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DRAPER

Zero Power Wake-Up Sensors for Acoustic and Vibration Wireless Detection

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Outline

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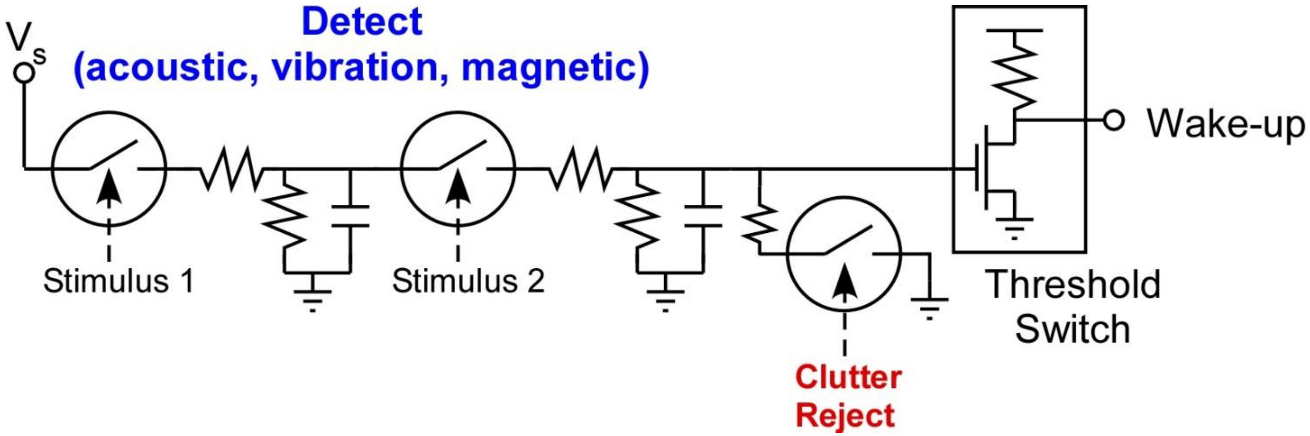
  - DARPA “Near Zero Power RF and Sensor Operations” (N-ZERO) Problem Statement and targets
  - Why not a linear sensor?
- Rotary Vibration Switch
  - Frequency and Q Tuning
  - Vibration switch fabrication
- Rotary Acoustic Switch
  - Fabrication
  - Frequency tuning by cavity compliance
- Test Results
  - Sensing Trucks and Generators
    - Acoustic
    - Vibration
- 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 based on spectrogram of recorded signals
- 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

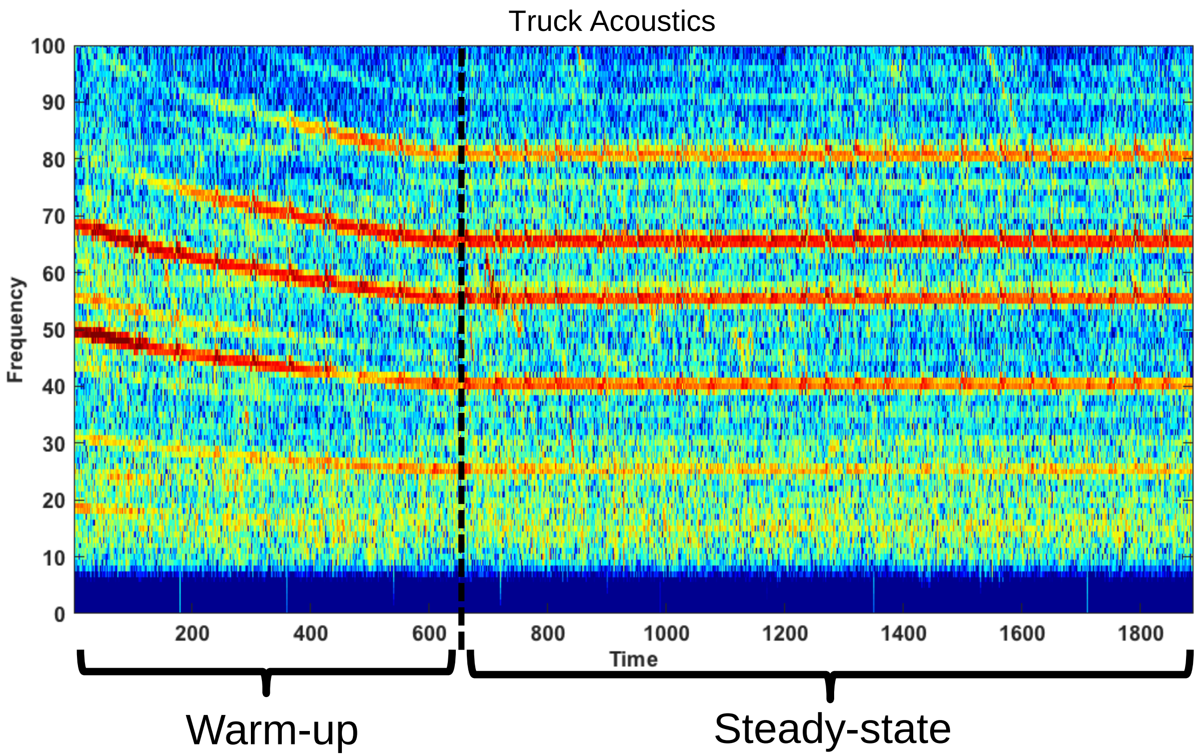
Honda Generator
(20 Hz & Harmonics)

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

Toyota Corolla
(70-75 Hz)

