iMAPS New England 45th Symposium & Expo

Resonant MEMS Acoustic Switch Package with Integral Tuning Helmholtz Cavity

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DRAPER

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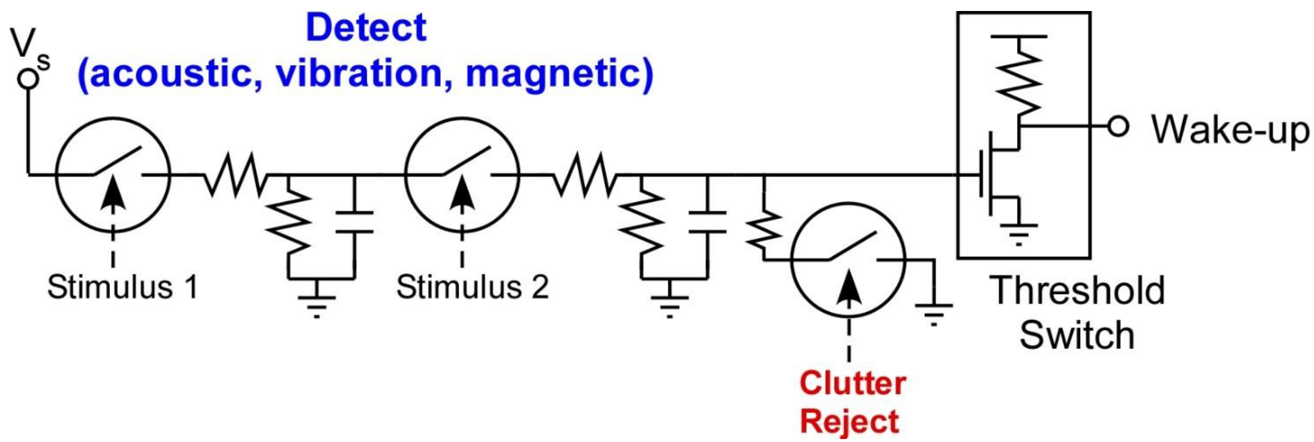
Outline

- Introduction
  - DARPA “Near Zero Power RF and Sensor Operations” (N-ZERO) Problem Statement and targets
  - Why not a linear sensor?
  - Proposed rotary solution
- Analysis
  - Equivalent Circuit Model
  - Role of cavity: compliance and Q
  - Scaling of cavity size with paddle dimensions
- MEMS Fabrication
- Custom Package: Acoustic Cavity
  - Small, Medium and Large cavities
  - Tuning resonant frequencies
- Test Results
  - Sensing Trucks and Generators
- Conclusions

Introduction

- The DARPA N-ZERO program was established to reduce the stand-by power of detection systems such as UGS (Unattended Ground Sensors) or Internet of Things to “Near Zero” or < 10 nW
- Draper has built **zero-power** acoustic and vibration wake-up switches that will enable sensor arrays that last for years, limited only by battery self-discharge rates.
- MEMS resonant switches close a relay when they sense an acoustic (or vibration or magnetic) signal at their resonant frequency



Zero Power physical sensor/switches in example logic architecture.

Targets of Interest

- DARPA supplied acoustic, vibration and magnetic signatures from several targets of interest:
  - Generator (Honda 6500)
  - Truck (Ford F-150)
  - Car (noise or clutter source)
- Draper's approach was to trigger off one or more characteristic frequencies of each target
- Spectrograms of signals revealed frequencies with strong spectral content for each target
- Generator: output contains 20 Hz and harmonics acoustic content
  - Output must be 60 Hz so pistons fire at 20 Hz with good precision
- Truck: various frequencies are present at idle, but vary with warm-up
- Cars: frequencies vary widely with model, reclassified as noise source

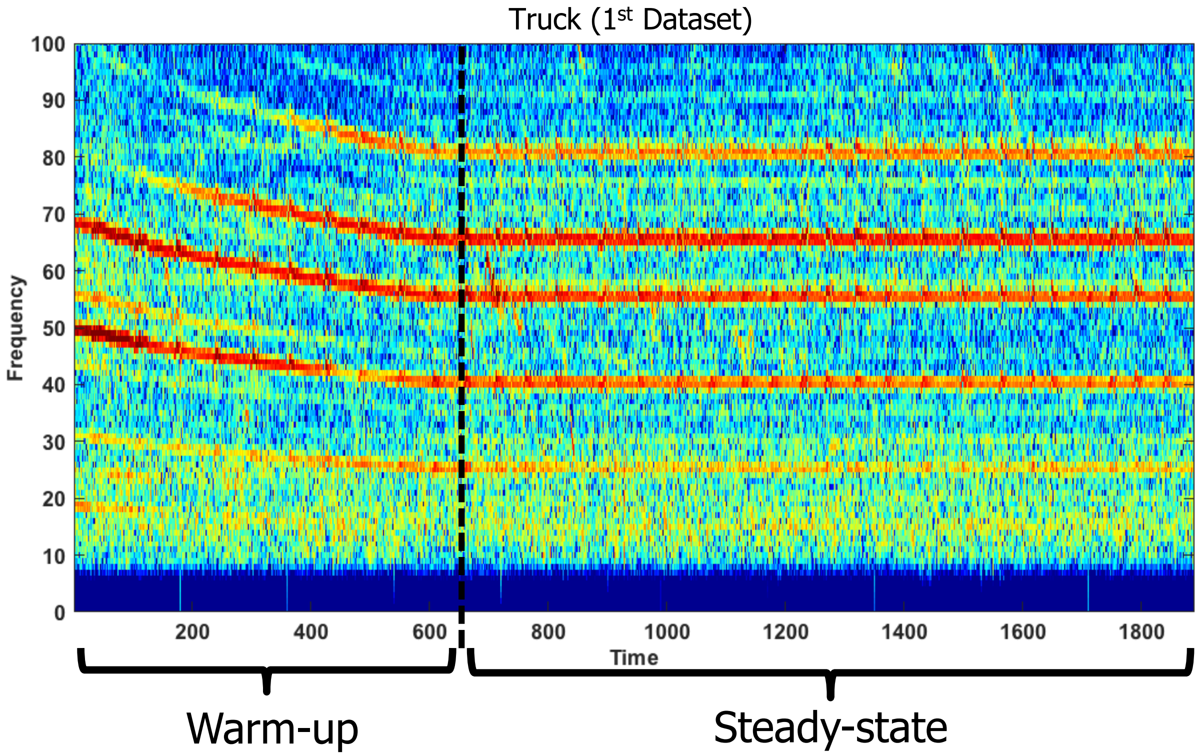
Honda Generator
(20 Hz & Harmonics)

Ford F-150 Pickup Truck
(55 and 65 Hz)

Toyota Corolla
(70-75 Hz)

