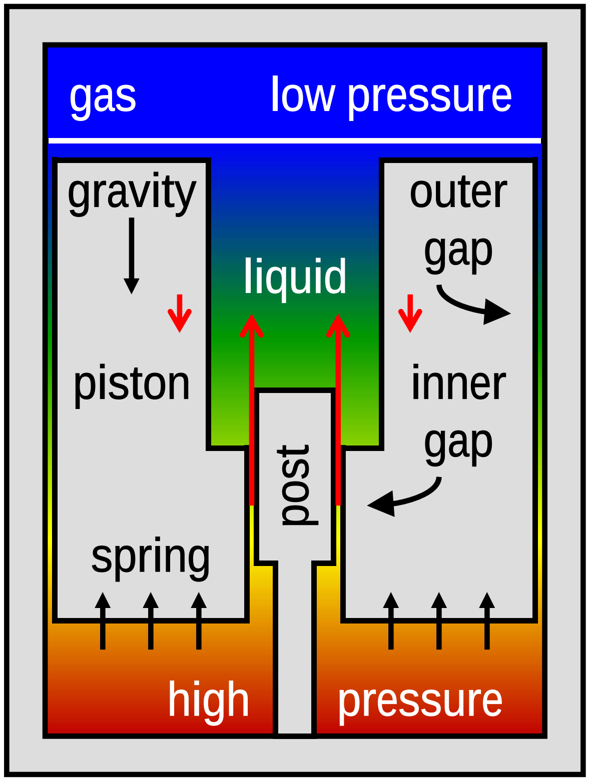
Gas is generally at top of system

- Buoyancy

Some could be trapped under piston

- For the moment, suppose not

Try Again to Move the Piston



Piston and liquid motions still coupled

- **Suppose piston moves down**
- **Liquid still must flow up through gap**

Gas volume cannot change, no effect

- **Liquid and solids are incompressible**

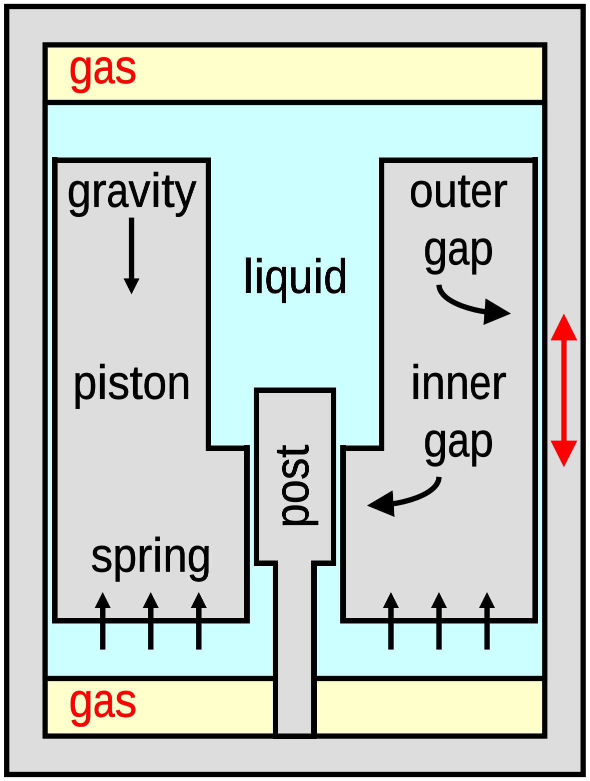
Resistance to piston motion still large

- **Inner gap has small cross section**
- **Liquid velocity in gap still very large**
- **Opposing pressure still large**

Gas-at-top system still overdamped

- **Acting as intended: still a dashpot**

Now Vibrate System Vertically



Bubbles under vibration can move in unexpected ways!

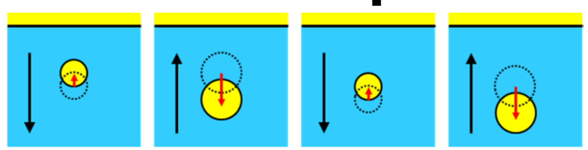
$g = g_0 + g_1 \cos\omega t$

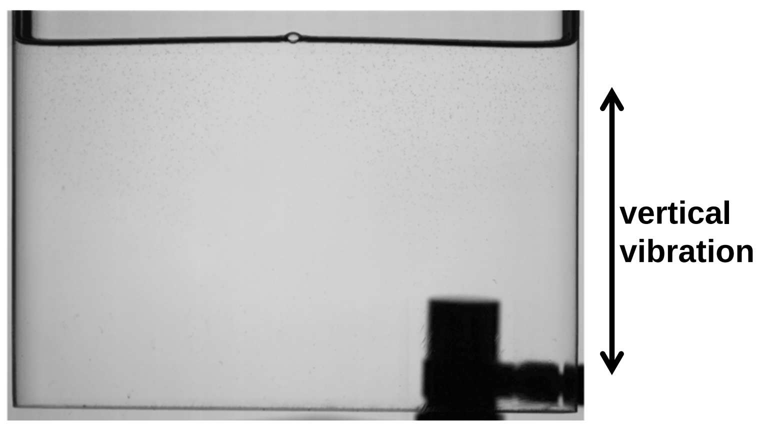
Some gas moves down below piston!