Truck Signature Analysis: Data from Lincoln Labs

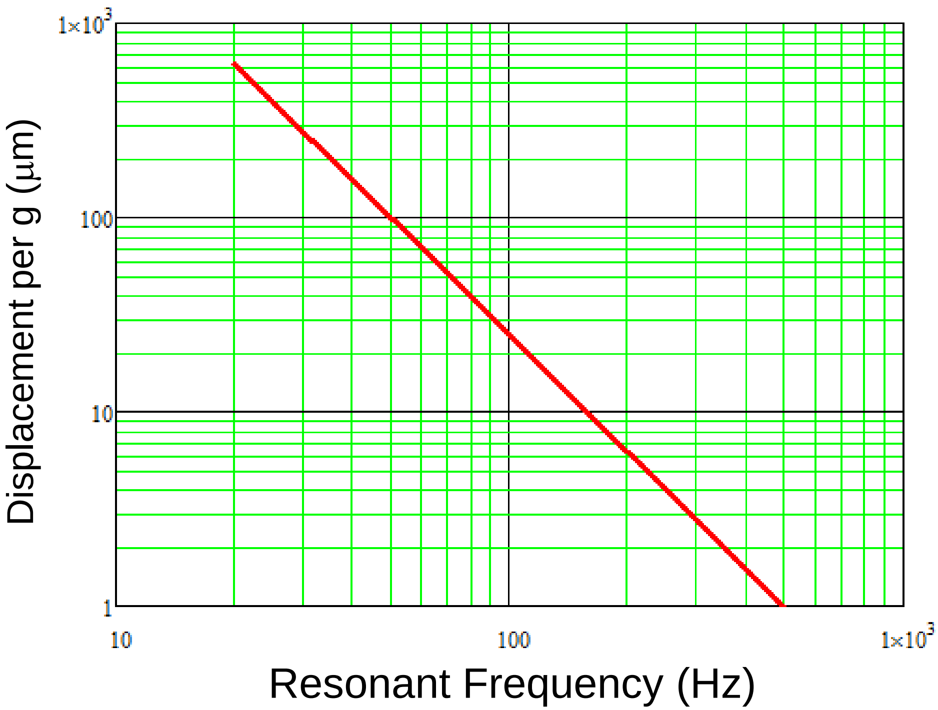
- Truck output frequencies have a warm-up transient.
- We used data from the steady-state frequency component.
- These sensors work best with fixed, known frequency targets
  - Sensor frequency can be tuned electrostatically or by acoustics

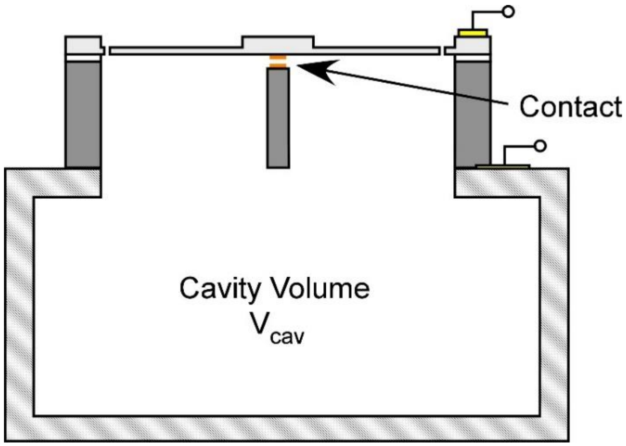


Source: Truck Acoustic Data from MIT Lincoln Laboratory

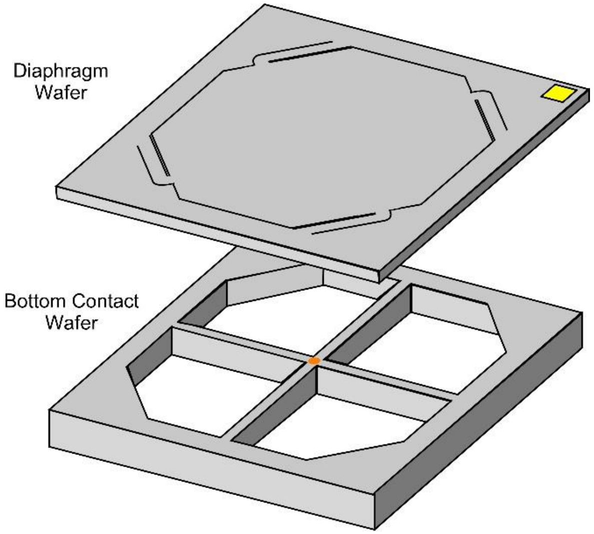
Why Not a Linear Microphone or Vibration Switch?

- Target frequencies are low (50-150 Hz)
- Displacement per g for linear spring/mass is too large at 60 Hz (70 μm/g)
- We want a detection gap ~ few μm
- Acoustic sensor should be insensitive to vibration



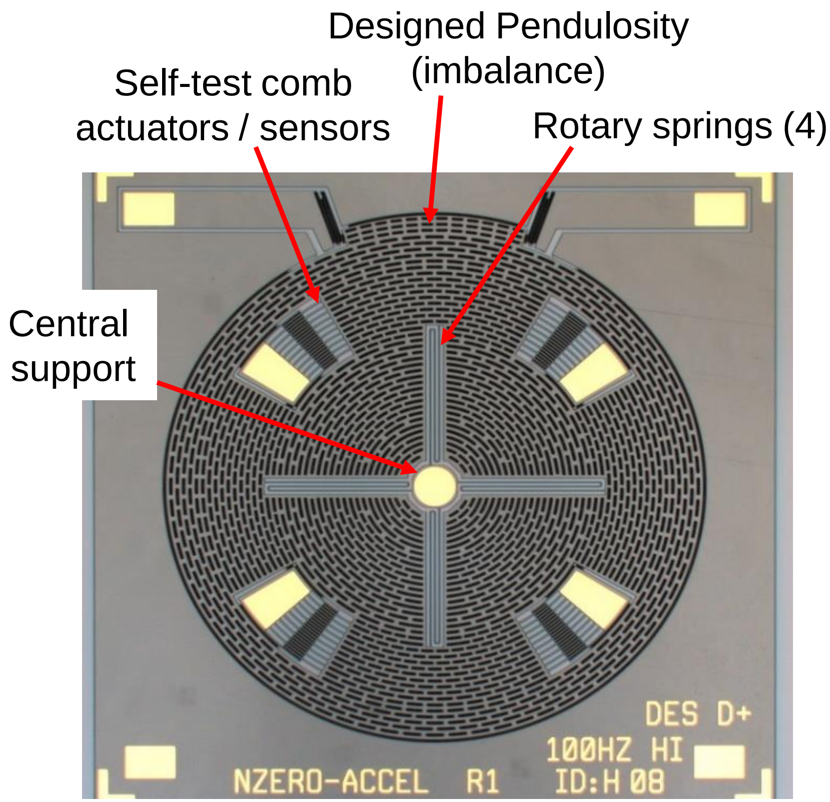


Linear Motion Design
(not selected)