Truck Signature Analysis: Data from Lincoln Labs

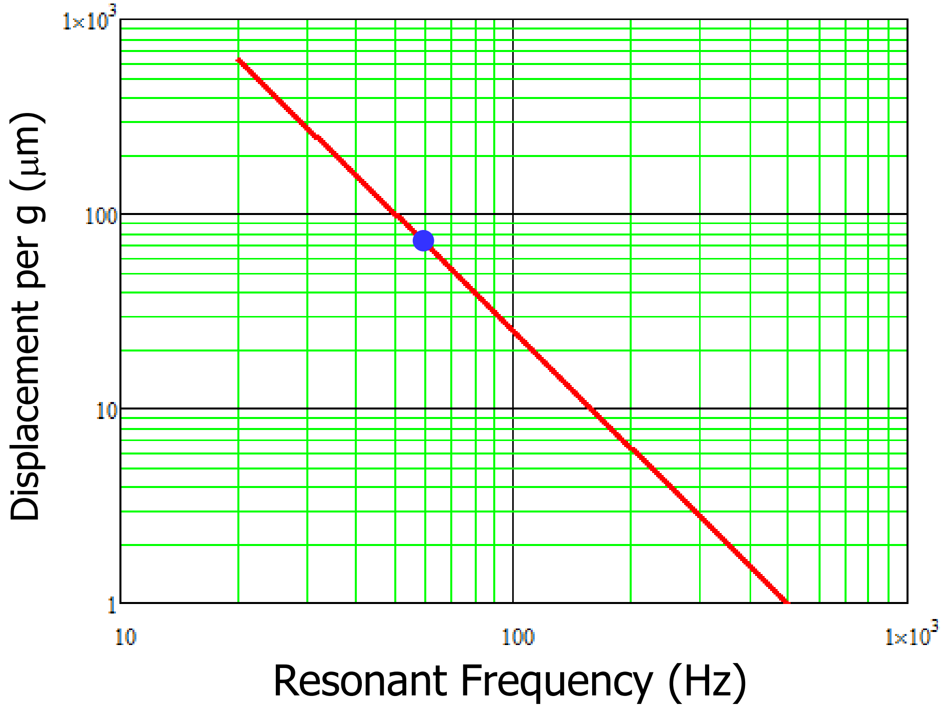
- Truck output frequencies have a warm-up transient.
- We used data from the steady-state frequency component.

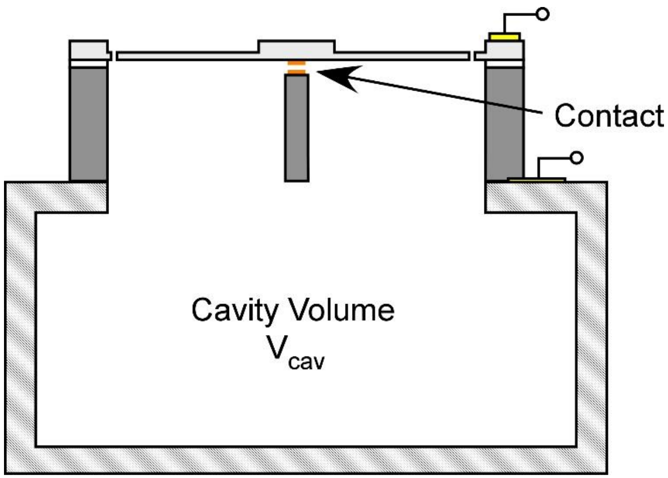


Source: Data from MIT Lincoln Laboratory

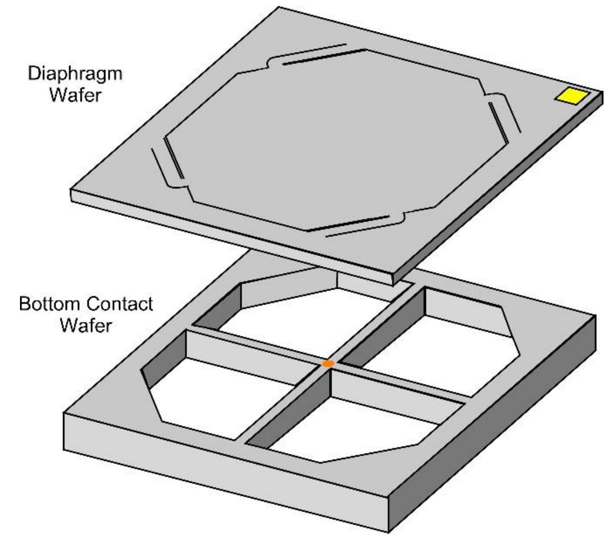
Why Not a Linear Microphone Switch?

- Initial concept was a linear motion microphone
- Our target frequencies are too low (50-150 Hz)
- Displacement per g for linear spring/mass is too large at 60 Hz (70 μm/g)
- We want a gap ~ 2-3 μm and we don't want to be sensitive to vibration





Linear Motion Design (not selected)



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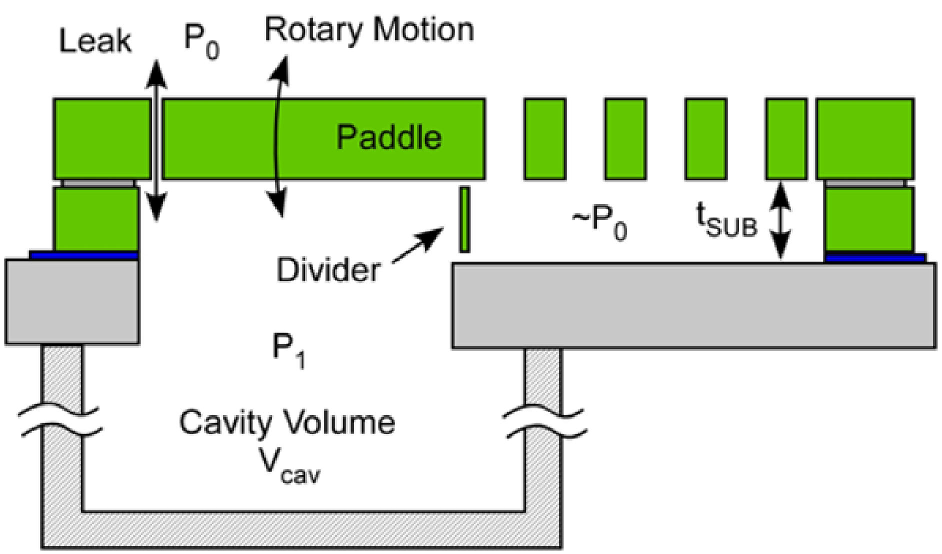
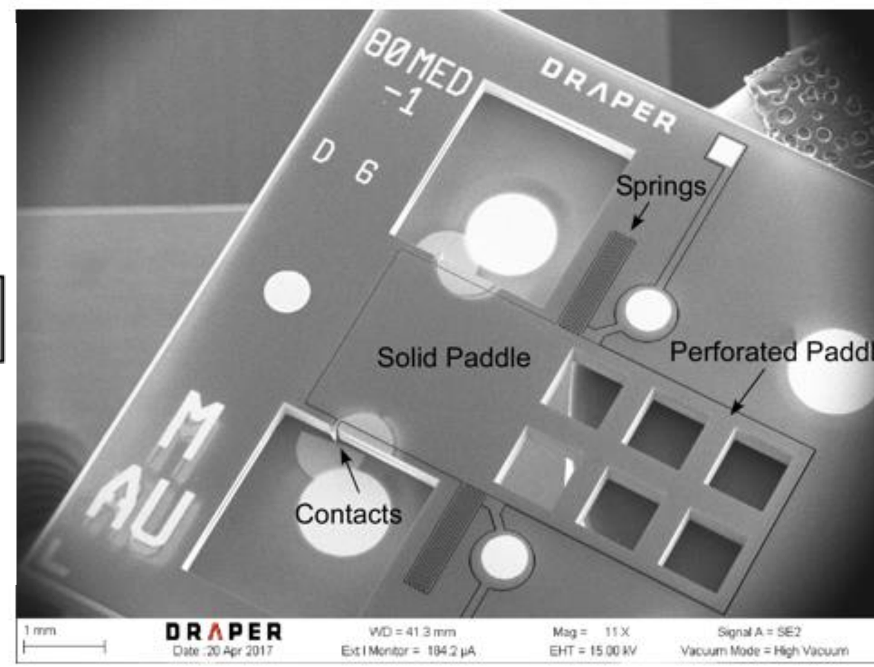
Rotary Acoustic Switch: Operating Principles