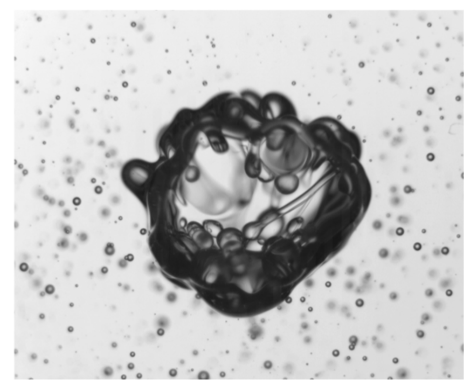
- **Bjerknes forces push bubbles down**
- **Create & stabilize a lower gas region**

Two gas regions: upper and lower

- **Both are quasi-stable (stationary)**

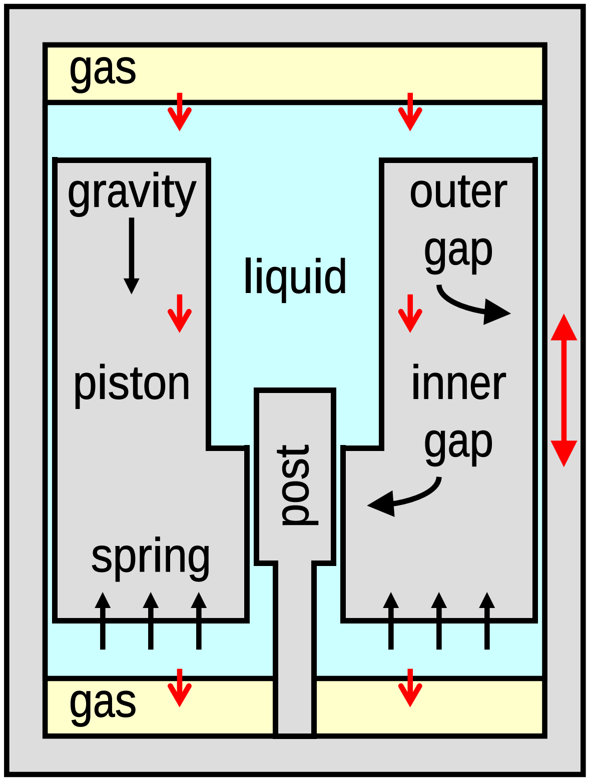






T. J. O'Hern et al., Phys. Fluids, 091108 (2012).

Vibration Makes Piston Move Down



Couette flow in gaps

Gas regions form pneumatic spring
- **One expands, the other compresses**
- **Stiffness is ~10^2 of helical spring**

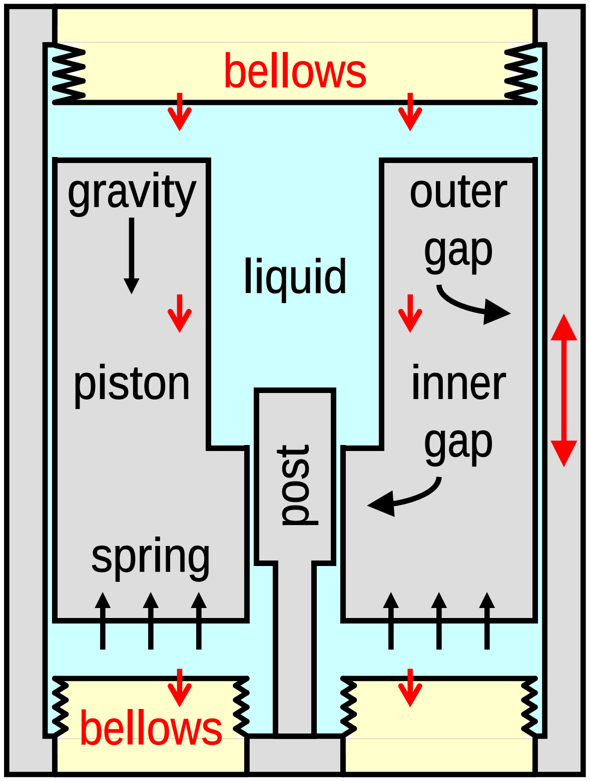
Enables new mode with low damping
- **Piston and interfaces move together**
- **No liquid is forced through inner gap**

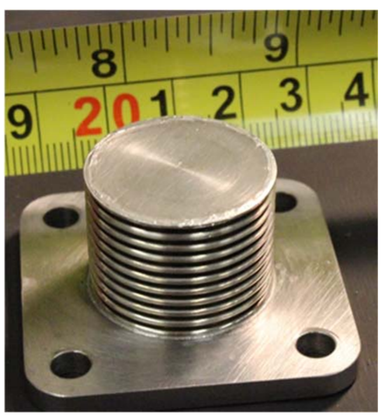
Low damping gives strong resonance
- **Piston+liquid mass and gas spring**