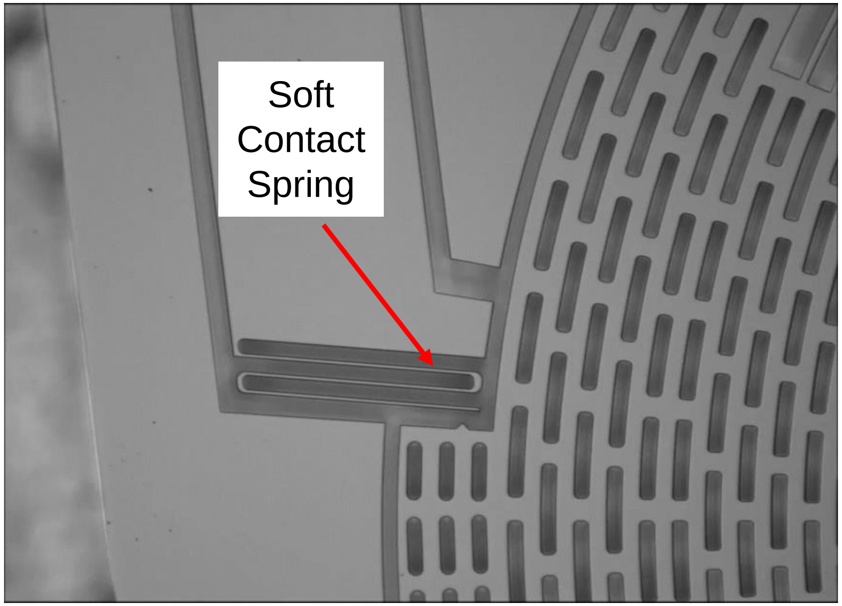


MEMS Rotary Vibration Switch

- Rotation switch separates linear translation/g from resonant frequency
- Rotational device allows low pendulosity for low static g sensitivity, while using the high Q in vacuum to gain sensitivity at the resonant frequency



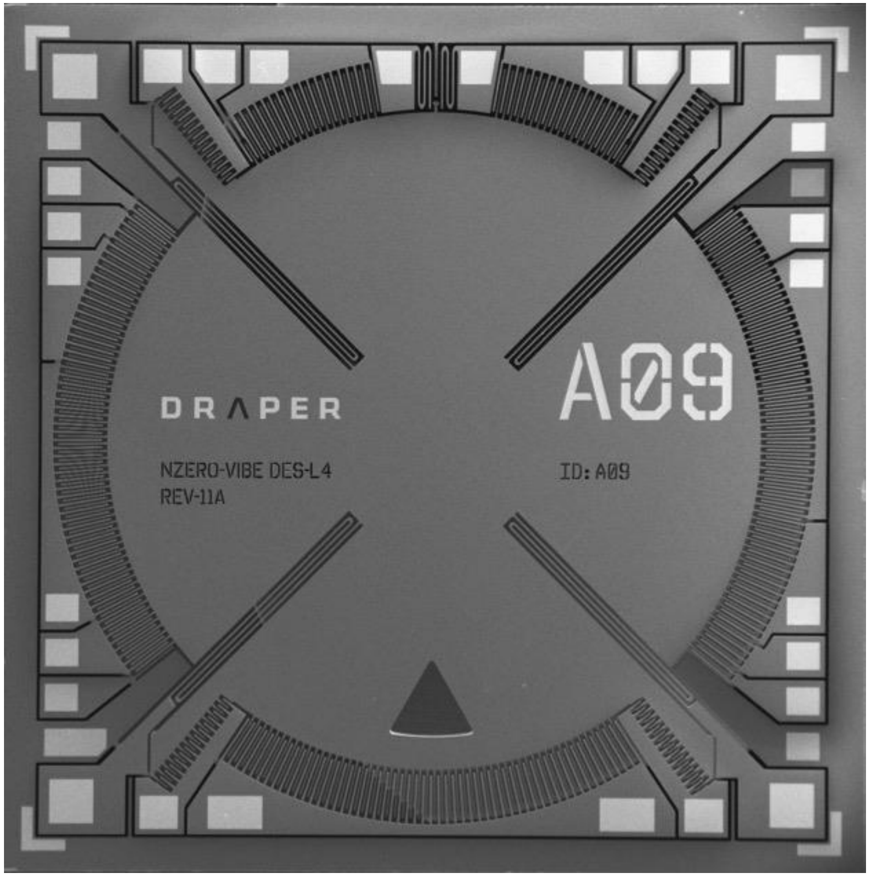
Acceleration Switch
(6 mm diameter rotor)



Vibration Switch Soft Contacts
Reduce Squegging

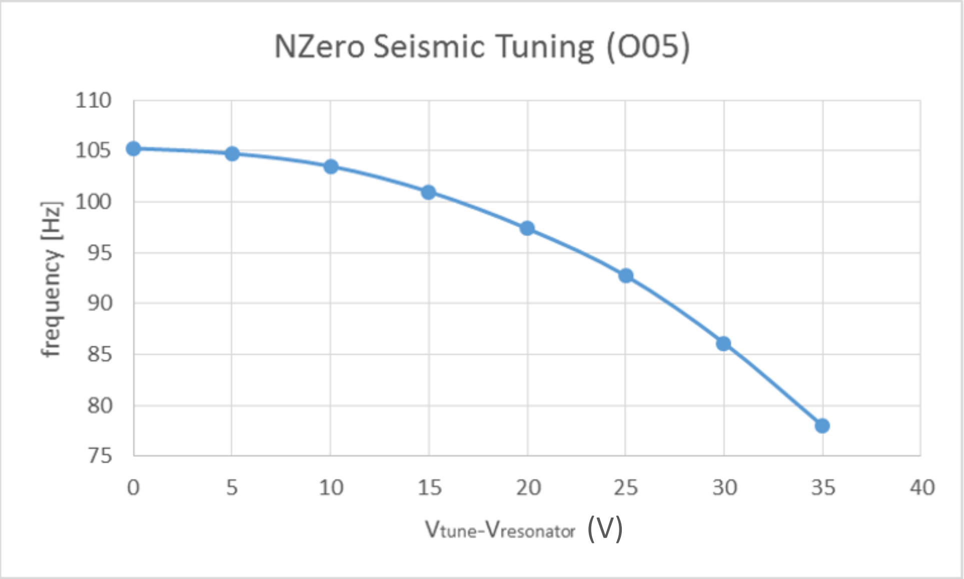
Electrically Tunable Vibration Switch

- Electrostatic tuning: voltage applied to outer electrodes lowers frequency by a few Hz
- Electrode and contact gaps and external capacitors are designed to work despite Duffing nonlinearity



