Resonant Evil: Measuring the Effect of MEMS Gyroscopes at Resonance

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Abstract

Ultrasonic attacks have become all of the rage in the security world as of late. One attack in particular, *Rocking Drones with Intentional Sound Noise on Gyroscopic Sensors*, by Son, et al. [1] involves the study of firing a loud ultrasonic wave at a quadcopter drone in mid-flight in order to "rock" it out of the air. In this paper, we extend *Rocking Drones* by measuring the effect different setups (such as critical distance of speaker to gyroscope, effect of damping materials) has on the perturbations seen at the gyroscope at sonic resonance. Using these results, we then comment on the efficacy of *Rocking Drones* in the real world, and suggest future directions for research.

Keywords: ultrasonic waves, drones

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1 Introduction

MEMS gyroscopes are susceptible to an attack where a sound wave at the gyroscope's resonant frequency will cause large amplitude swings in data to be read from the sensor as shown in Walnut [2]. We also note that other research has shown that this can be used to manipulate drones as shown Rocking Drones [1]. However, this paper is merely a denial of service attack and had the constraint of mechanical coupling. This paper extends the concepts presented in *Rocking Drones* and provides multiple reasons why it is not practical in the real world.

2 Background

2.1 Drones

A drone system consists of multiple rotors, a flight controller and wireless transmitter and receiver. The flight controller's receiver receives the control signals from the transmitter (or the remote control), and use a PID controller to probabilistically determine the speed of the rotors in accordance with the users control and sensor input.

2.2 MEMS Gyroscope

The principle underlying the MEMS gyroscope is the law of physics known as the Coriolis effect or Coriolis force. The Coriolis effect is the deflection of a moving object in a rotating reference frame. This effect appears only to an observer in the same rotating reference frame. In the observers view, the path of the moving object is observed to be bent by a fictitious force, i.e. the Coriolis force. In other words, when an object is moving in a rotating container or package, the path of the moving object is bent in a direction different from the moving direction. Therefore, the observer on the container or package can sense this bending. To sense motion with respect to one axis such as Z-axis rotation, there is a mechanical structure called a sensing mass in a MEMS gyroscope. While a sensing mass is continuously vibrating at a certain frequency with respect to the X-axis, the Coriolis force is applied in the Y-axis direction as a result of the Z-axis rotation. The amount of rotation

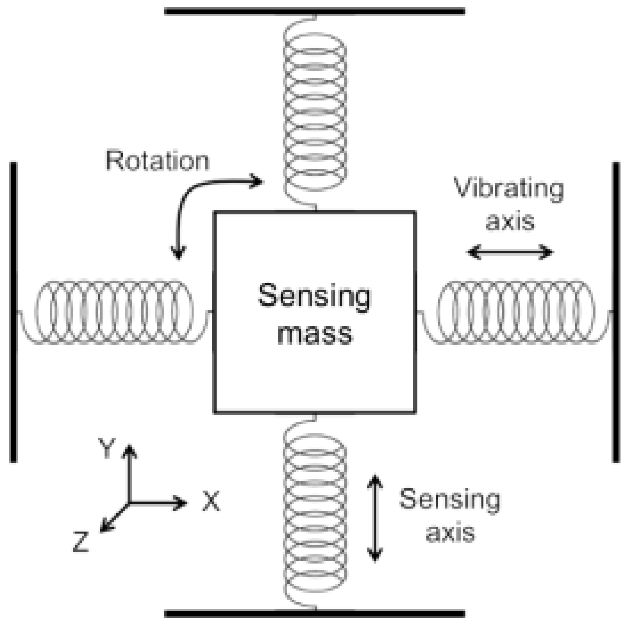

Figure 1: Internals of a MEMS Gyroscope

is proportional to the amount of bending [3].

Previous studies have shown that MEMS gyroscopes [1] exhibit large amplitude swings when resonating. It is currently possible to find the resonant frequency of a gyroscope by performing a frequency sweep with a signal generator and speaker.

