Computers in Biology and Medicine 104 (2019) 250–266

Contents lists available at ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/compbiomed

On Cuba, diplomats, ultrasound, and intermodulation distortion

Chen Yan[a], Kevin Fu[b], Wenyuan Xu[a,*]

[a] Department of Systems Science and Engineering, Zhejiang University, China
[b] Computer Science & Engineering, University of Michigan, United States of America

ARTICLE INFO

Keywords:
acoustic
Ultrasound
Intermodulation

ABSTRACT

This paper analyzes how ultrasounds could have unintentionally led to the AP news recordings of metallic sounds heard by diplomats in Cuba. Beginning with screen shots of the acoustic spectral plots from the AP news, we reverse engineered ultrasonic signals that could lead to those outcomes as a result of intermodulation distortion with non-linearity in the acoustic transmission medium. We created a proof of concept ultrasonic device that amplitude modulates a signal over an inaudible ultrasonic carrier. When a second inaudible ultrasonic source interfered with the primary source, intermodulation distortion created audible byproducts that share spectral characteristics with audio from the AP news. Our conclusion is that if ultrasound played a role in harming diplomats in Cuba, then a plausible cause is intermodulation distortion between ultrasonic signals that unintentionally synthesize audible tones. In other words, acoustic interference without malicious intent to cause harm could have led to the audible sensations in Cuba.

1. Introduction

In early 2017, diplomats in Cuba suffered hearing loss and brain damage after hearing strange metallic sounds. The news media published reports ranging from scientific analysis of sound recordings [1–3] to the diplomatic implications [4–7]. The mystery deepened after physicians published two dueling JAMA papers on neurological damage to diplomats [8,9]. The news media remained flummoxed on what may have caused the neurological damage [10–12]. Several news reports suggested that an ultrasonic weapon could have caused the harm. Other experts suggested toxins or viruses. The cause remains a mystery. The substantiated facts include:

- Ultrasonic tones are inaudible to humans.
- Diplomats in Cuba reported hearing audible sounds.

Therefore, any sounds perceived by diplomats are not likely the ultrasound itself. We were left wondering:

1. How could ultrasound create audible sensations?
2. Why would someone use ultrasound in the first place?

Why Ultrasound. It is well known that audible sounds typically propagate omnidirectionally and are difficult to confine to parts of a room. In contrast, ultrasounds tend to propagate within a narrower beam than audible sound and can focus a beam towards a more specific area. News reports cited diplomats discussing sounds that were narrowly confined to a room or parts of a room [1]. This type of observation is strongly correlated with ultrasound. We believe that the high-pitched audio signals confined to a room or parts of a room are likely created by ultrasonic intermodulation distortion.

How to Produce Audible Sound from Ultrasound. Humans cannot hear airborne sounds at frequencies higher than 20 kHz, i.e., ultrasound. Yet the AP news reported that “It sounds sort of like a mass of crickets. A high-pitched whine, but from what? It seems to undulate, even writhe.” The AP's spectrum plot shows a strong audible frequency at 7 kHz. We believe that this 7 kHz sound is caused by intermodulation distortion, which can down-convert the frequency of ultrasound into the audible range—resulting in high-pitched noises. Nonlinearity typically causes intermodulation distortion. The engineering question boils down to: assuming an ultrasonic source, how can the audible byproducts consist of a mixture of several tones around 7 kHz separated by 180 Hz, as described by the AP news recording?

Sources of Ultrasound. There are many potential sources of ultrasound in office, home, and hotel environments. Energy efficient buildings often use ultrasonic room occupancy sensors in every room (Fig. 1). Ultrasonic emitters can repel rodents and other pests with powerful ultrasonic and near-ultrasonic noises (Fig. 2). HVAC systems and other utilities with pumps or compressors can vibrate entire buildings. Certain burglar alarm sensors, security cameras, and

* Corresponding author..
E-mail addresses: yanchen@zju.edu.cn (C. Yan), kevinfu@umich.edu (K. Fu), xuwenyuan@zju.edu.cn (W. Xu).

https://doi.org/10.1016/j.compbiomed.2018.11.012
Received 23 June 2018; Received in revised form 15 November 2018; Accepted 15 November 2018

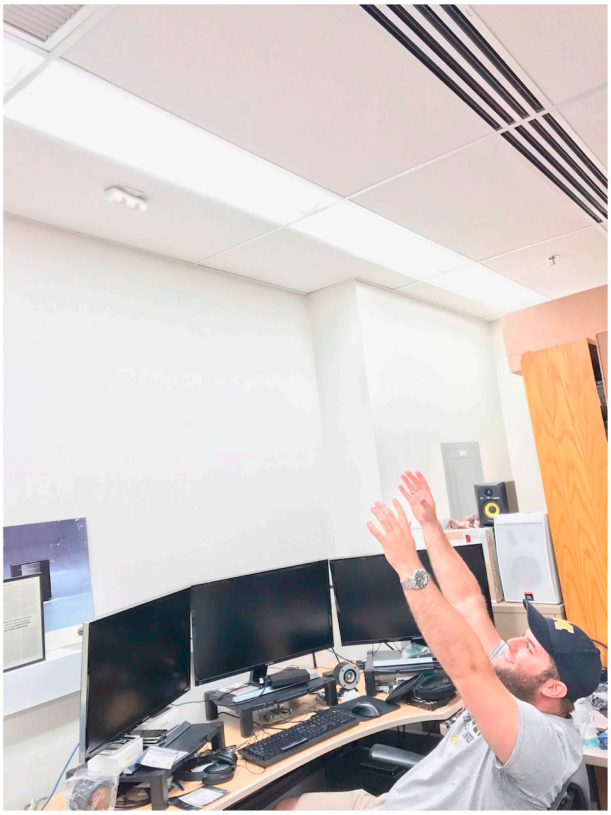


Fig. 1. Many offices contain ultrasonic emitters in the ceiling to determine room occupancy for controlling lights. The offices at the University of Michigan use a continuous 25 kHz ultrasonic tone. Computer Science & Engineering Ph.D. student Connor Bolton notices one such unwanted, inaudible ultrasonic emitter.

automated doors use ultrasound for detection of movement. Researchers from Illinois recently proposed using specially crafted ultrasound to jam microphones [13], and there have already been commercial ultrasonic jammers (e.g., in Fig. 3) that prevent audio recording by emitting strong ultrasound noises to interfere with the microphones. Ultrasounds are also used in offices for inaudible and location-restricted communications and control between different devices. An example is the Cisco Proximity system[1] that utilizes ultrasound to pair a personal device with the video endpoint in a conference room so that meeting content can be shared on that device. The inaudibility of ultrasound may be used in other emerging applications that are required to be wireless and quiet, and may also be adapted for stealthy scenarios unknown to the general public, such as eavesdropping.