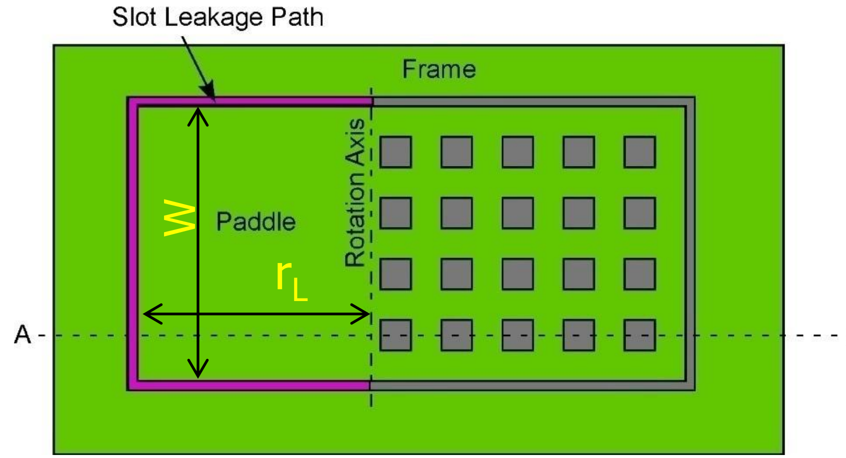
- Instead of linear motion, use a rotational design to reduce sensitivity to vibration and static gravity
- Balanced see-saw design: one solid side responds to pressure, other perforated side does not
- Cavity tuning to adjust the frequency
- These are low frequency, resonant switches (40 to 100 Hz), rather than wide band sensors: It's not a microphone!

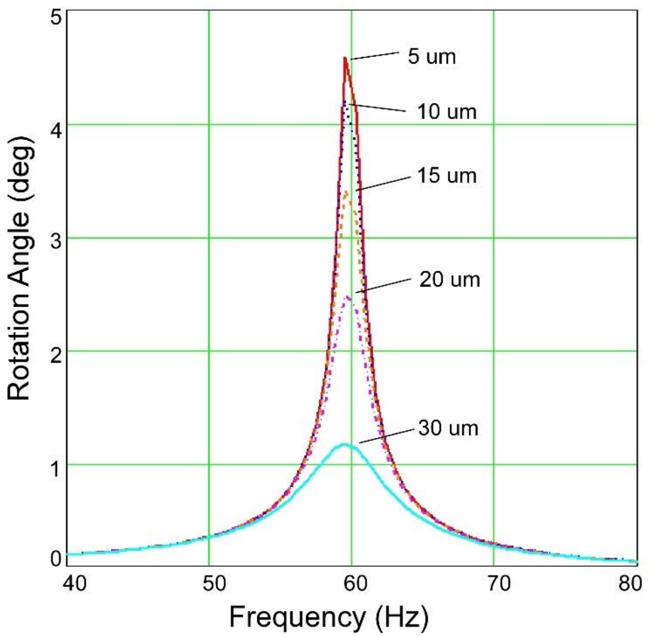




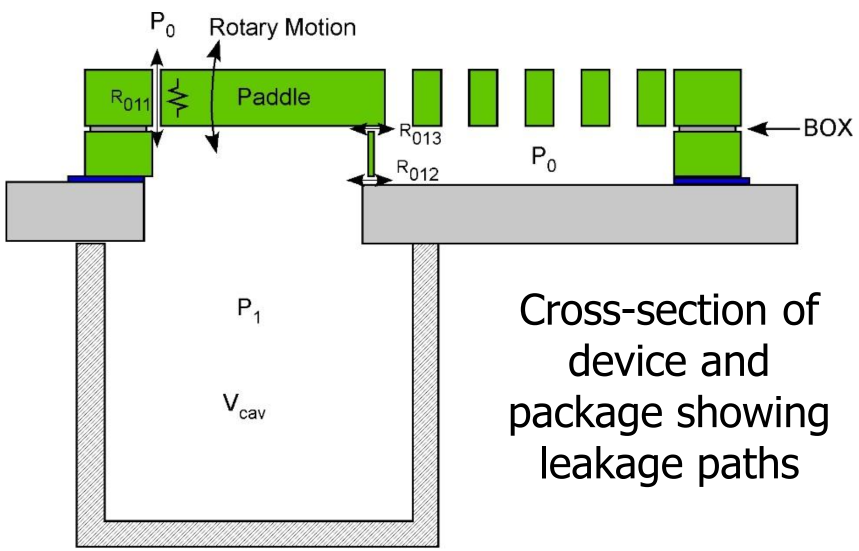
Acoustic Modeling

- Acoustic model for rotating paddle, acoustic cavity, and leakage paths
- Results show need for narrow channel around the paddle to reduce leakage resistance
- Decreasing slot from 30 um to 15 microns yields 3X improved Q and sensitivity