3 Methods

3.1 Setup

Our experimental setup is reminiscent of many acoustic-based hardware attacks. First, an IMU with gyroscope is connected via Arduino, with raw measurements recorded and logged to a connected PC. Our experiments made use of the Invensense MPU9250 gyroscope. The PC connects to an Agilent 33220A Signal Generator, which drives an Ultrasonic Speaker. Using this setup, we are able to programmatically conduct a frequency sweep via the signal generator and log the data returned by the gyroscope using a Python script. Our experimental layout is shown in Figure 3. Please refer to Section 8 for code used in the

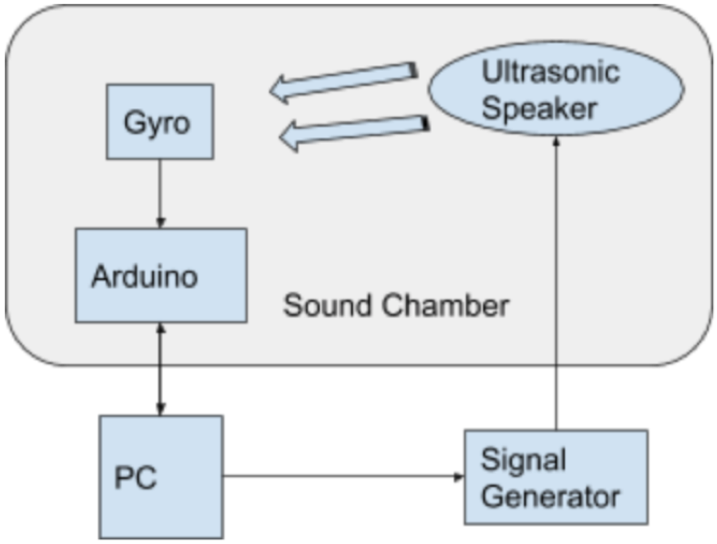

Figure 2: Experiment Layout

project.

Several considerations had to be made while writing the Python script. First, we had to ensure that we had enough time intervals between setting the frequency and actually gathering the output from the Arduino. Additionally, since the data from two devices' had to be collected concurrently proper steps had to be taken to ensure that only correct correlated data was logged and associated for a particular frequency. We achieved this by triggering a read operation on the Arduino by first writing to the serial port to tell the Arduino to start sending back the readings from that point in time. Finally, we had to ensure that running the experiment was safe. This required the use of a sound chamber to contain the speaker and gyroscope to protect us from the loud ultrasonic output of the speaker. The actual experiment setup is depicted in Figure 2 and Figure 3.

3.2 Identifying Attack Features and Viabilities

Initially, it must be ensured that the gyroscope behaves differently when at rest and when introduced to a sufficiently loud signal source at the gyroscopes resonant frequency. A simple frequency sweep for each tested gyroscope yields good results. Beyond this, we are also interested in observing how the gyroscope responds to different parameters of the