Frequency and Q Tuning the Vibration Sensor

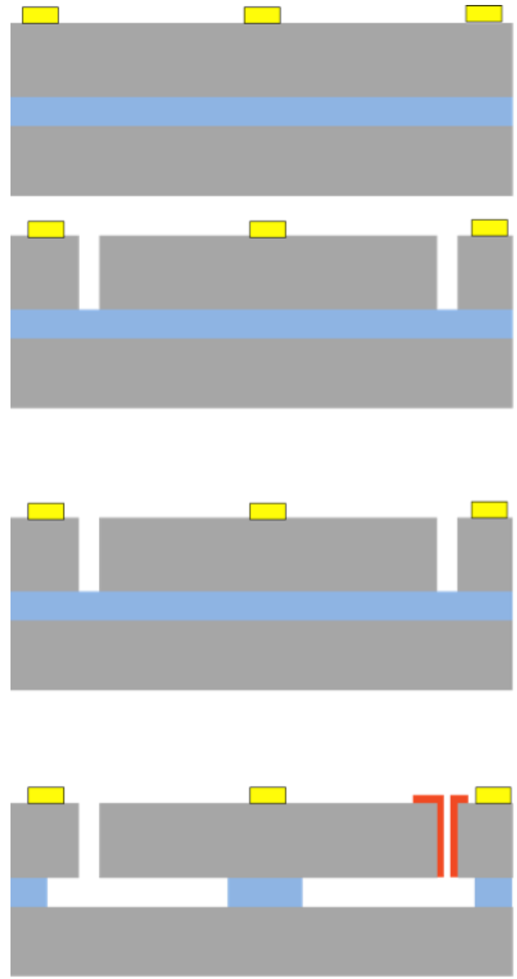
- To hit target frequencies within a fraction of a Hz, tuning is required
- XeF_2 tuning was used to tune frequency down by up to 35 Hz (110 Hz → 75 Hz) by thinning the flexures
- In addition, voltage tunability could be valuable in the field to re-program for a different target, or to track a target with variable frequency
- Voltage tuning demonstrated to reduce the frequency by 10’s of Hz but useful range limited to 2 Hz by non-linearities
- Q > 55,000 as packaged in vacuum results in high sensitivity, however in most cases we want a lower Q due to phase changes on contact impact (squegging)
  - *Can hermetically seal at low pressure gas to reduce Q*
  - *Q can also be reduced via electronic damping using a DC bias voltage and a series resistor*



Frequency tuning Seismic Sensor

MEMS Fabrication-Vibration Switch

- Novel process based on availability of high quality silicon-on-insulator wafers.
- Acoustic and vibrations switches use similar, not identical processing.
- 400 µm thick silicon on oxide
  - *Thickness allows out-of-plane strength*