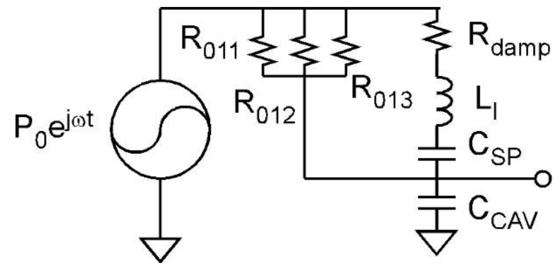




Simulation of 60 Hz sensor with various etched slot widths



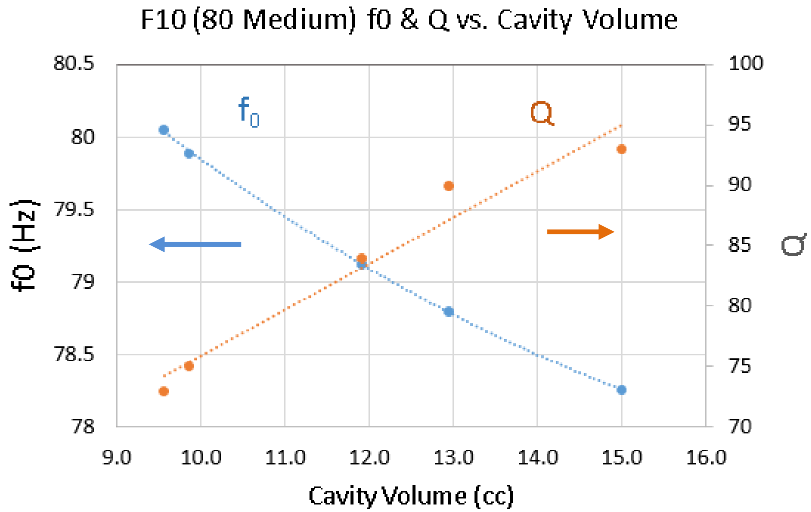
Cross-section of device and package showing leakage paths



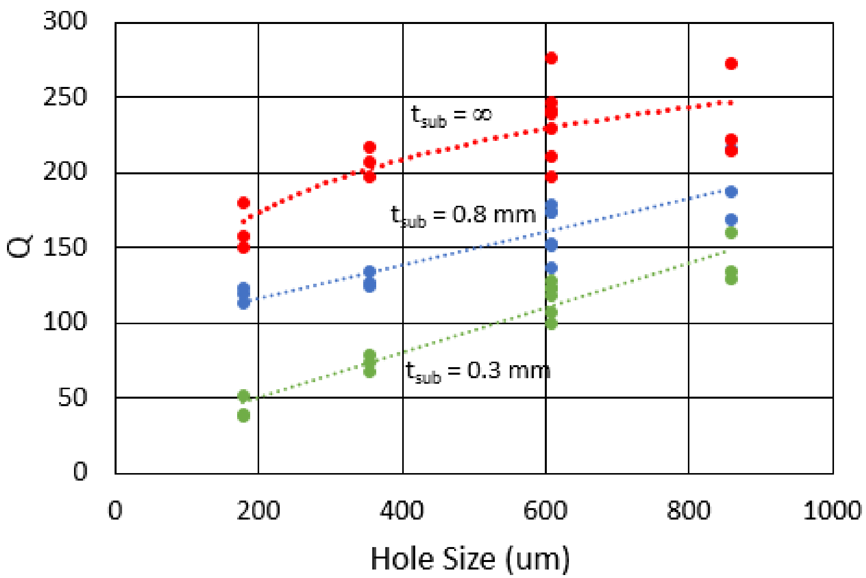
Equivalent Circuit Model

Damping Optimization

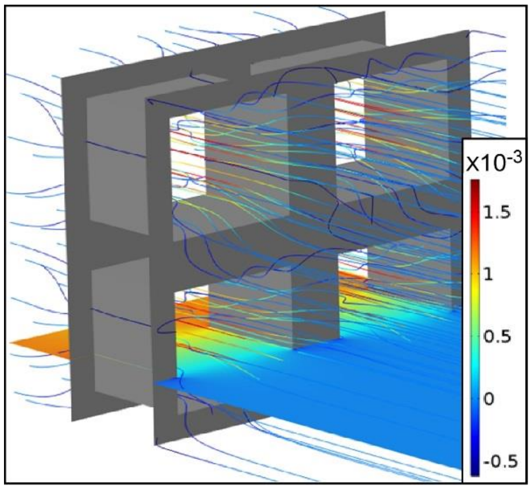
- Dominant energy loss is leakage resistance around 3 sides of the solid paddle
  - Hole side damping and squeeze film damping reduced with larger holes and spacer chip
  - Q > 300 (best observed) free-space
  - Q > 100 (best observed) with tuning cavity
- Mechanically robust: 75% mechanical yield
- Contact switches close at 5 mPa (48 dB)