There are also hailing devices such as the Long Range Acoustic Device (LRAD) that many people claim use ultrasound. There may be LRADs that use ultrasound, but modern LRADs tend to use parametric audible sound below 3 kHz. Using an array of several dozen piezo speakers that emit sound in a synchronized fashion to improve directionality, a LRAD can generate sound waves with a wavelength much smaller than the size of the speaker. Under such conditions (which also tend to be true of ultrasonic emissions), the sound will propagate in a tight, directional beam—enabling long distance delivery of sound.

If sounds from an ultrasonic source were to collide with another such source, the two signals could combine to form audible byproducts in both air and microphones due to nonlinearity. The interference between ultrasonic devices is common because many such devices adopt the same frequency band of ultrasound, generally between 20 kHz and 40 kHz. Compared with RF signals, the bandwidth of ultrasounds is narrow, and there is no spectrum allocation schemes or mechanisms that detect collision on existing ultrasonic devices.

Assumptions and Limitations. We assume that the sound came from ultrasound, then work backwards to determine the minimal characteristics of an ultrasonic source that would explain the observed audible sensations.

We assume the recordings from AP news [1] are authentic, but remain skeptical because we are unaware of where and how these recordings were made. There could be added distortion in the AP audio, so we cannot assume the recordings reflect what humans actually perceived. In one video, the AP news is seen playing a sound file from one iPhone to a second iPhone, essentially making a recording of a recording. Each traversal through a speaker or microphone will add distortion and filtering.

Our experiments focus on spectral properties and objective acoustic data pertaining to airborne ultrasound. Although we do provide scientific background of human factors for context, our experimental outcomes are independent of self-reported symptoms and human perception except for one ultrasonic experiment where we opine on a difference between our hearing and what a microphone perceives. We do not experiment with non-ultrasonic, non-airborne hypotheses such as contact ultrasound, toxins, RF, psychosomatic effects, or LRADs. We do not experiment with direct mechanical coupling such as unwittingly standing on an ultrasonic vibrator.

2. Spectral analysis of AP news audio

We initiate our study with two observations from the AP news: (1) the original audio recordings and (2) description on the high-pitched sounds heard by those in Cuba. Our goal is to construct ultrasonic signals that can lead to similar spectral and audible characteristics.

Audio Clips. The AP News [1] published several recordings from Cuba described as a high-pitched whine or “cricket” sound.[2] In the video, a piercing, metallic sound is evident which is not pleasant to hear. As a common method to analyze signals, a frequency spectrum was obtained by Fourier transform of the original sounds. The AP news performed the spectral analysis on a smartphone (Fig. 4) and showed a spectral plot centered at 7 kHz (Figs. 5 and 6). The spectral plot demonstrates that there are roughly 20 or more different frequencies embedded in the audio recording. Watching the AP video frame by frame, we immediately noticed a few oddities. In one sequence, someone plays a sound file from one smartphone while a second smartphone records and plots the acoustic spectrum. Thus the data may be significantly corrupted, because each microphone and speaker introduces some distortion. Moreover, what humans hear isn't necessarily the same as what a microphone detects. Cleverly crafted sounds can lead to auditory illusions to microphones akin to optical illusions [14].

Nevertheless, we decide to begin our analysis from the AP news audio clips. We considered the question: given its authenticity, what source can produce the sound while satisfying the description provided by the personnel in Cuba? Firstly, we compare the recording to that of a similar sound, i.e., that of cicada vocalization. Fig. 7 shows the spectrum of sound from real cicadas.[3] The AP news recording is similar to the call of cicadas, because of the overlap at the 7 kHz frequency band, and the presence of multiple pitches with separation. Despite the similarity, the sound patterns have substantial differences as well. For instance, swarms of cicadas are not known for their ability to perform collective acoustic beam forming or phased arrays to create localized sound.

Audio Analysis. We acquired the audio from the AP news,[4] which is

[1] https://proximity.cisco.com/.

[2] https://youtu.be/rgbnZG85IRo.

[3] https://youtu.be/MNJ6DL_1R9I.

[4] https://youtu.be/Nw5MLAu-kKs.

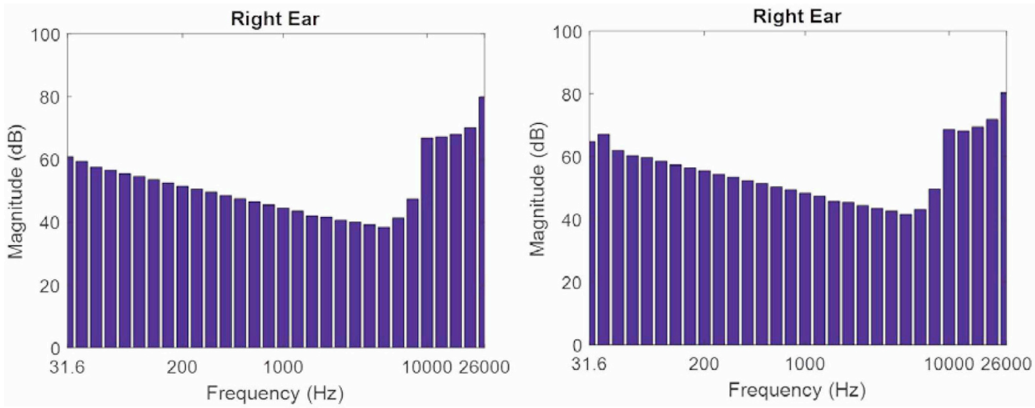


Fig. 2. 1/3 octave spectrum for 60 s (left) and 1 s (right) noise signals generated by a Zoonic pest repeller at the high frequency setting. (Courtesy of Dr. Jun Qin at Southern Illinois University Carbondale).