SOI wafer

Lift off bond pads and backside metal

DRIE defines features

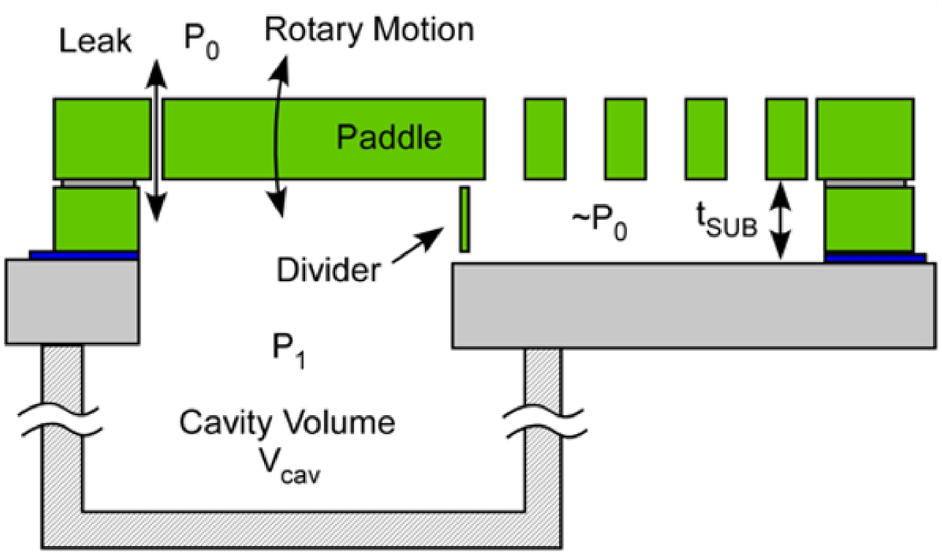
Backside holes for release & cleaning

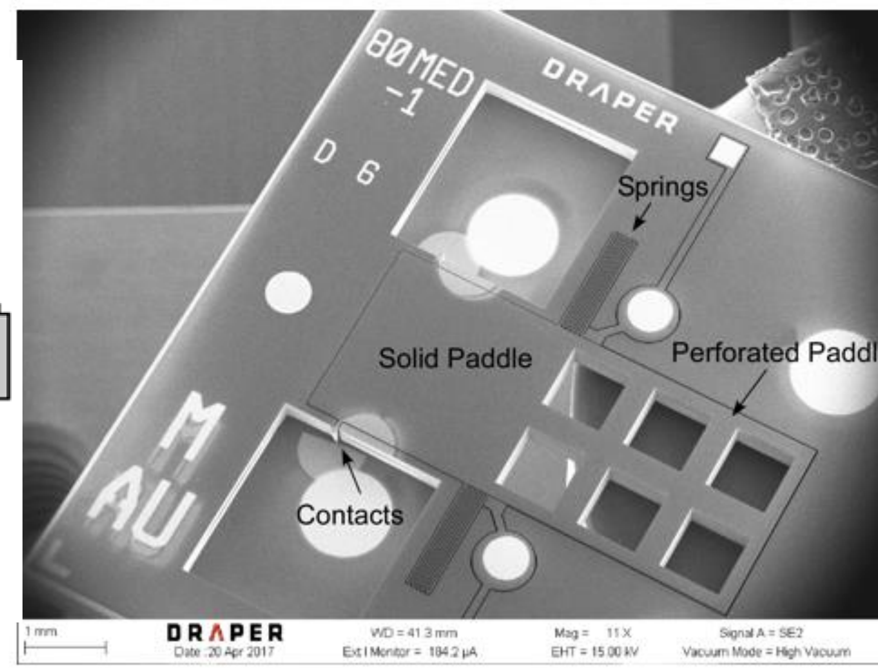
Timed vapor-HF release defines anchors

Shadow mask evaporated ruthenium contact

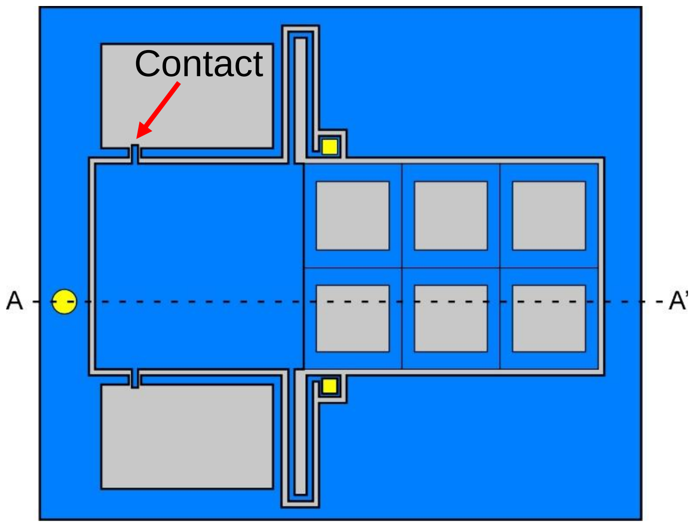
Rotary Acoustic Switch: Operating Principles

- Rotational design to reduce sensitivity to vibration and static gravity
- Balanced see-saw design: solid side responds to sound pressure, 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





Acoustic Chip Fabrication Process



Top and cross-sectional views of device fabrication:

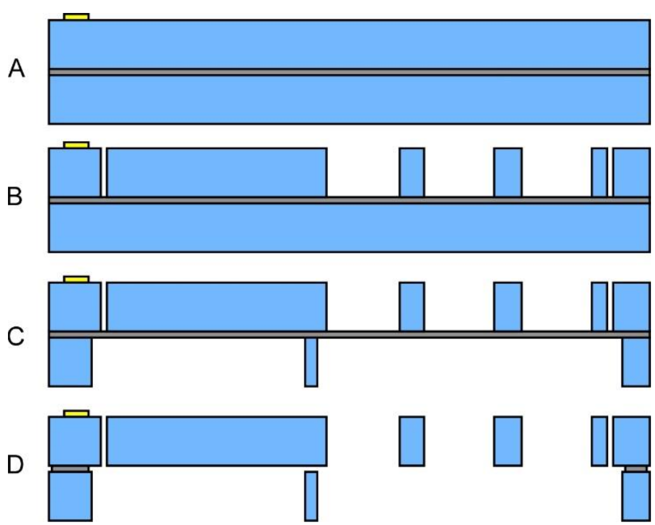
(a) Lift-off bondpad metal

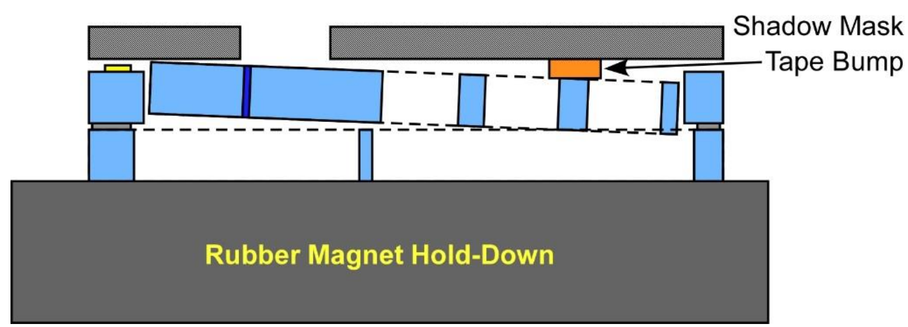
(b) Front ICP etch

(c) Back ICP etch (dice and clean chips)

(d) Vapor HF release

(e) Contact metallization through shadow masks

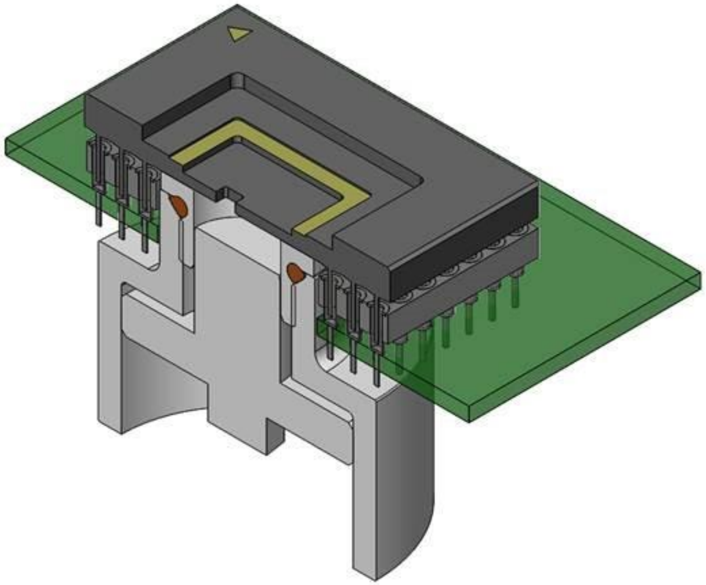




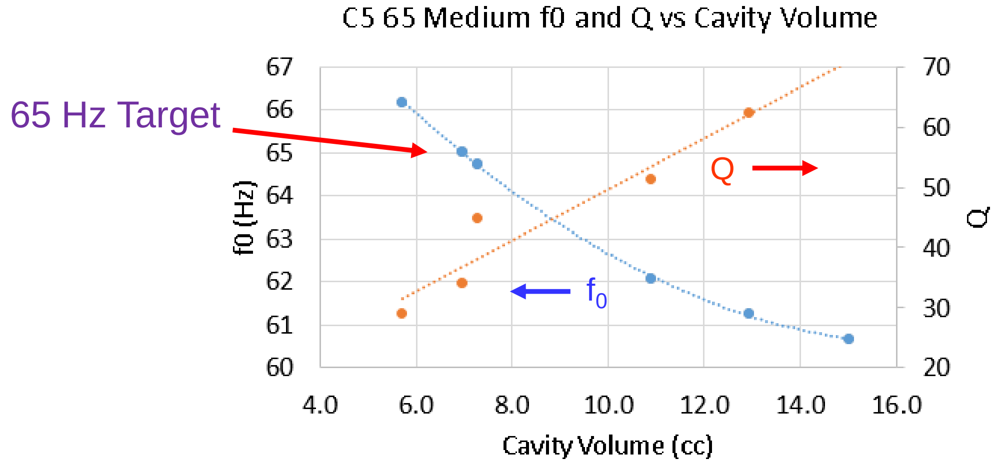
(e) Contact Metallization (top side): shadow mask with bump to lift contacts apart