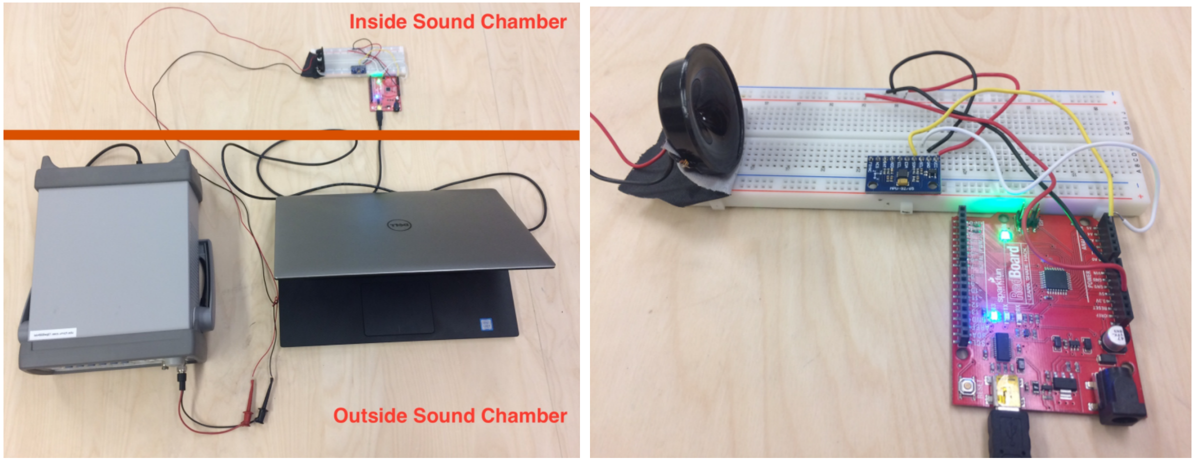

Figure 3: Experiment Setup

attack. Specifically, we wish to observe what effects, if any, the following have on the gyroscope output: frequency, speaker-to-IMU distance, speaker signal amplitude (dB), and gyroscope attitude/pose relative to speaker.

4 Results

4.1 Initial Data Collection

The first piece of information that our group sought to find was the resonant frequencies of the gyroscope on the MPU9250. The datasheet for the MPU9250 [4] states the resonant frequency of the device is 27±2 kHz. The *Rocking Drones* paper [1] found the range to be 26.5 - 27.9 kHz. Our results show the resonant frequency centered at 27.66 with a much tighter range of 27.45 - 27.8 kHz. The discrepancy between our results and previous results may lie in one of several factors, though most likely this is due to the fact that the resonant frequencies of a system will shift due to differences in mechanical coupling [5], such as PCB mounting.

It is interesting to note that all three rotations are affected by the ultrasonic waves. The y-axis (pitch) rate is the most affected out of the three orientations. The z-axis (yaw) is the least affected, and perturbations are approximately negligible at distances larger than 2 inches.