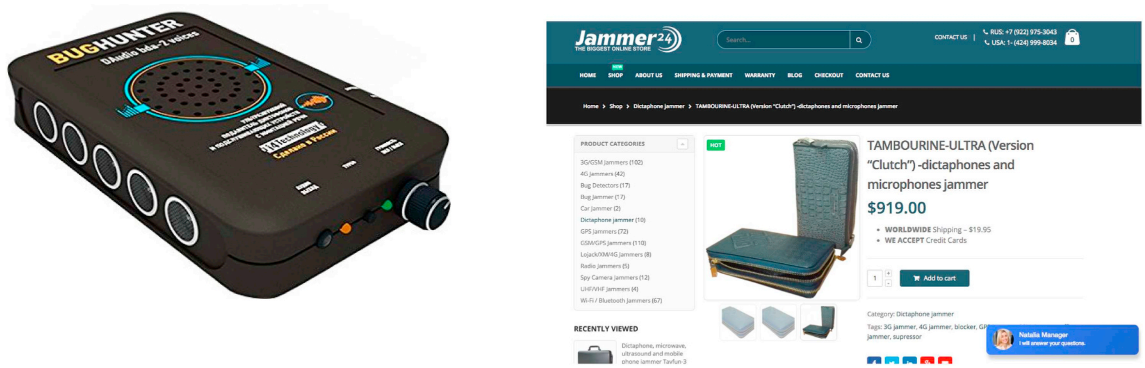


Fig. 3. Commercial products with several ultrasonic transducers can jam nearby microphones. One manufacturer sells a clutch, presumably for fashionable people to jam microphones at cocktail parties.

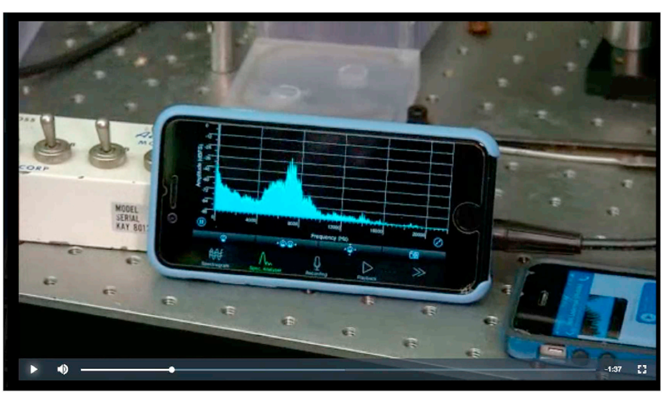


Fig. 4. Screen shot of the AP news itself showing a screen shot of a recording of yet another recording from Cuba. Note that the recording device appears to have removed the spectrum above 14 kHz.

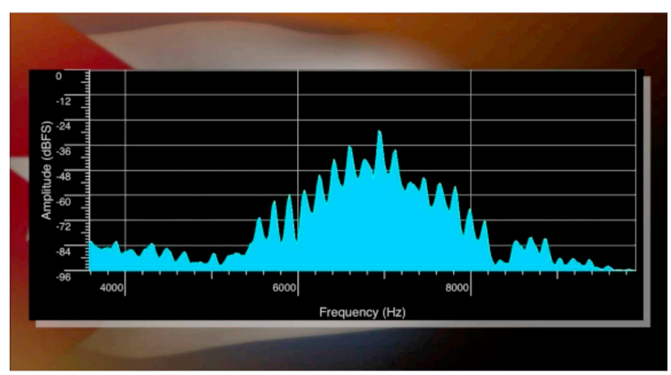


Fig. 5. Screen shot of the AP news showing the Fourier transform of what was reported as sounds heard by diplomats in Cuba.

claimed to be a recording of what some U.S. embassy workers heard in Havana. The recording extracted from the video is 5 s long, and was sampled at 44.1 kHz with 32-bit floating point resolution. We analyzed the sound in time (Fig. 8), frequency (Fig. 9), and time-frequency domains (Fig. 10).

After observing the time signal with high resolution, nothing remarkable was apparent in the AP news recording. No modulation appears in the waveform (at least not amplitude shift keying (ASK)), and the waveform does not resemble frequency shift keying (FSK) or phase shift keying (PSK), among other common modulation schemes. We tried to demodulate the signal as amplitude modulation (AM), but found no obviously modulated hidden messages.

Our own spectral plot of the sound from the AP news (Fig. 9) shows major frequency components centered around 7 kHz. The peaks (6704 Hz, 6883 Hz, 7070 Hz, 7242 Hz, 7420 Hz) are separated by approximately 180 Hz.

However, in the waterfall plot (Fig. 10), the major frequencies (in yellow) do not change over time. This lack of change again suggests that there is no frequency-related modulation, such as frequency modulation (FM) or FSK. Hence, wherever the sound originates from, it produces a mixture of several tones around 7 kHz separated by 180 Hz.

3. Simulation: intermodulation distortion of ultrasound

Intermodulation distortion (IMD) is the result of multiple signals propagating through nonlinear systems. Without loss of generality, a

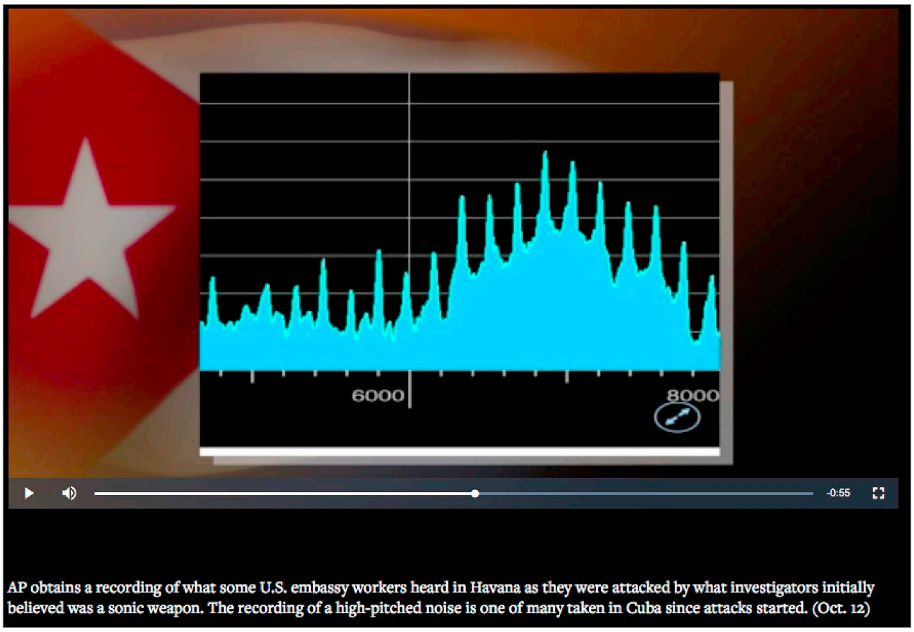


Fig. 6. Screen shot of the AP news analyzing a different recording showing emphasis on spectrum near 7 kHz.