Acoustic Frequency Tuning by Cavity Volume

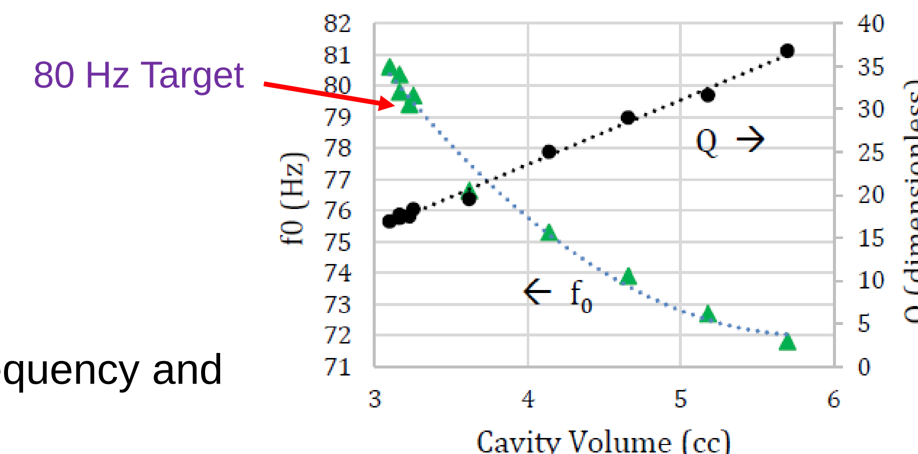
- Cavity tuning successfully implemented to hit target frequencies



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

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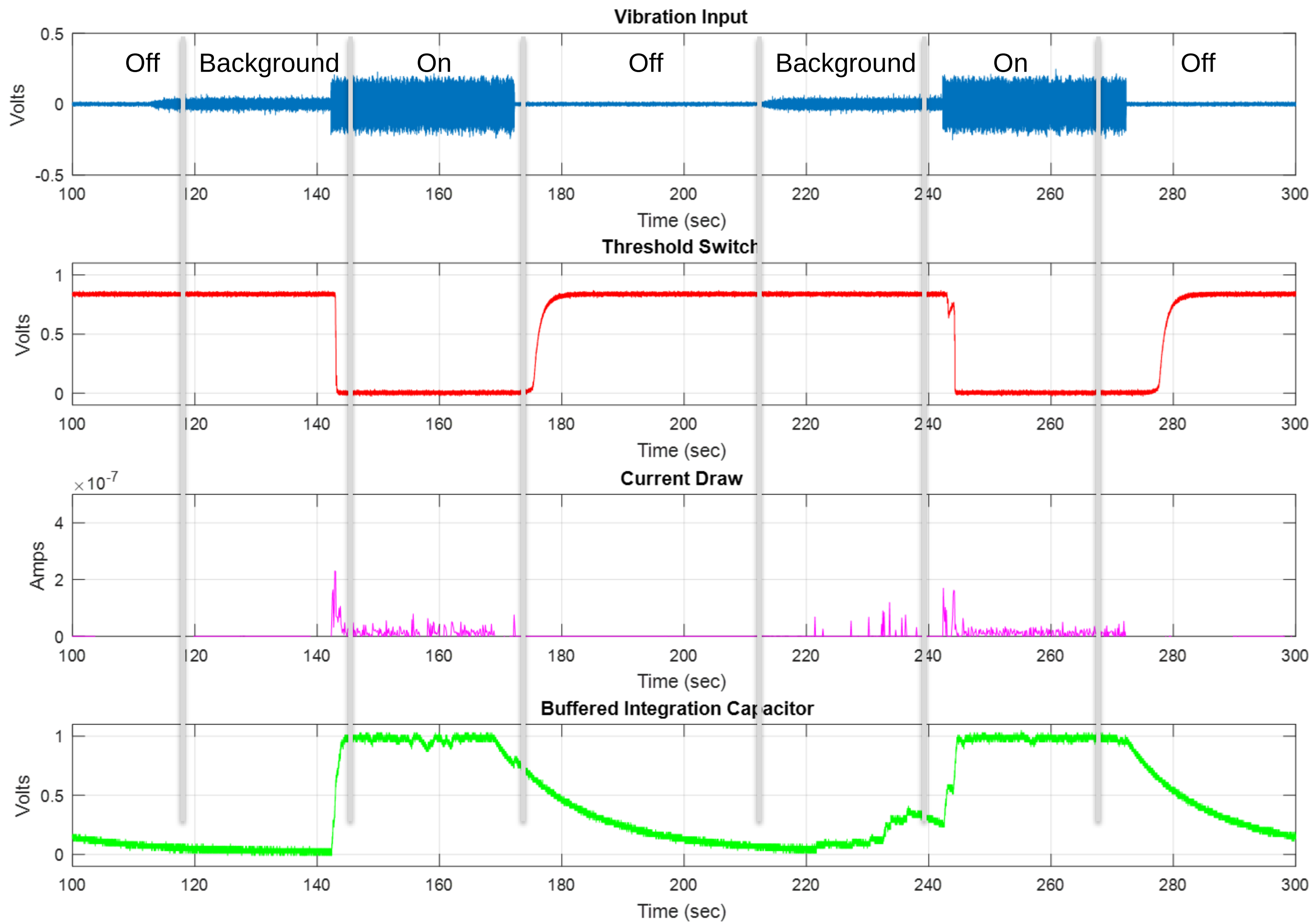
Test Results