Gap nonlinearity produces net force
- **Damping depends on piston position**
- **Moves piston down to shorten gap**

$$\omega = \sqrt{\frac{K_{\text{gas}}}{M_{\text{total}}}}$$ has very low damping

Analyze Analogous Bellows System





Gas regions are hard to analyze

- **Upper/lower split of gas is not known**
- **Motion is transient and complicated**

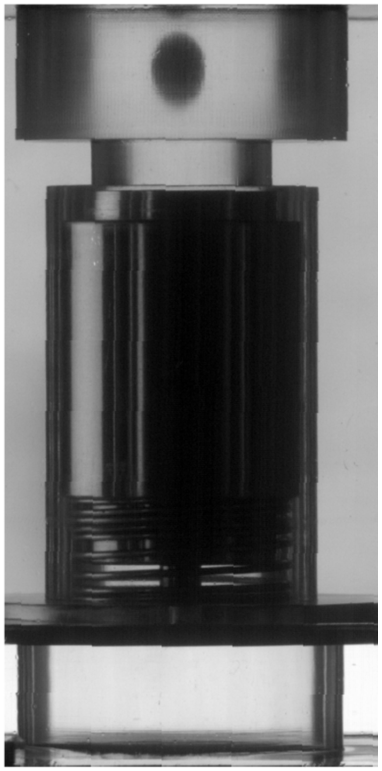
So replace gas regions with bellows

- **Compressibility is well characterized**
- **Choose pressure-volume properties to be similar to gas regions**
- **All incompressible materials between bellows so they must move in unison (one extends, other contracts)**

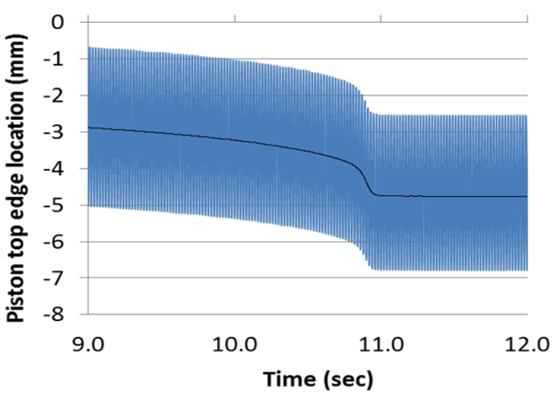
System suited to theory & simulation

- **Liquid: incompressible Navier-Stokes equations with moving boundaries**
- **Solids: Newton's 2nd Law ("F = ma")**

Experiments with Bellows



20 cSt, 70 Hz, 9.4 g (recorded 2000 fps, decimated to 40 fps)



Different bellows sizes chosen to act as bubbles of typical sizes

- **Commercial Servometer bellows**
- **d = 2.5 cm and d= 1.9 cm bellows span expected compressibility range**
- **Control experiments without bellows**
  - **No bellows**
  - **Single bellows**

  } **no piston motion**

Vibration conditions

- **Commercial Labworks shaker**
- **Frequency: 40-200 Hz**
- **Acceleration: up to 30 g (30×9.81 m/s^2)**
- **Peak-to-peak displacement: 0-2 mm**

Experimental Data

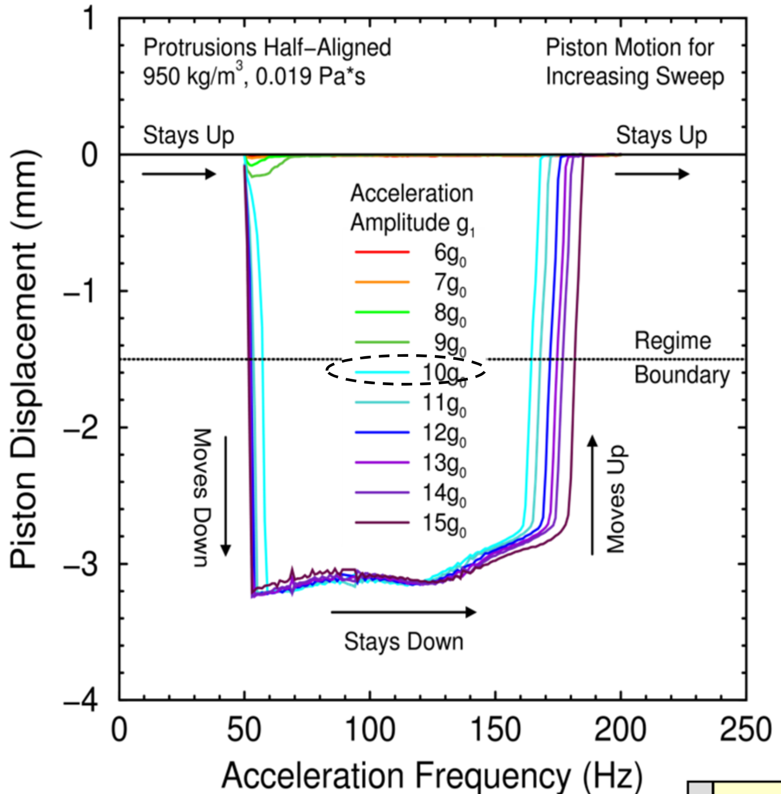
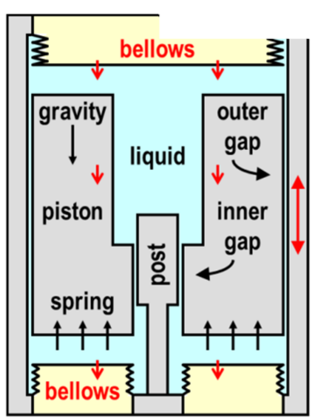