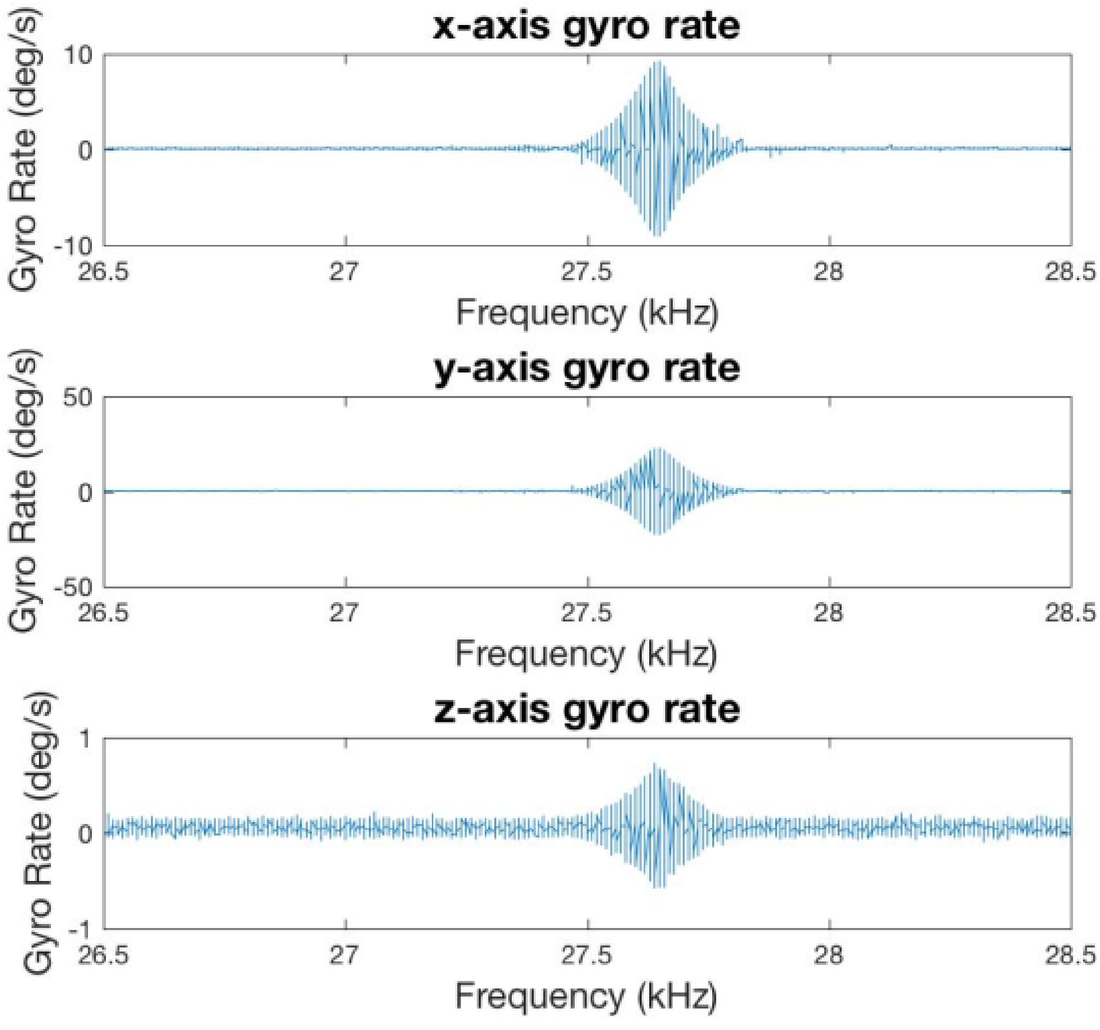

Figure 4: Raw gyroscope data when speaker placed 2 inches in the +z direction

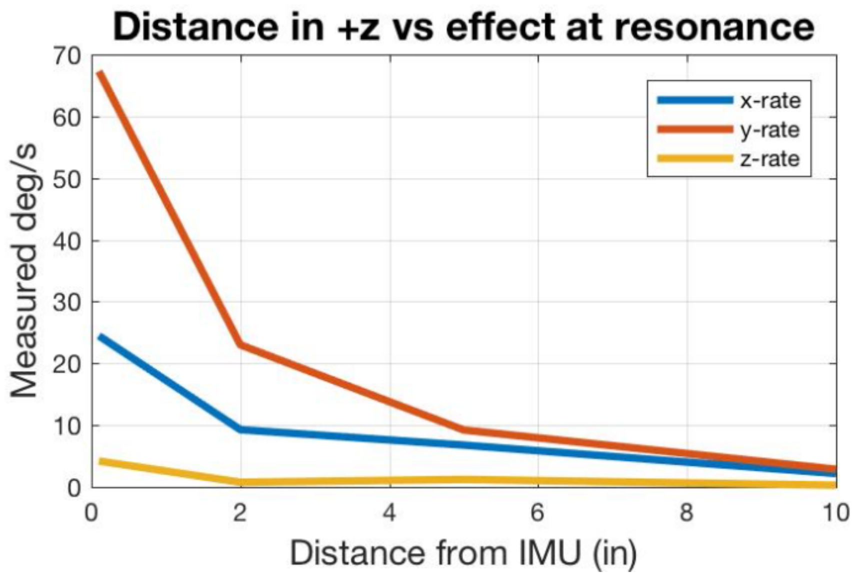

Figure 5: Effect of ultrasonic speaker distance on gyroscope readout

4.2 Effect of Speaker Distance From Gyroscope

There exists a limit of how far the speaker and gyroscope may be placed from each other in order for an attack to work. In order to find this limit, we placed the speaker at various distances away from the gyroscope, in the +z direction. The results of this test are shown in Figure 5. As can be guessed, perturbations in the gyroscope's output are decreased as the speaker moves away from the IMU. The plots appear to follow the inverse square law of sound, meaning that there is a linear relationship between sound amplitude at resonance and the amplitude of the gyroscope reading. From this experiment, we found that the limit exists at just above 10 inches with an absolute loudness of 100 dBSPBL.

4.3 Effect of Speaker Orientation with respect to Gyroscope

MEMS gyroscopes are built with axial springs that are used as parameters in the rotation estimate. Due to this axial alignment, it is a good assumption that the orientation of the speaker to the gyroscope has an effect, e.g. it will resonate better with some of the spring pairs than the others. We ran an experiment to see if this is the case. Results are shown in Figure 6.