M. Tomaino-Iannucci

Vibration Switch Performance: Response to Generator Vibration



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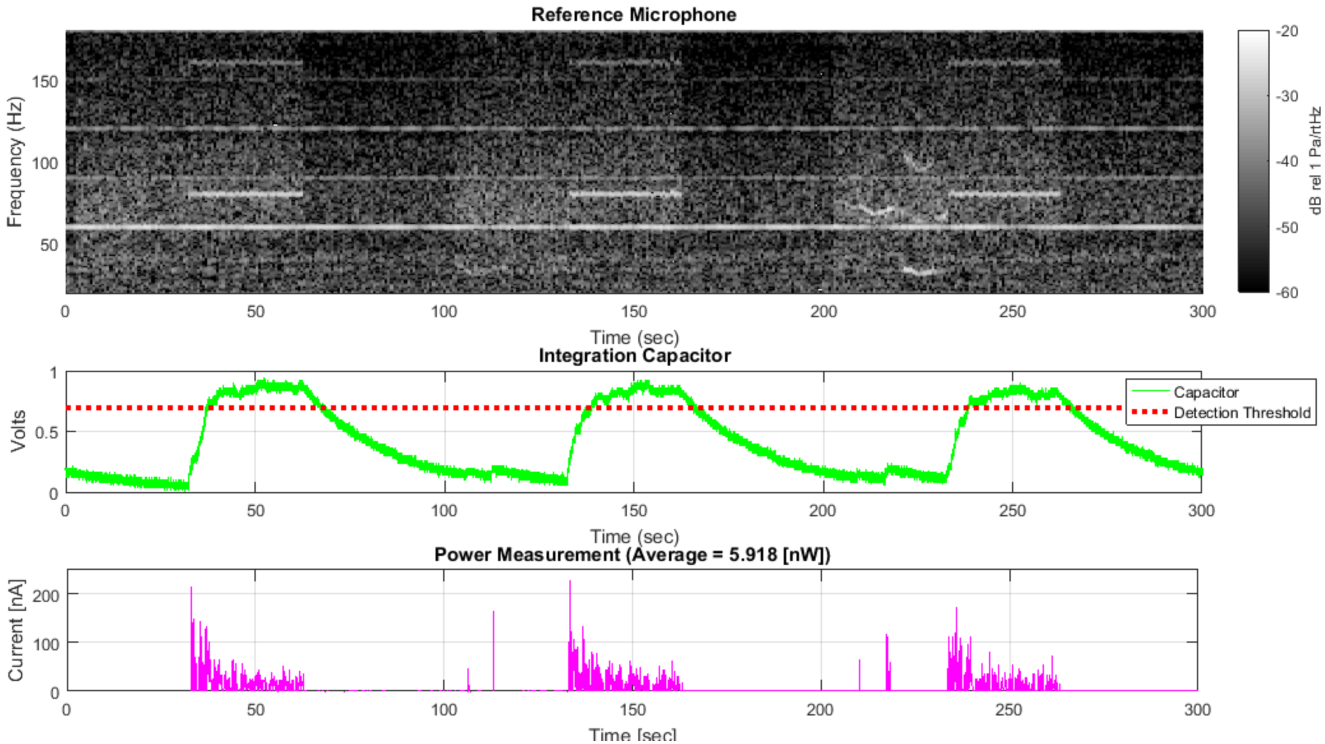
Acoustic Testing: Phase I Test at Lincoln Labs

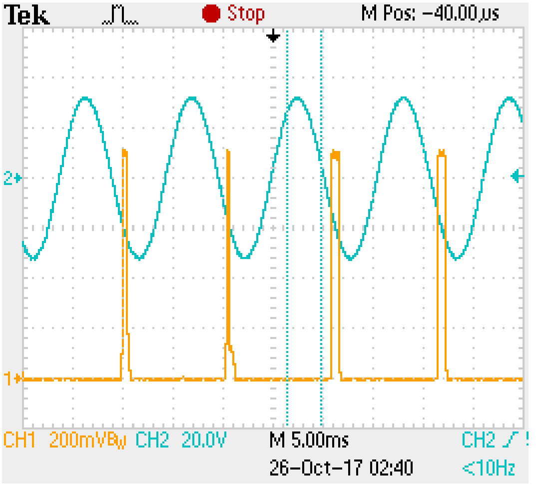
- Phase I program test metrics met
- The generator was successfully detected at a range of 1.5 meters.
- ~ 0.1 nW consumed when no target present.
- Ambient noise and idling automobiles did not trigger any false alarms.

Source: Photos from MIT Lincoln Laboratory

Phase I Generator Acoustic 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.