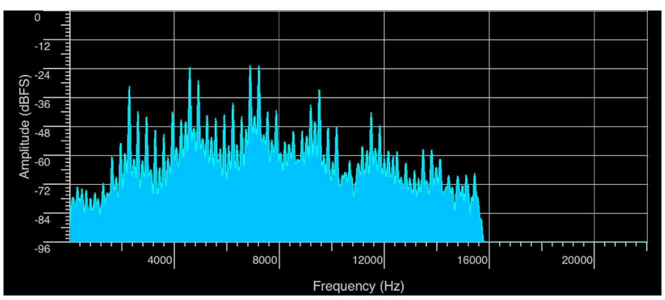


Fig. 7. The spectral analysis of sounds from cicadas contains energy near 7 kHz, but without evidence of localization.

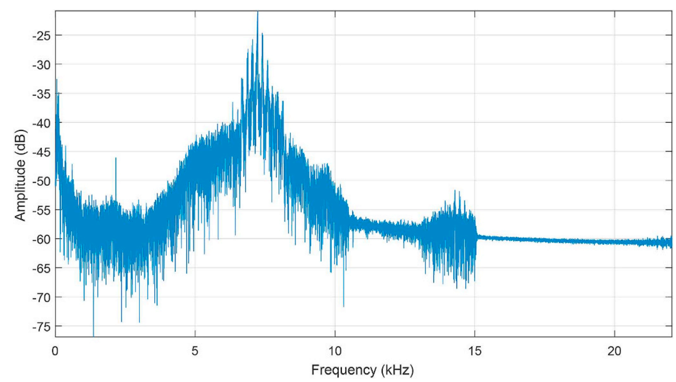


Fig. 9. The spectrum of metallic sounds extracted from the AP news video. The spectrum of the AP news audio ends abruptly at 15 kHz. We suspect this is an artifact of either the AP audio filtering, YouTube audio filtering that is known to roll off beginning at 16 kHz, or iPhone audio filtering that begins to roll off at 21 kHz on our equipment.

nonlinear system can be modeled as a polynomial equation of the form:

$$s_{out} = a_1 s_{in} + a_2 s_{in}^2 + a_3 s_{in}^3 + \cdots + a_n s_{in}^n$$

where s_{in} is the system input and s_{out} is the system output. The $a_n s_{in}^n$ for $n > 1$ is called the nth order IMD. When s_{in} contains multiple frequency tones, the IMDs introduce new frequency components.

3.1. Simulation of 20 kHz and 21 kHz IMD

To illustrate the principle of intermodulation distortion independent of what may have happened in Cuba, let $s_{in} = s_1 + s_2$, where $s_1 = \sin(2\pi f_1 t)$ and $s_2 = \sin(2\pi f_2 t)$. When $f_1 = 20$ kHz and $f_2 = 21$ kHz, the spectrum of s_{in} will have two spikes with one at 20 kHz and another at 21 kHz (Fig. 11(a)).

After the signals pass through the nonlinear system, s_{out} will contain new frequency components that are determined by the order of IMD. For example, the 2nd order IMD introduces new frequencies at $f_2 - f_1$ (1 kHz), $f_2 + f_1$ (41 kHz), $2f_1$ (40 kHz), and $2f_2$ (42 kHz). Fig. 11(b) shows the spectrum of these new frequencies. Notice that $f_2 - f_1$ is below 20 kHz and audible. Higher order IMD products can reinforce the 2nd

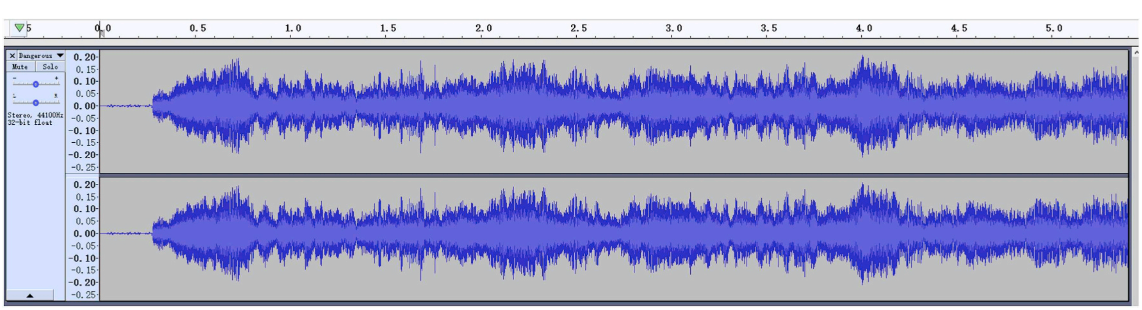


Fig. 8. The time domain signal of metallic sounds extracted from the AP news video.