f_0 tuning and Q for 80 Hz sensor



Q vs. hole size with gap (t_{sub}) as a parameter for medium sized devices

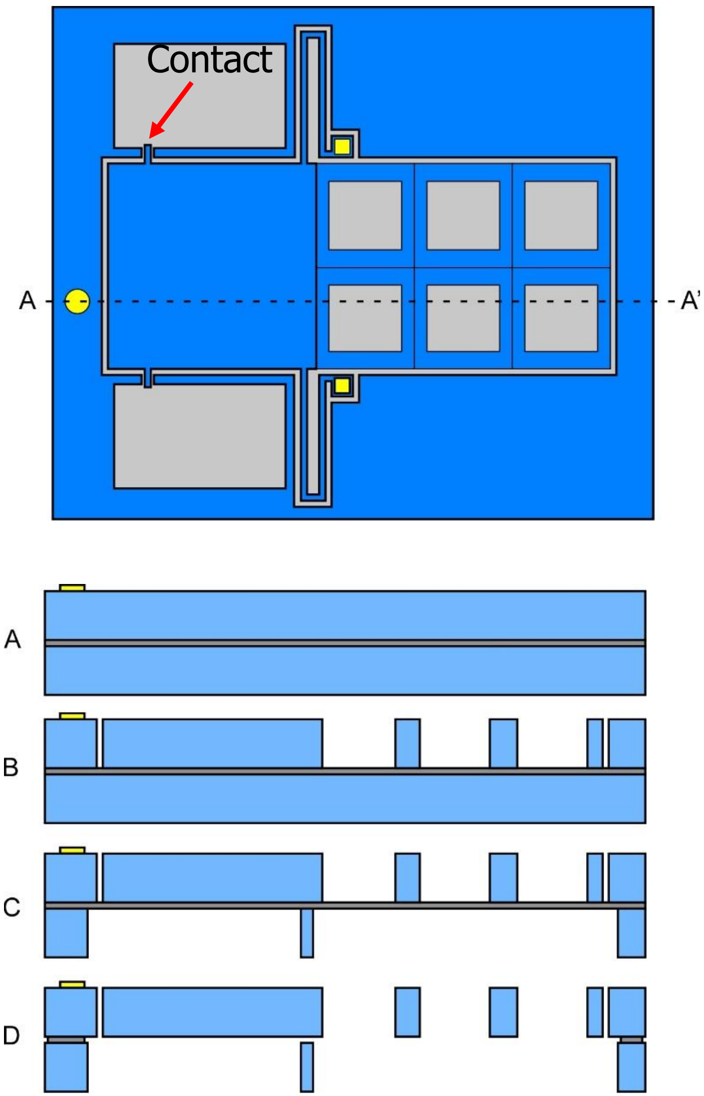


FEA of fluid flow through hole with squeeze film damping for damping predictions

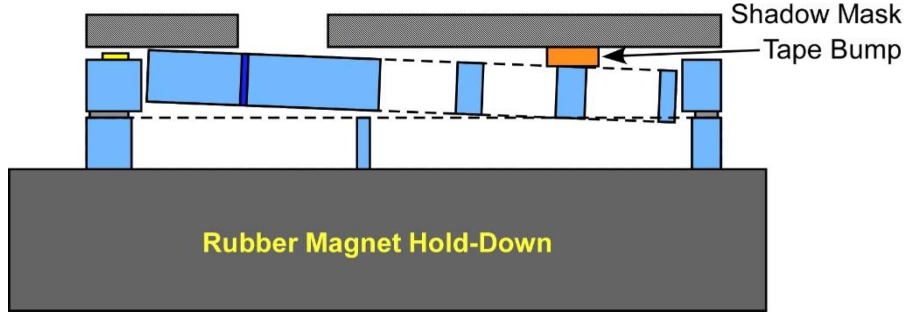
Acoustic Wake Up Fabrication

J. Bernstein

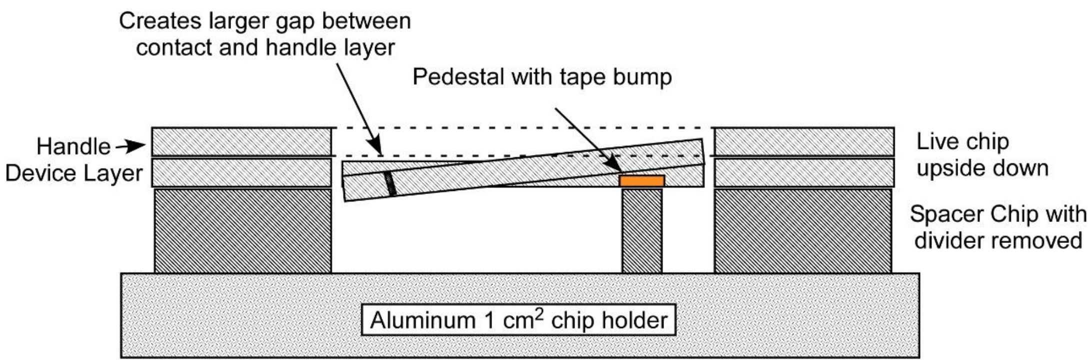
Acoustic Chip Fabrication Process



Top and cross-sectional views of device fabrication:
(a) Lift-off bondpad metal
(b) Front ICP etch
(c) Back ICP etch (dice and clean chips)
(d) Vapor HF release
(e, f) Contact metallization



(e) Contact Metallization (top side): shadow mask with bump

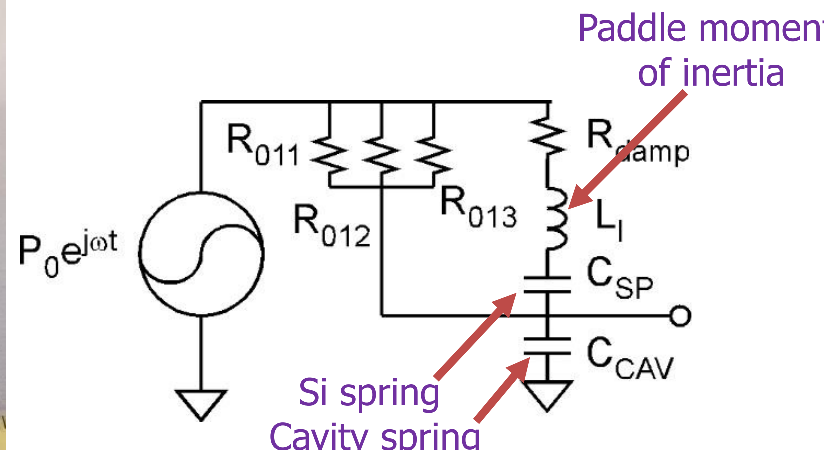


(f) Contact Metallization (bottom side): sputter fixture

Acoustic Cavity Considerations

- Both the physical springs and the acoustic cavity add stiffness and affect f_0
  - Only the physical springs provide anti-stiction "pull-off" forces at DC
  - We generally require that cavity compliance is at least 2 or 3 X larger (impedance smaller) than the spring compliance
  - If cavity is to be used for tuning frequency, then it can't be too large, or it won't have much effect on the frequency
  - Large cavities are undesirable for small systems
- Modeling and experiments show cavity size also strongly affects Q and sensitivity

Small (2 cc), medium (5.7 cc) and large (15 cc) adjustable cavities



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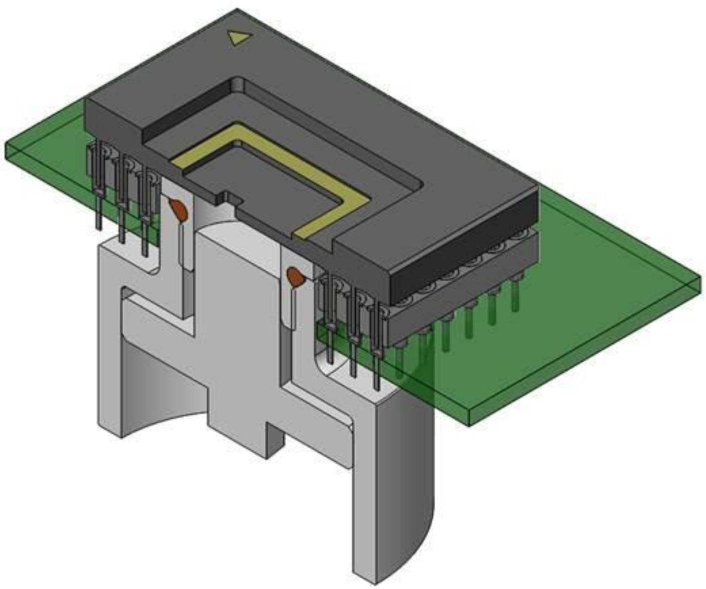
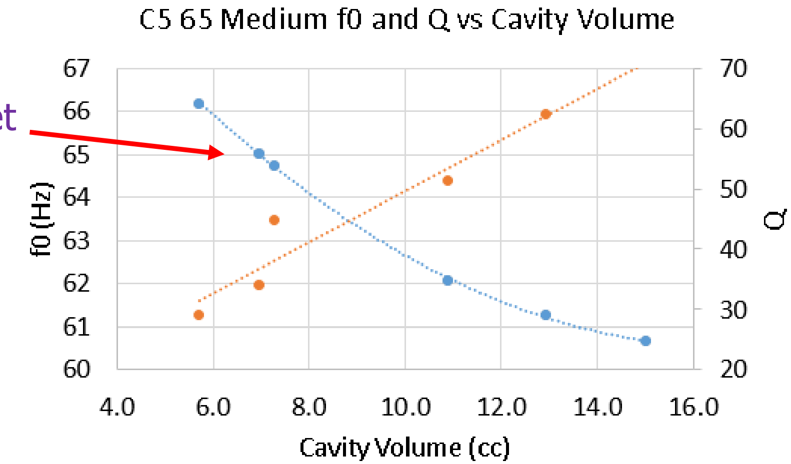
Tuning Cavity Packaging