Figure 9. Piston-displacement data from increasing sine sweeps of frequency at different fixed acceleration amplitudes.



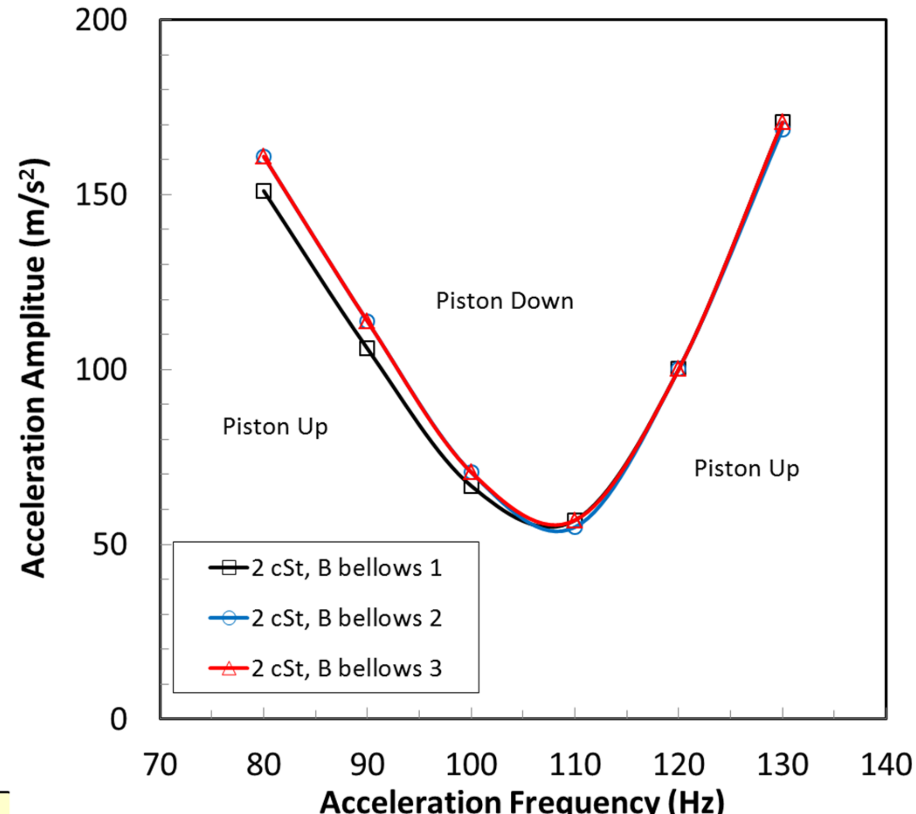


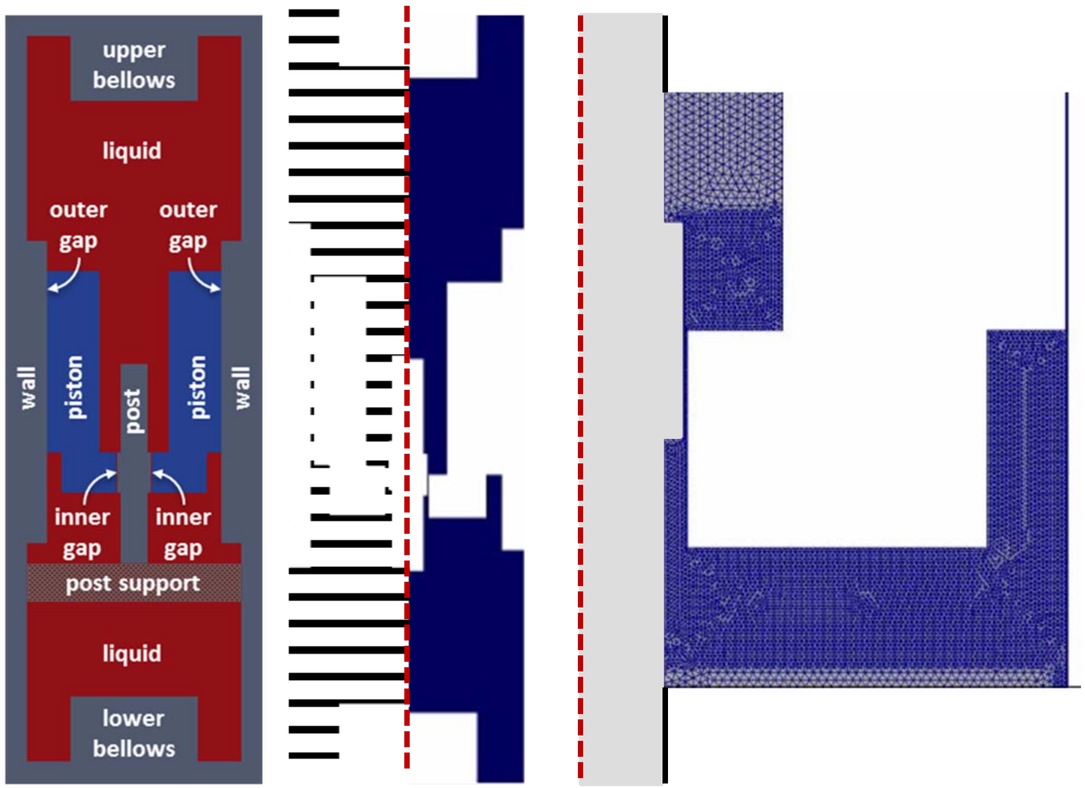
Figure 10. Regime map from increasing sine sweeps at fixed acceleration. Piston starts up, then goes down at some frequency, and then goes back up at a higher frequency.