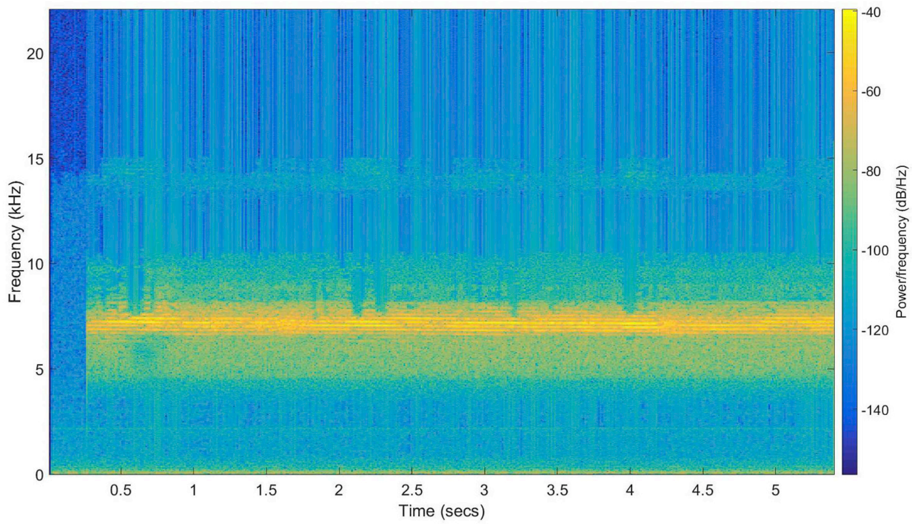
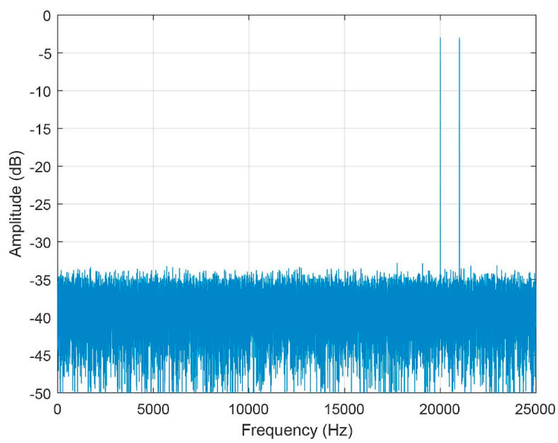
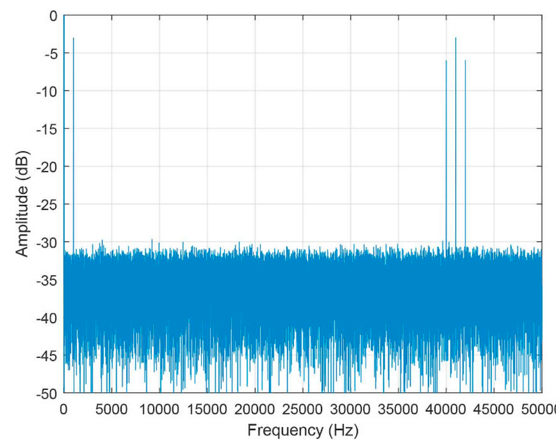


Fig. 10. The spectrogram-time plot (waterfall) of metallic sounds extracted from the AP news video.



(a) The fundamental signal.



(b) The 2nd order IMD (without the fundamental).

Fig. 11. Simulated spectra of (a) a fundamental signal with pure tones at 20 kHz and 21 kHz, and (b) its 2nd order IMD derivative (which will be added on top of the original fundamental signal) after passing a nonlinear equation in MATLAB.

order IMD while introducing other new frequencies. For example, the 4th order IMD introduces both $f_2 - f_1$ (1 kHz) and $2f_2 - 2f_1$ (2 kHz). The final picture of all the IMDs is a mixture of peak clusters at various frequencies, as shown in Fig. 12. We show the mathematics and provide a discussion concerning higher order IMDs in the Appendix.

3.2. Simulation of IMD of three ultrasonic tones

In practice, most signals contain multiple tones. To illustrate the effects of IMD on three ultrasonic tones, let us explore the case of three signals at 25 kHz, 32 kHz, and 32.18 kHz. That is, $s_{in} = s_1 + s_2 + s_3$, where $s_1 = \sin(2\pi f_1 t)$, $s_2 = \sin(2\pi f_2 t)$, and $s_3 = \sin(2\pi f_3 t)$, $f_1 = 25$ kHz, $f_2 = 32$ kHz, and $f_3 = 32.18$ kHz. We selected 32.18 kHz to mimic the observation of a 180 Hz separation in the AP news spectrum.

When there are more than two signals, intermodulation transpires between each pair of the signals. To explore the phenomenon that intermodulation of ultrasound creates audible sound, we focus on the audible component of IMD products. As shown in Fig. 13(a), the 2nd order IMD introduces new frequencies (below 20 kHz) at $f_2 - f_1$ (7 kHz), $f_3 - f_2$ (180 Hz), and $f_3 - f_1$ (7.18 kHz). If there are more signals (e.g., another $f_4 = 31.82$ kHz), more IMD products are generated: $f_4 - f_1$ (6.82 kHz), and $f_3 - f_4$ (360 Hz), and existing IMD frequencies are enhanced ($f_2 - f_4 = 180$ Hz). The higher order IMD products (4th, 6th, 8th, etc.) will generate more frequencies around the existing ones (7 kHz and 180 Hz) with a separation of 180 Hz, and create new frequencies. For example, Fig. 13(b) shows that the 4th order IMD introduces new frequencies (below 20 kHz) at $f_3 - f_2$ (180 Hz), $f_3 - f_2$ (360 Hz), $2f_2 - f_3 - f_1$ (6.82 kHz), $f_2 - f_1$ (7 kHz), $f_3 - f_1$ (7.18 kHz), $2f_3 - f_2 - f_1$ (7.36 kHz), $2f_2 - 2f_1$ (14 kHz), $f_2 + f_3 - 2f_1$ (14.18 kHz), and $2f_3 - 2f_1$ (14.36 kHz). With the increase of IMD orders, there will be more frequency peaks rippling around 180 Hz, 7 kHz, and 14 kHz. Each ripple will be separated by 180 Hz. We also detail the discussion and simulation results in the Appendix.

Now consider the audible frequencies produced by all the IMDs up to and including the 7th order summed together in Fig. 14. The peaks near 7 kHz are beginning to resemble the AP news spectrum.

3.3. Simulation of IMD of ultrasonic modulation

To generate similar intermodulation of three ultrasonic tones, it is feasible to explore the IMD for two signals, where one is modulated on an ultrasonic carrier. In particular, to generate signals similar to the recording, i.e., signals centered at 7 kHz with a serial of multiples of 180 Hz signals nearby, we can utilize two signals and their intermodulation. Let $s_{in} = s_1 + s_2$. One of the signals can be a single tone, $s_1 = \sin(2\pi f_1 t)$, and the other will be a signal that is modulated with a