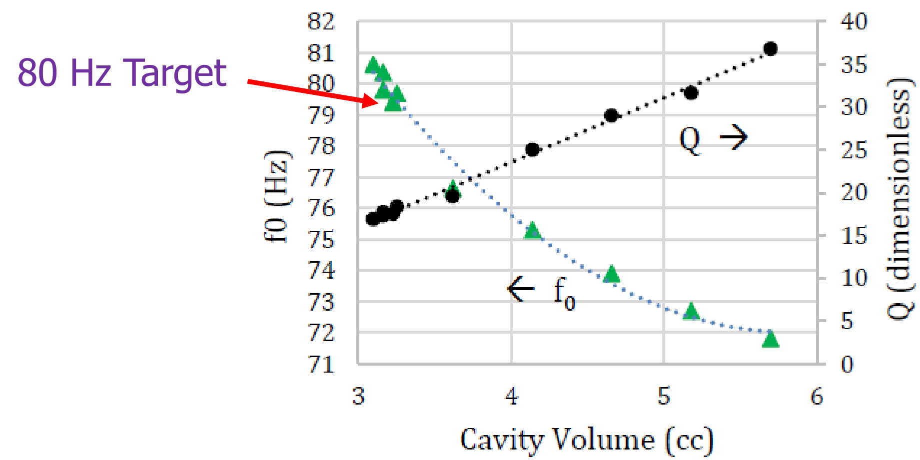
- Cavity tuning successfully implemented to hit target frequencies



Cross-section of a solid model of a large package and cavity Screw threads not shown



f_0 tuning and Q vs. cavity volume for a 65 and 80 Hz sensor



- Cavity volume affects both resonant frequency and quality factor.
- Larger volumes give higher Q but less tuning authority.

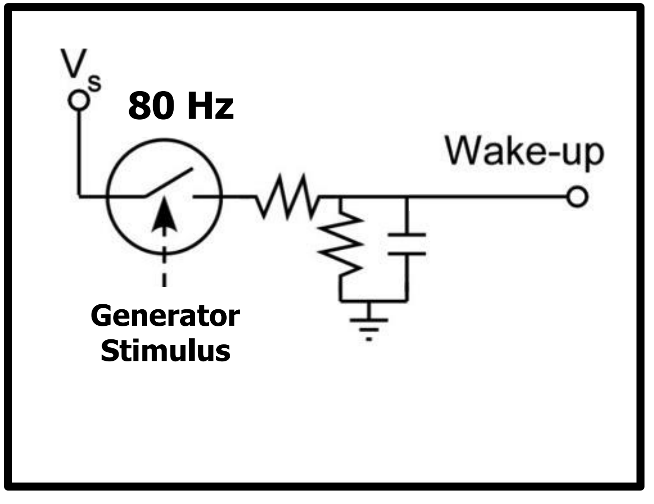
Acoustic Wake Up Test Results

M. Tomaino-Iannucci

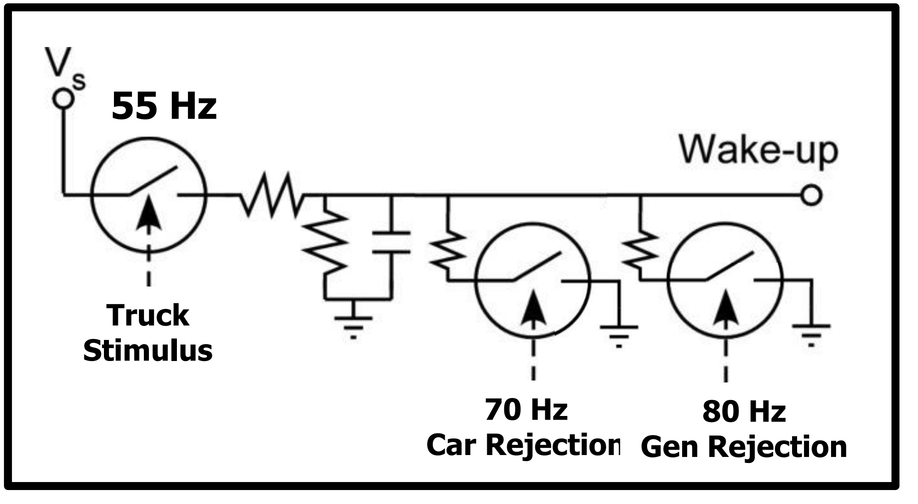
Simulation

- Simulated various detector configurations in Simulink.
- So far, the best detector configurations are:
  - Generator: 80 Hz
  - Truck: 65 Hz (Reject 70 Hz – car, and 80 Hz – generator)

Generator Detector



Truck Detector



*Sim sensor parameters: 55 [Hz]: CP = 9.8 [mPa], Q = 75, 70 [Hz]: CP = 26 [mPa], Q = 59.7, 80 [Hz]: CP = 50 [mPa], Q = 15