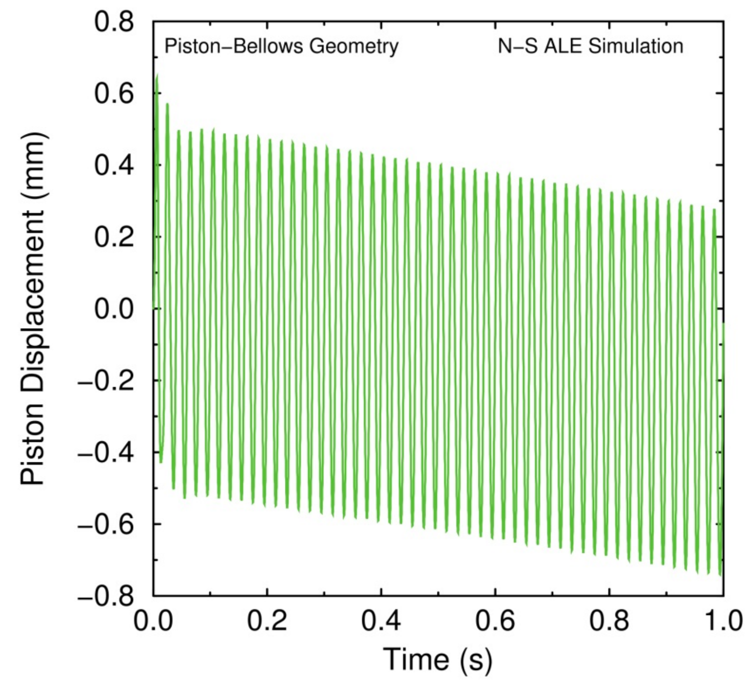
Numerical Simulation

Coupled ALE simulation of piston, bellows, & liquid motion

- **Moving-boundary incompressible Navier-Stokes eqns**
- **Sliding-mesh scheme mitigates sheared elements**
- **Newton's 2nd Law ("F = ma") for piston and bellows**

Piston oscillates strongly and drifts downward slowly





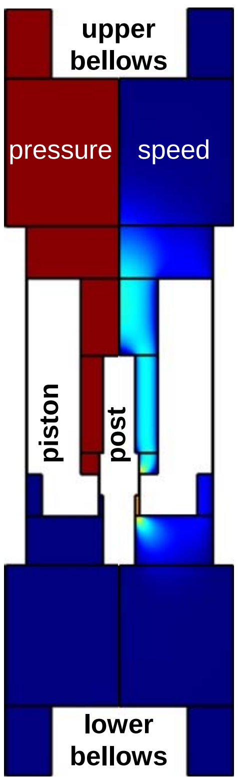
Sierra ARIA Finite Element Simulation

Theoretical Analysis

Theory yields 2-DOF nonlinear damped harmonic oscillator

- Newton's 2nd Law for solids, steady Stokes for liquid force
- Liquid damping & added mass depend on piston position