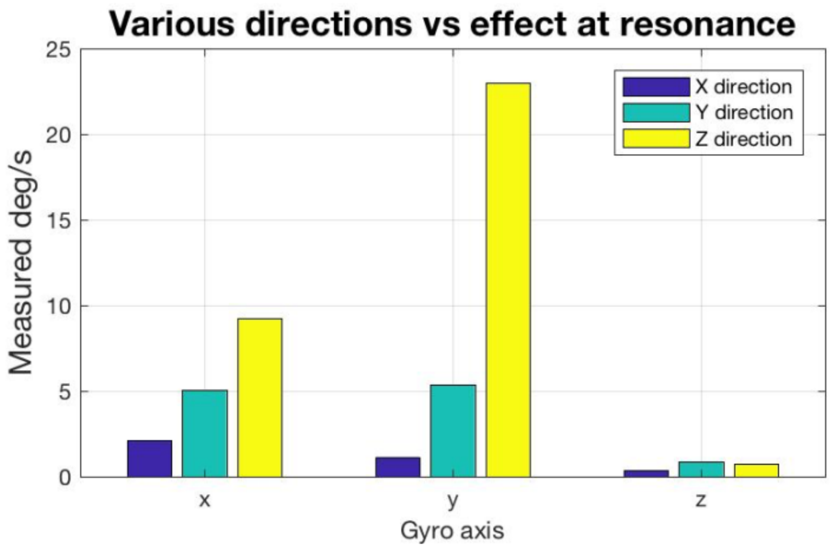

Figure 6: Effect of ultrasonic speaker direction on gyroscope readout

In this experiment, the setup with the speaker facing the gyroscope's z-axis yielded the best results. It should be noted that this is not necessarily the case for all gyroscopes, as the transistor layout and design of the chip die has a large effect on the sensitivity of each axis. The perturbations are decreased when the speaker is pointed in the y direction, and further decreased for the x direction. The effect of sensor directionality on the gyroscope's x axis is nearly negligible.

4.4 Effect of Damping Materials

The previous experiments were conducted in a relatively isolated environment, where the ultrasonic waves traveled through the air unobstructed. In the real world, IMUs are placed on PCBs which are then covered by an enclosure of some sort. Conventional acoustics tells us that noise loses much of its amplitude when passing through non-gaseous media.

We ran the experiment again, with the speaker 2 inches away in the z direction. This time, however, various materials were placed in between the speaker and the gyroscope. The results of these tests are shown in Figure 7.

As expected, all materials drastically reduce the perturbations in the gyroscope output. For the x-axis (roll) readout, amplitude was decreased by at least 2x, and in the y-axis

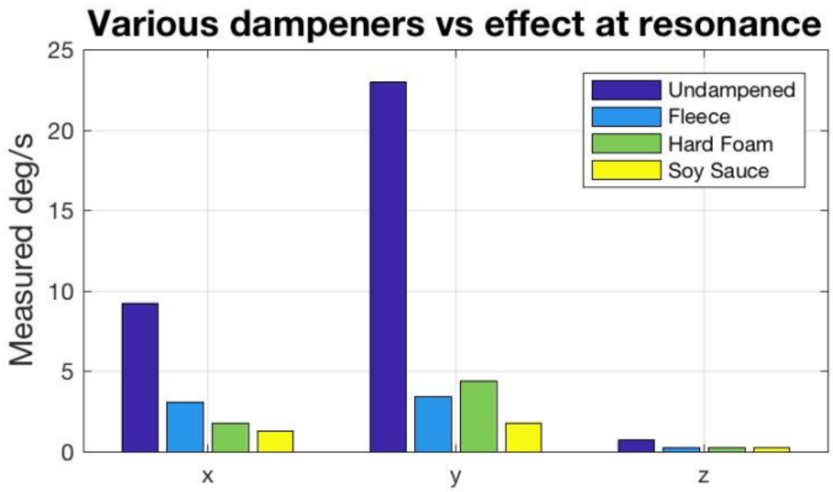

Figure 7: Effect of damping materials on gyroscope readout

(pitch) readout, by at least 4.5x.