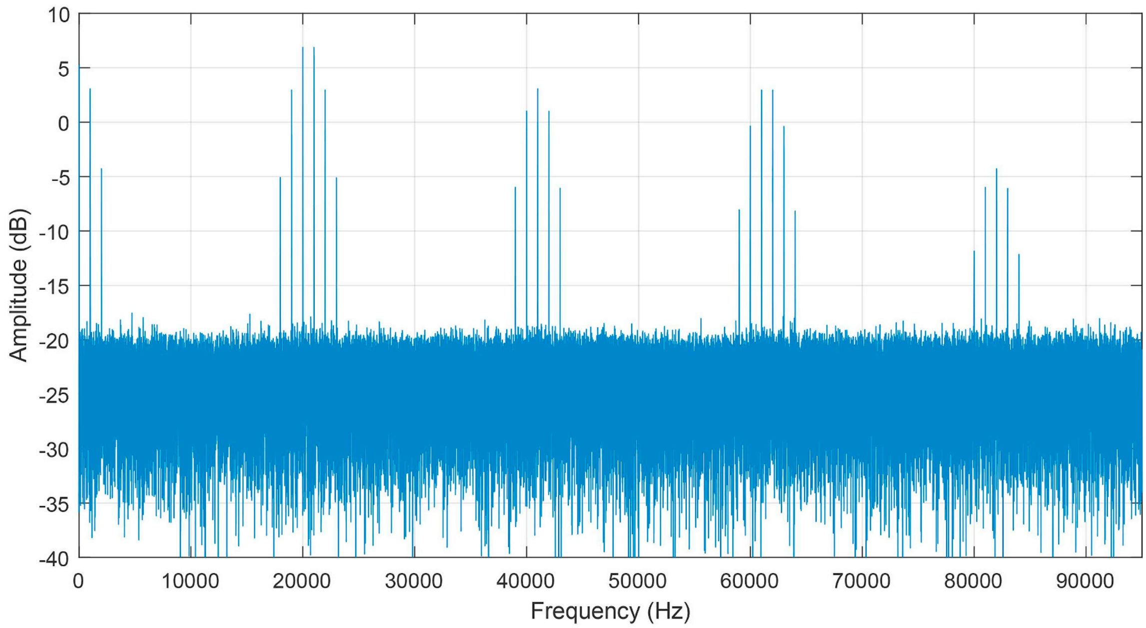
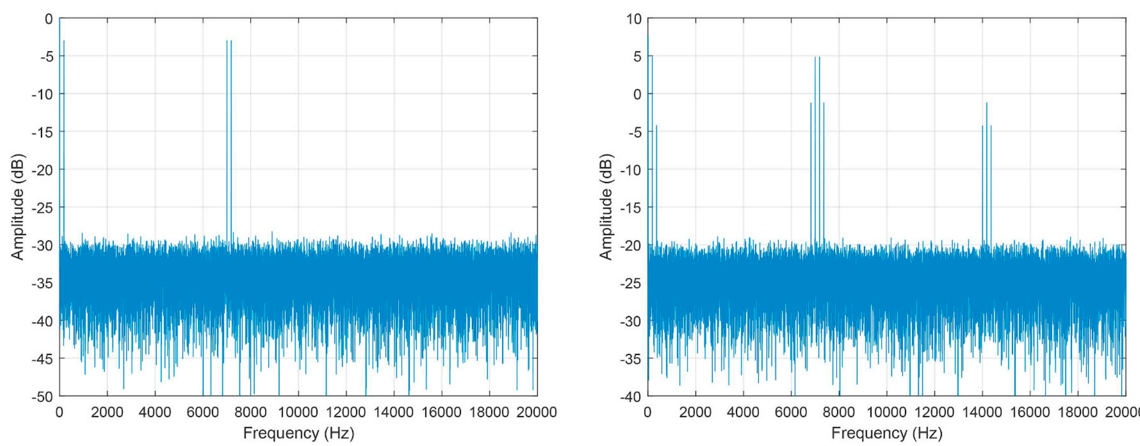


Fig. 12. Simulated cumulative audible spectrum of 2nd through 5th order IMD for 20 kHz and 21 kHz tones.



(a) 2nd order IMD.

(b) 4th order IMD.

Fig. 13. Simulated audible spectrum of the 2nd (a) and 4th order IMD (b) for 25 kHz, 32 kHz, and 32.18 kHz tones.

baseband of 180 Hz single tone. In particular, we utilize amplitude modulation (AM) that produces double-sideband and transmitted carrier. For example, when the baseband signal is a single tone at $f_m = 180$ Hz, and the carrier signal is at $f_c = 32$ kHz, AM with transmitted carrier will produce an output of $s_2 = \sin(2\pi f_c t) + \sin(2\pi f_c t)\sin(2\pi f_m t)$, which can be seen as the combination of three signals at f_c (32 kHz), $f_c + f_m$ (32.18 kHz), and $f_c - f_m$ (31.82 kHz), as shown in Fig. 15. When IMD happens between such an AM signal and a $f_1 = 25$ kHz single tone, the result will be exactly the same as the previous 4 tones example—signals around 7 kHz, 180 Hz, 14 kHz, and more.

The spectrum of the simulated IMD through the 7th order products with input of 25 kHz and 180 Hz AM modulated on a 32 kHz carrier is depicted in Fig. 16.

If the baseband signal is not a 180 Hz tone, but music or something else that is composed of many tones, it will only change the separation (f_m) of the ripples. The recovered signals always remain at approximately 180 Hz, 7 kHz, 14 kHz, etc. Lower order IMD products such as the 2nd are more dominant than higher order ones such as the 4th in nonlinear systems. Therefore, signals at 180 Hz and 7 Hz will be stronger than 14 kHz, which correspond with the spectrum of AP recording.

3.4. Discussion of simulation results

Different systems (e.g., recording devices) have different nonlinear properties that determine the strength of each order of IMD products. In the simulations, we use a_i coefficients of unity weight for the strengths. If we were to obtain the recording devices and emitters from Cuba, we could deduce the coefficients. We surmise that the reason that there are no obvious frequencies at 4 kHz, 11 kHz, and 18 kHz in the original AP news recording is because the intermodulation products at the odd orders are weak relative to the 2nd and 4th order IMDs on whatever devices recorded the sounds in Cuba.

The IMD can also transpire multiple times. IMD may occur during airborne transmission. The IMD can transpire again inside the circuitry of a microphone as well as in the human inner ear itself. Thus, the perceived sounds will differ depending upon where one is listening and what are the characteristics of the microphone.