Excellent agreement with simulations for oscillation amplitude and drift



Navier-Stokes Eqns.
Newton's 2nd Law

$$\lambda = \frac{A_B}{A_P + \left(A_G/2\right)}$$

$$F_{rect} = \lambda \frac{d\beta_{11}}{dz_1}\left\langle z_1 \dot{z}_2 \right\rangle$$

$$U_{rect} = \frac{F_{rect}}{\beta_{11}} \quad \text{(drift)}$$

liquid added masses — liquid damping coefficients — gravity-buoyancy

$$\left(\tilde{\mathbf{M}} + \mathbf{M}\right)\ddot{\mathbf{Z}} + \left(\tilde{\mathbf{B}} + \mathbf{B}\right)\dot{\mathbf{Z}} + \tilde{\mathbf{K}}\mathbf{Z} = \mathbf{f}$$

object masses — object damping coefficients — object spring constants

$$\frac{\partial}{\partial \mathbf{x}}\cdot \mathbf{u}_i = 0, \quad \frac{\partial}{\partial \mathbf{x}}\cdot \boldsymbol{\sigma}_i = 0$$

$$\mathbf{u}_i = \begin{cases} U\hat{\mathbf{e}}_z \text{ on } S_i \\ 0 \text{ on other walls} \end{cases}$$

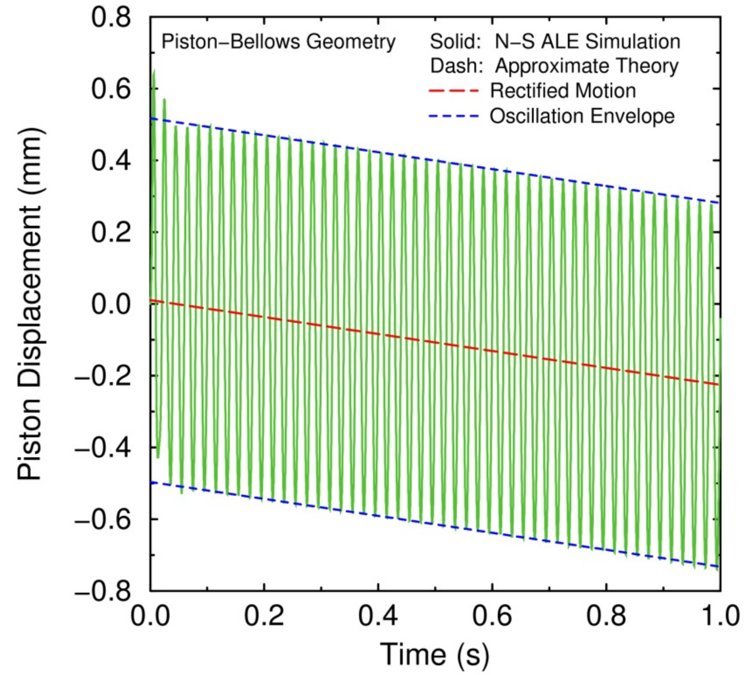
$$\mathbf{S}_i = \frac{1}{2}\left(\frac{\partial \mathbf{u}_i}{\partial \mathbf{x}} + \frac{\partial \mathbf{u}_i}{\partial \mathbf{x}}^T\right)$$

$$\mathbf{Z} = \begin{pmatrix} Z_P \\ Z_B \end{pmatrix} \qquad \mathbf{f} = -\begin{pmatrix} M_{PG} \\ M_{BG} \end{pmatrix} g_V \cos \omega t$$

$$\mathbf{B} = \begin{pmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \end{pmatrix} \qquad \beta_{ij} = \frac{2\mu}{U^2}\int_V \mathbf{S}_i : \mathbf{S}_j \, dV$$

$$\mathbf{M} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \qquad m_{ij} = \frac{\rho}{U^2}\int_V \mathbf{u}_i \cdot \mathbf{u}_j \, dV$$

$$\tilde{\mathbf{K}} = \begin{pmatrix} K_P & 0 \\ 0 & K_B \end{pmatrix} \qquad \tilde{\mathbf{B}} = \begin{pmatrix} B_P & 0 \\ 0 & B_B \end{pmatrix} \qquad \tilde{\mathbf{M}} = \begin{pmatrix} M_P & 0 \\ 0 & M_B \end{pmatrix}$$