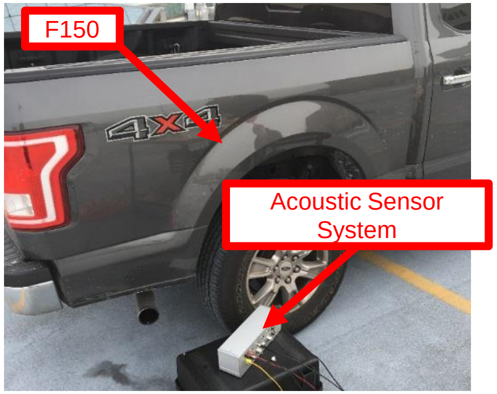


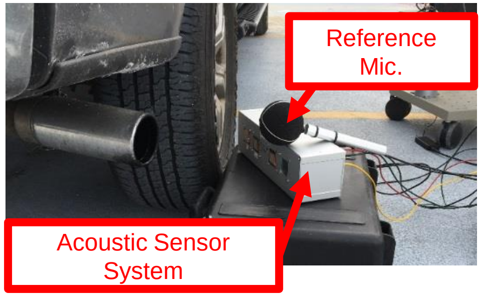


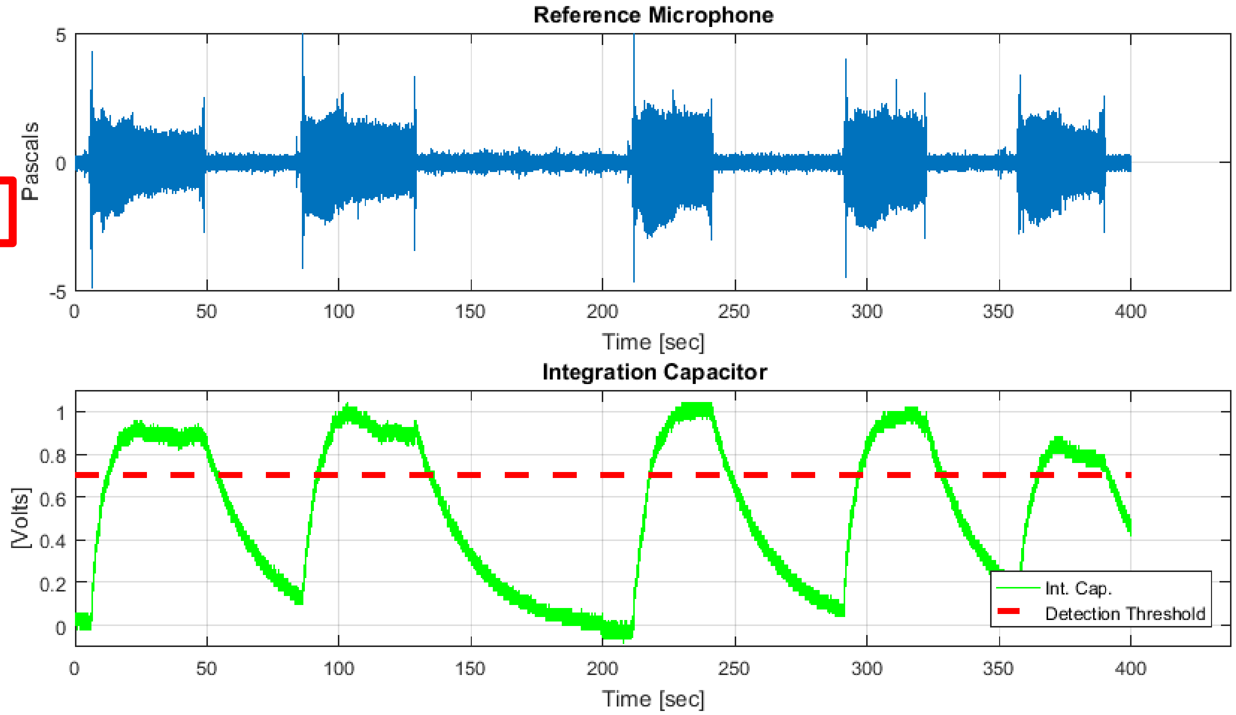
Current spikes during contact. Blue trace = voltage to speaker, orange is current through the contacts with 1 kΩ load.

Phase II Truck Tests at Draper

- 1 m testing performed at Draper
- At Lincoln Labs, acoustic system detected truck at 4 m



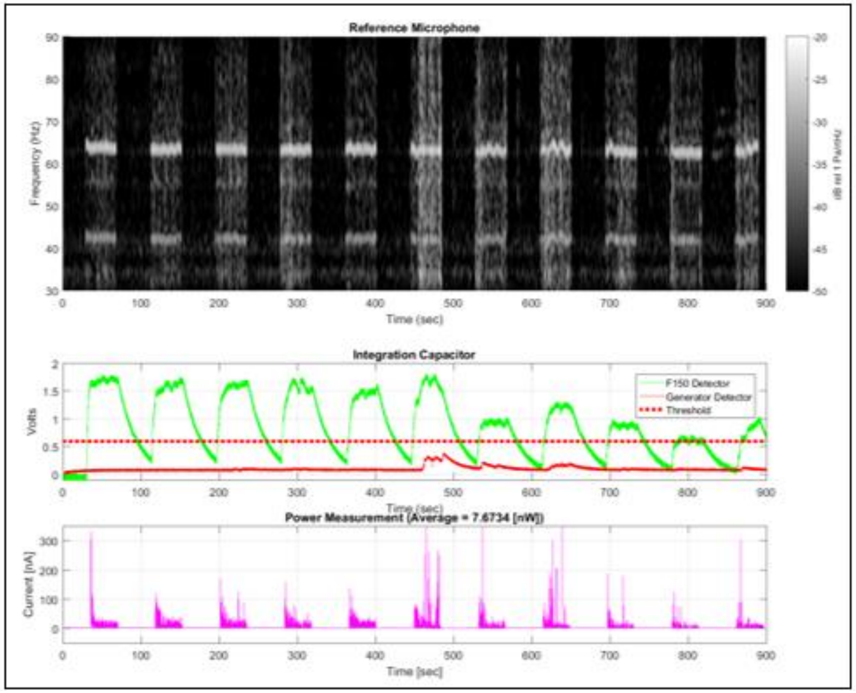




System Testing at Draper

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

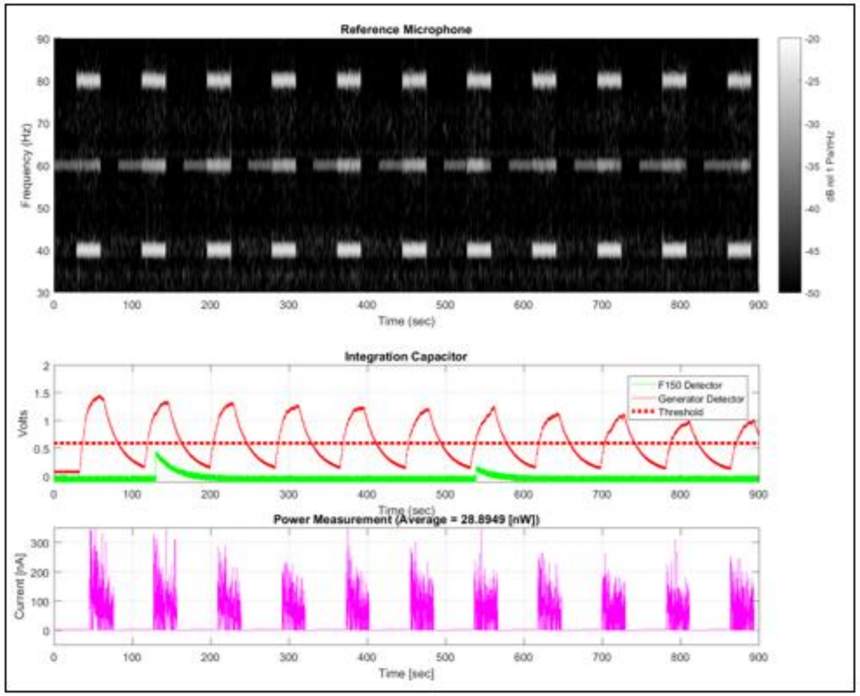
F150 Truck detections



11/11 F150 Detections

0/11 Generator Detections

Honda Generator detections



0/11 F150 Detections

11/11 Generator Detections

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Conclusions

- These resonant sensors detect fixed frequencies very well
  - Voltage tunability demonstrated on vibration sensor
- Off state power is essentially zero by design
- Background clutter and loud transients can be rejected with NOT detectors at off-target frequencies
- Phase II Achievements
  - Vibration sensors detect 0.2 g's, theoretical sensitivity 2 mg
  - Q of vibration sensors > 55,000, reduced with gas or electronic damping
  - Q of acoustic devices ~ 100
  - Demonstrated acoustic detection at 0.005 Pa (48 dB SPL)
  - Detected generator at 5.8 m and truck at 4 m

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