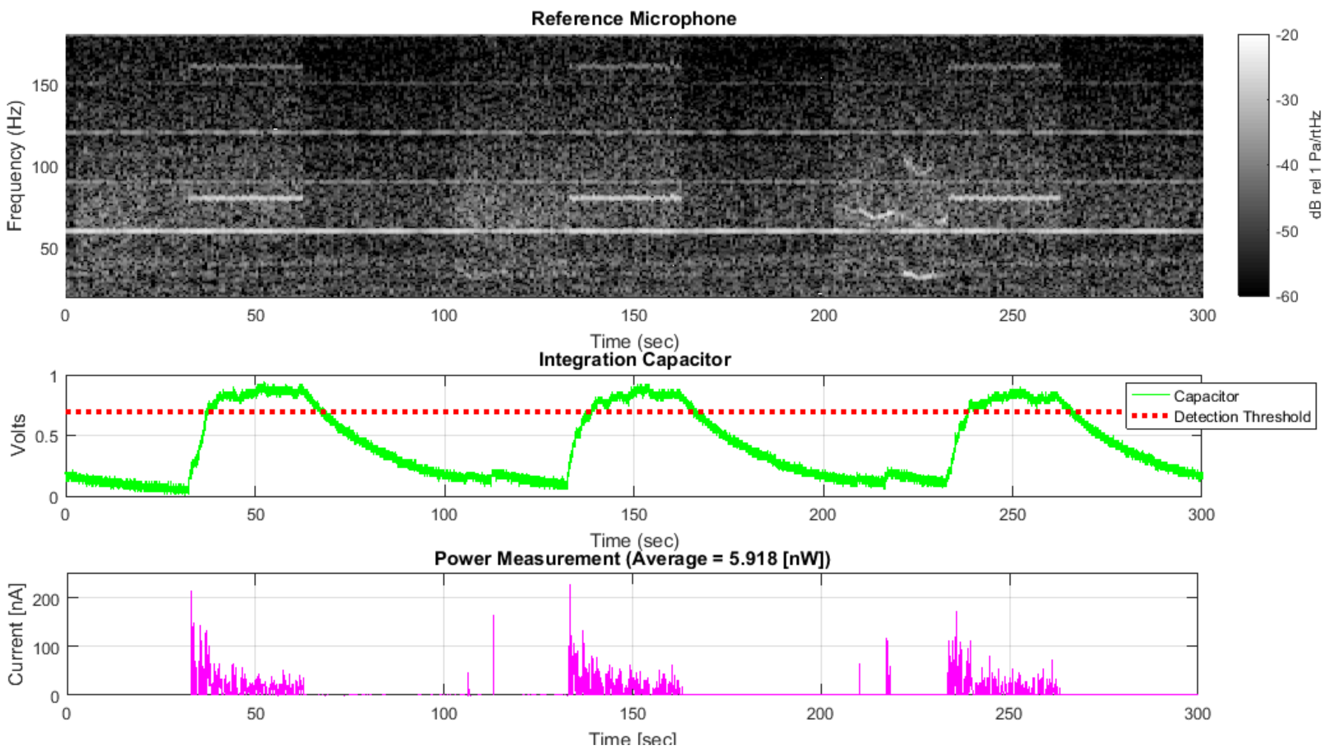
Phase I Lincoln Labs Test

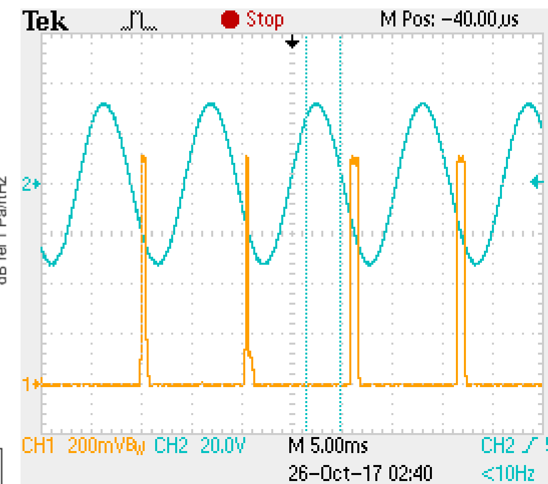
- Success. Phase I metrics met.
- The generator was successfully detected at a range of 1.5 meters.
- ~ 0.1 nW consumed when no target present.
- Ambient noise and idling automobiles did not trigger any false alarms.

Source: Photos from MIT Lincoln Laboratory

Phase I Generator Detection

- Representative test results are shown below.
- Detection of three generator on/off cycles.
- Out-of-band interferer at 200-250 seconds hardly excites the 80 Hz resonant device.





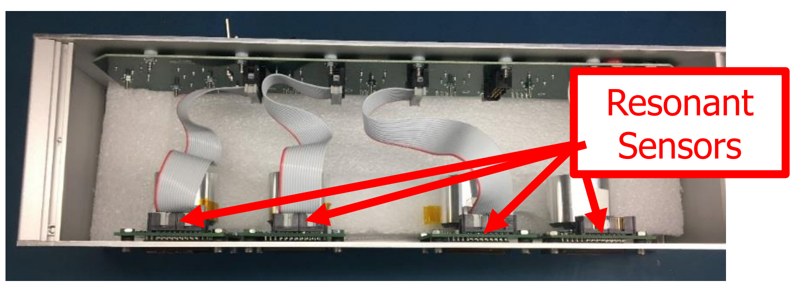
Current spikes during contact. Blue trace = voltage to speaker, orange is current through the contacts with 1 kΩ load.

Phase II Acoustic System Details

- Three Systems Constructed.
- AND and NOT logic included.
- Quiescent power less than 1 nW (theoretically zero).

Front

Back



Top (cover off)