3.5. Summary of IMD simulation

Our simulations confirmed the feasibility of reproducing the acoustic spectrum of the AP news recording with the intermodulation

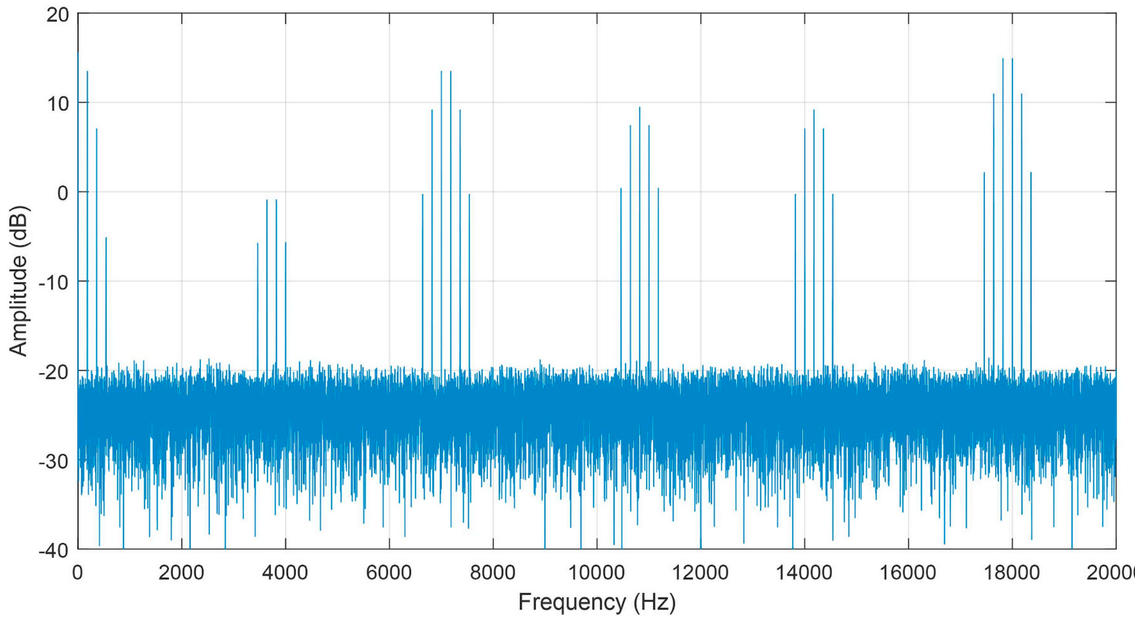


Fig. 14. Simulated cumulative audible spectrum of 2nd through 7th order IMD for 25 kHz, 32 kHz, and 32.18 kHz tones.

distortion of multiple ultrasonic signals. Notice that in the spectrum of the AP news recording, there were also frequency components at 180 Hz (not obvious to the eye), 360 Hz, 540 Hz, and around 14 kHz.

4. Feasibility experiments

With the theories validated by the MATLAB simulations, our next step is to generate real ultrasonic signals that cause audible sensations that resemble the sounds heard in Cuba. We start our experiments with ultrasonic emitters at a low power level to demonstrate the feasibility.

4.1. Experimental setup

Our experiments were used to test several different emitters and frequencies. We primarily use one wide-band ultrasonic speaker Vifa[5] in combination with a multitude of ultrasonic transducers with fixed frequencies at 25 kHz or 32 kHz to artificially create IMD. Each fixed transducer has enough bandwidth for the 180 Hz sidebands of AM modulation. We are motivated to choose 25 kHz and 32 kHz as the tested frequencies because these frequencies are widely used in common ultrasonic devices. For example, the frequencies commonly used by ultrasonic occupancy sensors are 25, 32 and 40 kHz [15]. The occupancy sensor in our lab (Fig. 1) transmits a continuous 25 kHz ultrasonic tone. The Zoonic pest repeller[6] found at the Havana airport [16] emits ultrasounds alternating between 15 and 35 kHz or 20–50 kHz. We found six commercial ultrasonic jammers that disclose their parameters, and all of them work at around 25 kHz. We believe our choice of frequency represents a realistic case of ultrasound sources in office, home, and hotel environments.

We drive the ultrasonic emitters with two signal generators, a basic function waveform generator and a vector signal generator[7] for experiments involving modulation.

We receive and validate the sound waves generated by our experiment with two setups, either a professional measurement microphone with a frequency response of 4 Hz–100 kHz,[8] or the microphones used in smartphones that run spectrum analysis applications such as SpectrumView and Ultrasonic Analyzer. Note that microphones can also add extra distortion from their non-linearity and their detected sound may differ from what a human would have heard in the room.

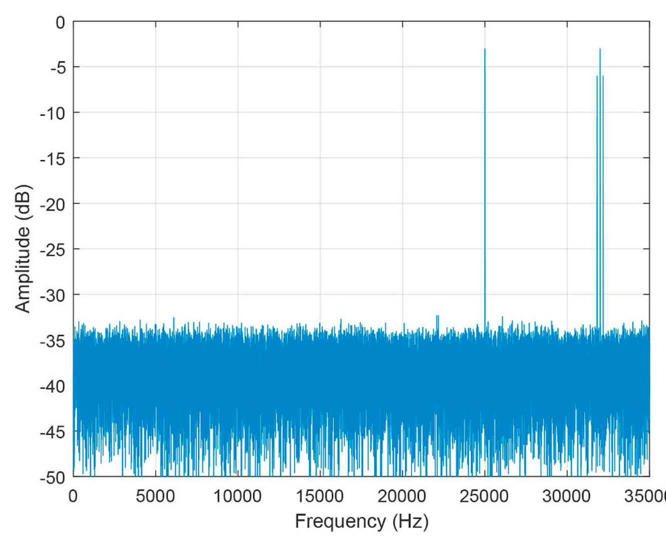


Fig. 15. Simulated spectrum of 25 kHz tone and 180 Hz AM modulated over a 32 kHz carrier.

4.2. Experiment with three ultrasonic tones

As shown in Fig. 17, we generate ultrasound at three different frequencies (25 kHz, 32 kHz, 32.18 kHz) with three devices—two 32 kHz ultrasonic transducers (for 32 kHz and 32.18 kHz) and a wide-band ultrasonic speaker (for 25 kHz). A smartphone receives the ultrasounds

[5] https://www.avisoft.com/usg/vifa.htm.

[6] https://www.toscano.es/en/product/zoonic.

[7] We used a Keysight N5172B EXG X-Series RF Vector Signal Generator for the AM modulation, but many function generators also have modulation capabilities.

[8] National Instruments Inc., G.R.A.S. 46BE 1/4″ CCP Free-field Standard Microphone Set, http://www.ni.com/pdf/manuals/G.R.A.S._46BE.pdf.