Theory and Simulation

Conclusions and Future Work

gas above + vibration = gas below

⇩

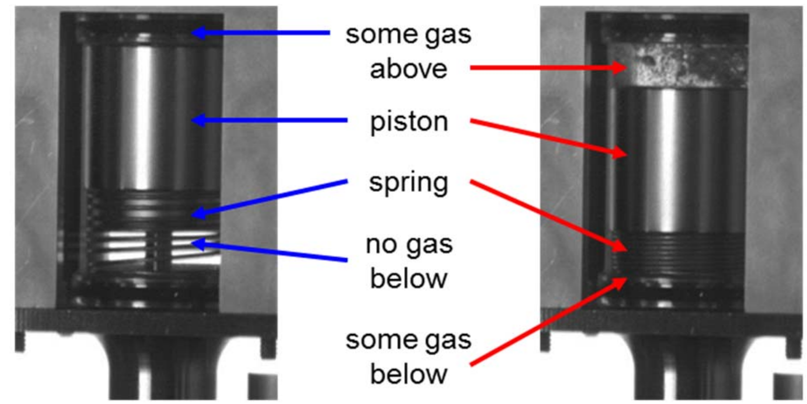
gas above + gas below = gas spring

⇩

gas spring + piston mass = resonance

⇩

resonance + gap nonlinearity = net motion



Vibration off
Spring supports piston

Vibration on
Piston compresses spring

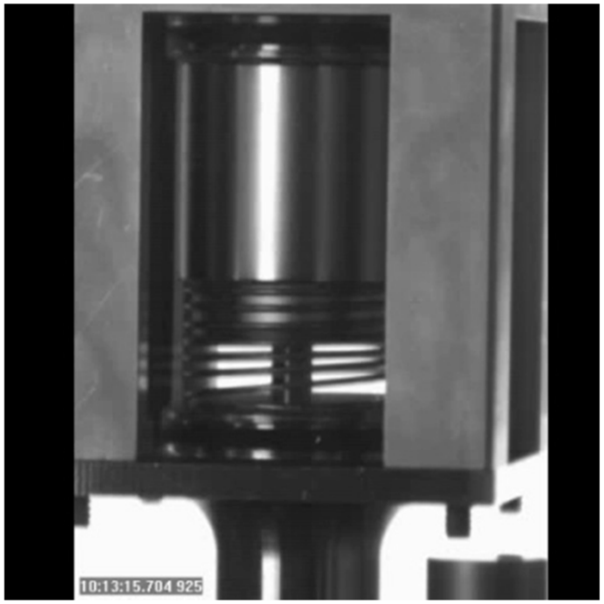
Gas changes how an immersed body responds to vibration

- Clear physical picture of route to net motion (rectification)
- Couette mode dominates Poiseuille mode in gap-dominated case of interest
- Good agreement between theory & simulation (bellows)

Much work remains to be done for complete understanding

- Compare theory, simulation, and experiments in detail
- Investigate effects of friction and contact forces (at stops in experiment)
- Study how gas divides between upper & lower regions

“Gas-Enabled Resonance and Rectified Motion of a Piston in a Vibrated Housing Filled with a Viscous Liquid,” (2016), Romero, L. A., Torczynski, J. R., Clausen, J. R., O’Hern, T. J., Benavides, G. L., *ASME Journal of Fluids Engineering*, 138(6), 554-573.



Questions?

- Instructions for the speakers:
- Regular contributed talks will be assigned 17 minutes for presentation, plus additional 3 minutes for questions and change of speaker.
- Chair persons are kindly asked to strictly maintain the schedule, even in the case of no-show.
- Each presentation room will be equipped with a PC (capable of displaying PDF and Powerpoint presentations) and an LCD projector. Laser presentation pointers can be provided upon request of the Chair person and depending on availability.
- Speakers are kindly asked to upload their presentations in the PC assigned to the room and test their presentation well beforehand.
- In case of technical difficulties, it is the speaker's responsibility to contact the staff person assigned to the room ahead of the scheduled time of the presentation.
- Please prepare a good quality portable PDF version of the presentation in the case other formats are not supported by the PC.
- Make folder with PDF and all of the movie files! Make DVD, take flashdrive

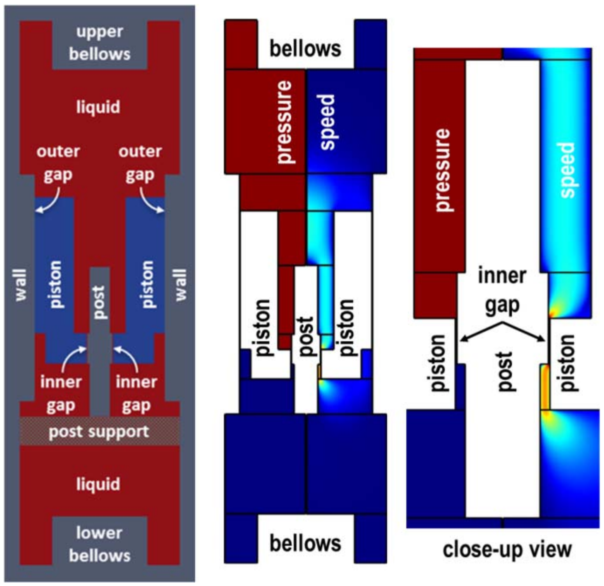


Figure 3. Left: axisymmetric computational domain. Right pair: one of two steady-Stokes solutions used to compute **B** and **M**. Inner-gap protrusions are initially half-aligned.

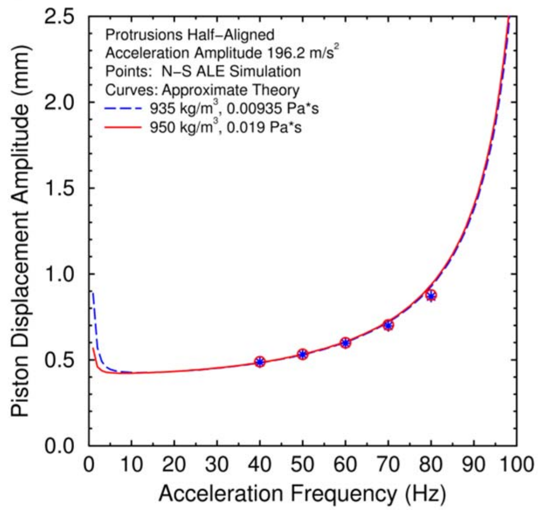


Figure 5. Piston displacement amplitude at fixed acceleration amplitude versus frequency for both liquids from theory and simulations (resonance is at 107 Hz).