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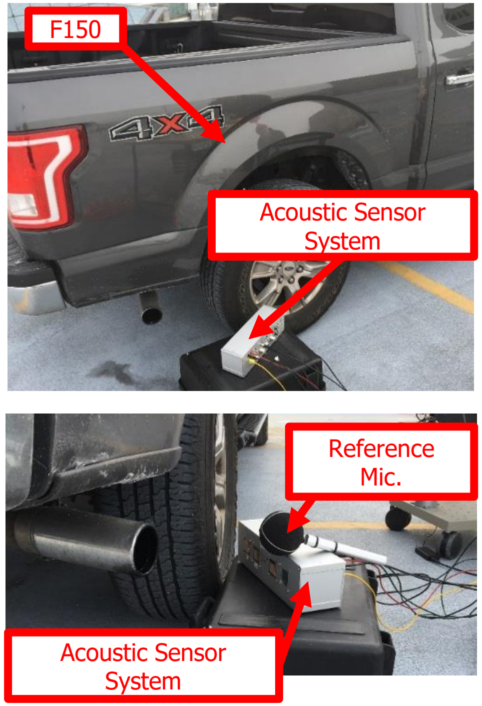
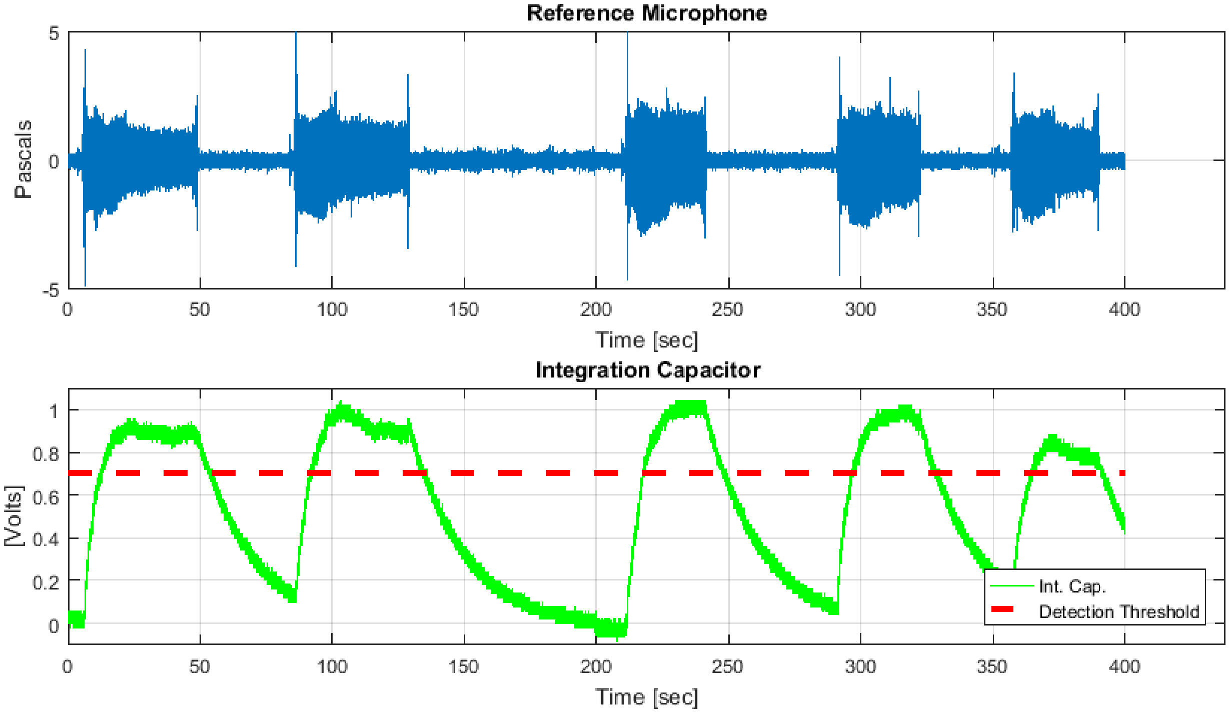
Phase II Truck Tests at Draper

- 1 m testing performed at Draper
- At Lincoln acoustic System detected truck at 4 m.

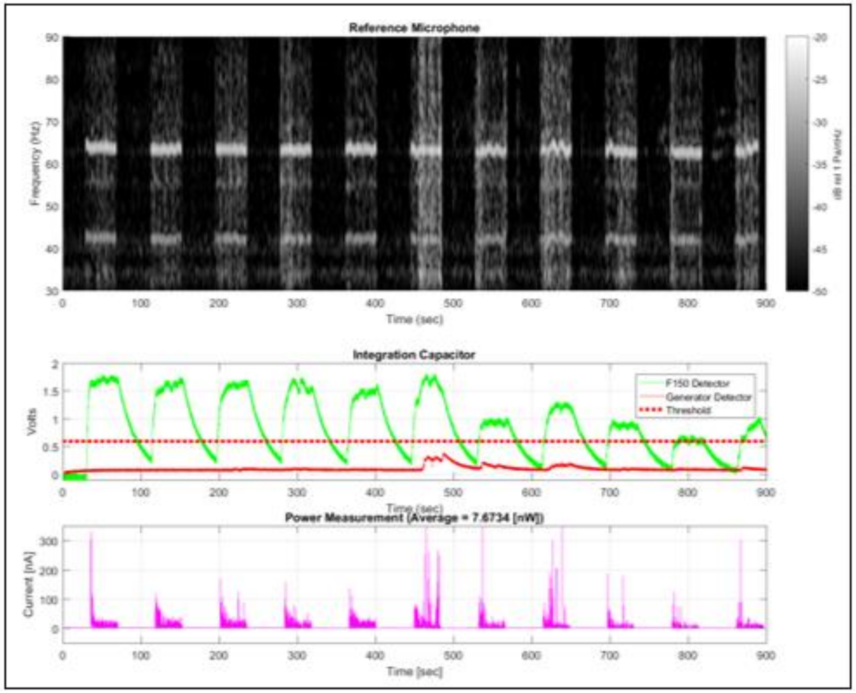




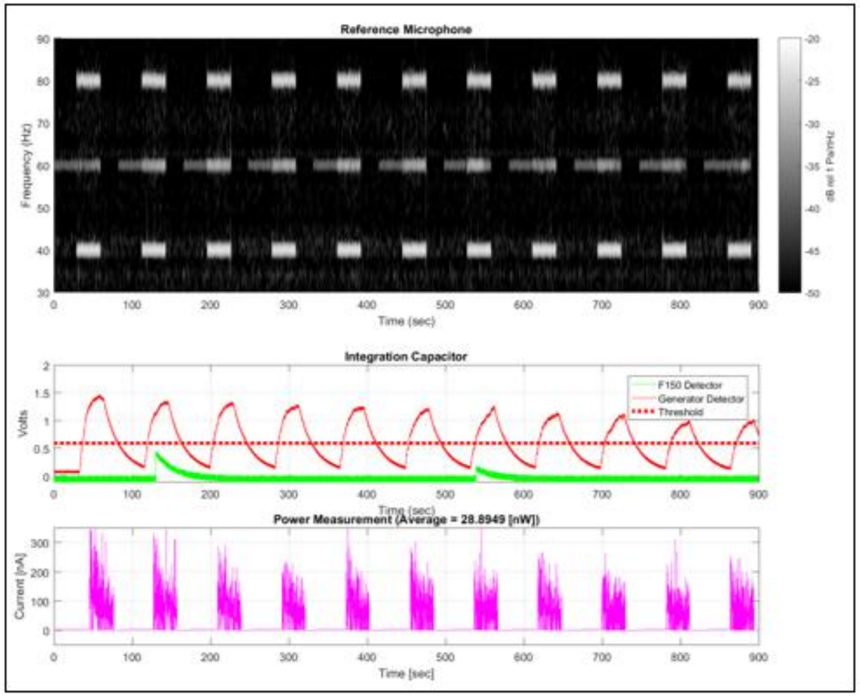
System Testing at Draper

- Successful audio detection of cars and trucks
- System #1, Sensor G5 (65 Hz), Sensor L7 (80 Hz)

F150 data



Generator data



11/11 F150 Detections
0/11 Generator Detections

0/11 F150 Detections
11/11 Generator Detections

Conclusions

- The sensors work as designed: they detect fixed frequencies
- Off state power is essentially zero by design
- Background clutter and loud transients can be rejected with NOT detectors at non-target frequencies
- Phase II Improvements:
  - Increased sensor fabrication yield to ~ 75%
  - Improved designs using analytic and FEA modeling to increase Q (5X improvement from 20-100)
  - Demonstrated detection at 0.005 Pa (48 dB)
  - Detected generator at 5.8 m and truck at 4 m

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