Surprisingly, a packet of soy sauce is a very good material for damping. This is due to its low viscosity, which yields a low bulk modulus, meaning that is very resistant to compression. A bit of useful information - sonic waves propagate through the air through the processes of compression and rarefaction. If compression is difficult, the wave will expend more energy in this phase and thus lose amplitude.

5 Efficacy of *Rocking Drones*

The initial goal of this paper was to reimplement *Rocking Drones* with the added feature of knocking a physically decoupled drone out of the sky. This, in practice, proved quite difficult to do.

Most commercial quadcopter drones come with remote control transmitters. These transmitters have knobs that impart commands to the motors on the drone. These controls can be rather finicky and subject to quick jerks in motion. In our initial tests using the ARRIS FPV 250 Quadcopter [6], shown in Figure 8, hover control proved difficult, and the machine was quite fast, reaching speeds near 20 m/s.

Due to the difficulties of isolating a drone in flight within a sound chamber, we will instead enumerate the reasons why knocking a drone out of the air is difficult in practice.

1. Drones often fly at very high speeds (20 m/s). As the gyroscope reading drops off to near zero motion at 10 inches away, it is impractical to rock a drone that is flying at this speed.

2. We have seen that the largest pertubations occur when the speaker is pointed directly at the z-axis of the IMU, and that firing ultrasonic waves off-axis yields heavily attenuated and suboptimal results. It would be very difficult in practice to fire the sonic attack from directly above the drone (directly facing z-axis).

3. The gyroscope/IMU package is often covered in hard plastic housing. This chassis serves to damp any incoming sonic wave.

4. The drone's flight control software uses the gyroscope reading as only one out of a few measurement modalities (i.e. altimeter, barometer, accelerometer) to infer its true state. Good control algorithms will be able to account for even large perturbations in gyroscope output

6 Future Directions

6.1 Sonic Beamforming

A potential exploration that could be made with future research is whether sonic beamforms can be used to improve the efficacy of the attack. Sonic beamforms use less energy and can target the gyroscope precisely [7]. This can give an adversary better performance of the attack especially with respect to distance. The research in this paper shows the inverse power law in effect where an increase in distance can cause an exponential dropoff in the amplitude and thus, the impact on the gyroscope.

6.2 Controlling Drones

The WALNUT attack shows us how we can control a signal using a readout. A potential space that could be explored with more time and resources is attempting to take control of

Figure 8: Drone used for testing: ARRIS FPV 250 Quadcopter.
The drone uses the InvenSense MPU6050 IMU, a variant of the MPU9250.

a drone using these methods. This would require much more sophisticated techniques as detailed information about the implementation of the PID controller on the drone would be required. Additionally, a recommendation for this attack would be to first try to influence a simulated PID controller instead of attempting to directly try this in the real world. Another observation is that instead of using racing drones more stable drones like video-streaming drones would be easier to evaluate which can be attributed to the increased stability of the system.

6.3 Drone Fighting

Drone fighting leagues have sprung up all over the world, and mostly have consisted of several drones in a netted cage battling by physically attacking each other. Using an ultrasonic speaker as a weapon in these arenas would increase the complexity and add to the joy of the game. Most drone chassis are naturally set up to attenuate backpropagating noise, and in our initial experiments, we see that the gyroscope readout is not affected when the speaker is 3 inches pointed away from the IMU.

7 Conclusion

It is common knowledge in the security world that MEMS devices are susceptible to a change in response near resonant frequencies. Here, we measured the effects of different parameters in the acoustic attack setup, commented on the efficacy of rocking drones using ultrasonic waves in real life, and come up with a resoundingly negative result.

8 Open Source Project

The code use to run our experiments, as well as data taken during the experiments is available online at https://github.com/pringithub/drone-gyroscope-attack under the GPLv3 license.

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