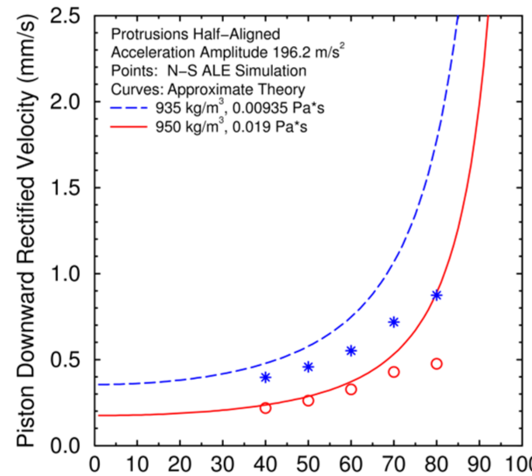


Figure 7. Piston downward rectified velocity at fixed acceleration amplitude versus frequency for both liquids from theory and simulations (resonance is at 107 Hz).

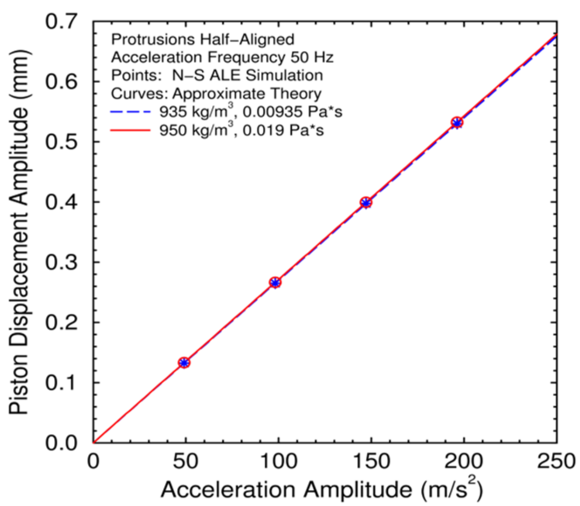


Figure 6. Piston displacement amplitude at fixed frequency versus acceleration amplitude for both liquids from theory and simulations.

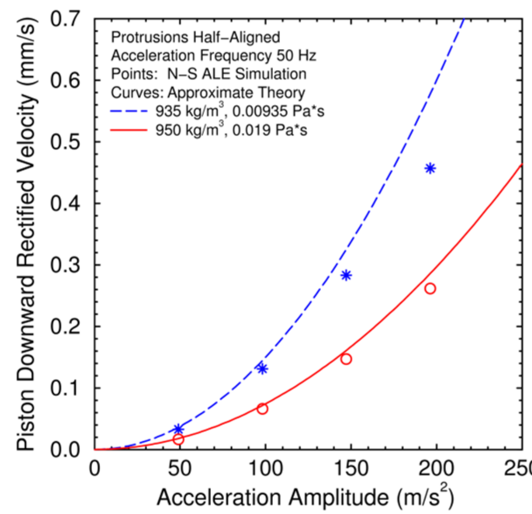


Figure 8. Piston downward rectified velocity at fixed frequency versus acceleration amplitude for both liquids from theory and simulations.

• Movies

- PredCompModRev_20141202_ESDs_Torczynski_Video1_Piston_Actuation_30s.wmv
- PredCompModRev_20141202_ESDs_Torczynski_Video1_Piston_Actuation_30s.wmv
- 25g Around 215Hz Start of Motion converted.avi
- 70Hz_9pt4g_trimmed-dec50_straight.avi
- zoom_in_mesh_pressure.wmv
- zoom_out_domain.wmv
- Adding a little gas can completely change the dynamics of a spring-mass-damper system subject to vibration. Experiments and modeling have been performed on a spring-supported piston in a liquid-filled cylinder, where the gaps between piston, cylinder, and shaft through the cylinder are narrow and depend on the piston position. When gas is absent, the piston's vibrational response is highly overdamped due to viscous liquid being forced through narrow gaps. When a small amount of gas is added, Bjerknes forces cause some of the gas to migrate below the piston. The resulting gas regions above and below the piston form a pneumatic spring that enables the liquid to move with the piston, with the result that very little liquid is forced through the narrow gaps. This “Couette mode” has low damping and thus has a strong resonance near the frequency given by the pneumatic spring constant and the piston mass. At this frequency, the piston response is large, and the nonlinearity from the gap geometry produces a net force on the piston. This “rectified” force can be many times the piston's weight and can cause the piston to compress its supporting spring. Experiments have been performed with liquid-only systems, with bubbles present, and with flexible bellows that act as non-mobile bubbles with bubble-like compressibility. *Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.