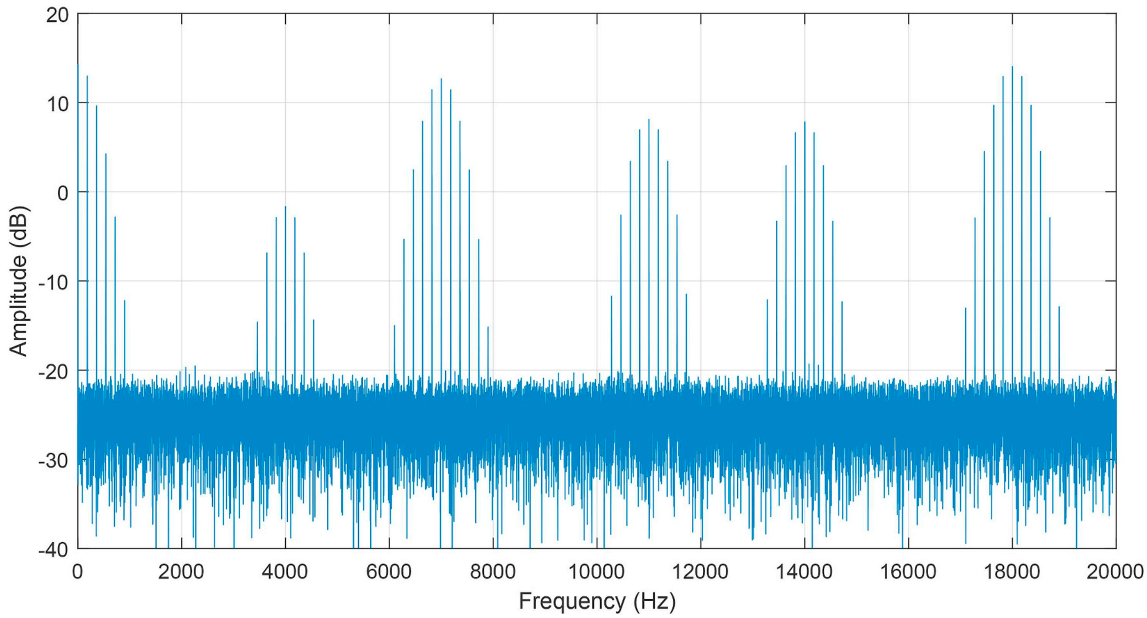


Fig. 16. Simulated cumulative audible spectrum of 2nd through 7th order IMD for 25 kHz tone and 180 Hz AM modulated over a 32 kHz carrier.

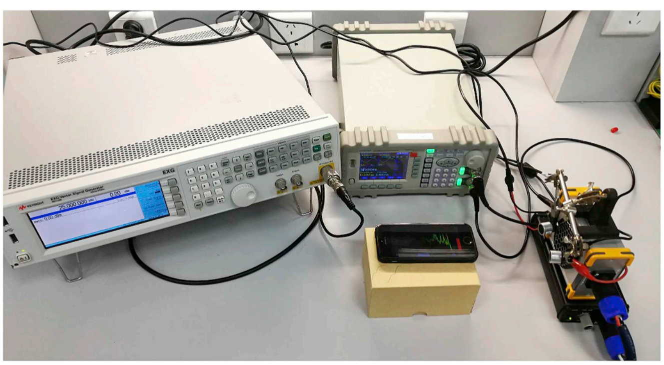


Fig. 17. Our benchtop equipment to carry out the proof of concept reproduction of tones heard in Cuba. Note, we would expect emitters to be smaller than a paperback book in practice, if not smaller. We use large equipment because of our general-purpose laboratory.

and generates a spectrum estimate. The spectrum, the magnified spectrum around 7 kHz, and the waterfall plot are shown in Figs. 18–20. The experimental findings are consistent with the results of simulation. Notice that the logarithmic scale spectrum resembles that which was observed in the simulations, which supports the nonlinearity model.

4.3. Experiment with modulation

Our experiments tested several modulation schemes, including AM and FM. The FM (Fig. 22) does not appear to match well with the AP news recording, but the AM modulation does (Fig. 21).

4.4. Experiments with video demonstrations

The following videos show our experiments in action. The white appliance is the Keysight N5172B EXG X-Series RF Vector Signal Generator for the AM modulation, and it is connected to the silver ultrasonic speaker with orange rims on the right (the ultrasonic Vifa Speaker); the grey appliance is the signal generator that drives the fixed ultrasonic transducers. Note that there are two fixed ultrasonic transducers instead of one in Fig. 17. The black smartphone in the center serves as a spectrum analyzer.

Science of Synthesizing Audible Sounds from Ultrasonic Intermodulation Distortion. How can inaudible ultrasonic signals lead to audible byproducts? When multiple ultrasonic tones pass through a nonlinear medium such as air or a microphone, the result is intermodulation distortion.[9] In our experiment, we have two signals. One is a 180 Hz sine wave AM modulated over a 32 kHz ultrasonic carrier. The second is a simple 25 kHz ultrasonic sine wave. The smartphone displays the Fourier transform of repeated intermodulation distortion in the air and smartphone microphone circuitry. The 2nd order intermodulation distortion includes the difference between the two signals, which appears centered at 7 kHz and peppered with sidebands from the modulated 180 Hz. The higher order intermodulation distortion products create additional ripples in the spectrum at 7 kHz as well as several other frequencies. MATLAB simulations predict the strong 7 kHz intermodulation distortion product, and we suspect the 4 kHz tones are the result of secondary intermodulation distortion in the microphone.

At the beginning of the video, only the AM modulated signal (32 kHz carrier & 180 Hz sinusoidal baseband) is played through the ultrasonic Vifa Speaker, and the modulated ultrasound cannot be heard or seen in the spectrum, which is out of the range of the spectral plots. Once the signal generator starts to drive the fixed ultrasonic transducer to transmit a 25 kHz tone, we observe the IMD, as the spectrum analyzer shows, and can hear the high-pitched sounds.

Localized Audible Sounds Synthesized from Ultrasonic Intermodulation Distortion. Using two signal generators of low-intensity ultrasonic tones, we demonstrate synthesis of audible byproducts below 20 kHz[10]. Note, there are likely two cascading instances of intermodulation distortion: once in the air that nearby humans can perceive, and a second instance in the microphone of this smartphone. Thus, recordings of sound in Cuba are unlikely to match perfectly what those working there perceived. In this experiment, our smartphone sensed a 4 kHz tone, but the student conducting the experiment could not hear a 4 kHz tone. Also note that the smartphone microphone has a frequency response that tapers off quickly after 20 kHz.

Absence of Audible Intermodulation Distortion from Single Ultrasonic Tone. Using two signal generators of ultrasonic tones, we demonstrate that the audible byproducts disappear when we disable one of the

[9] https://youtu.be/wA2MZshrafk.
[10] https://youtu.be/ZTLjs4dbnEA.

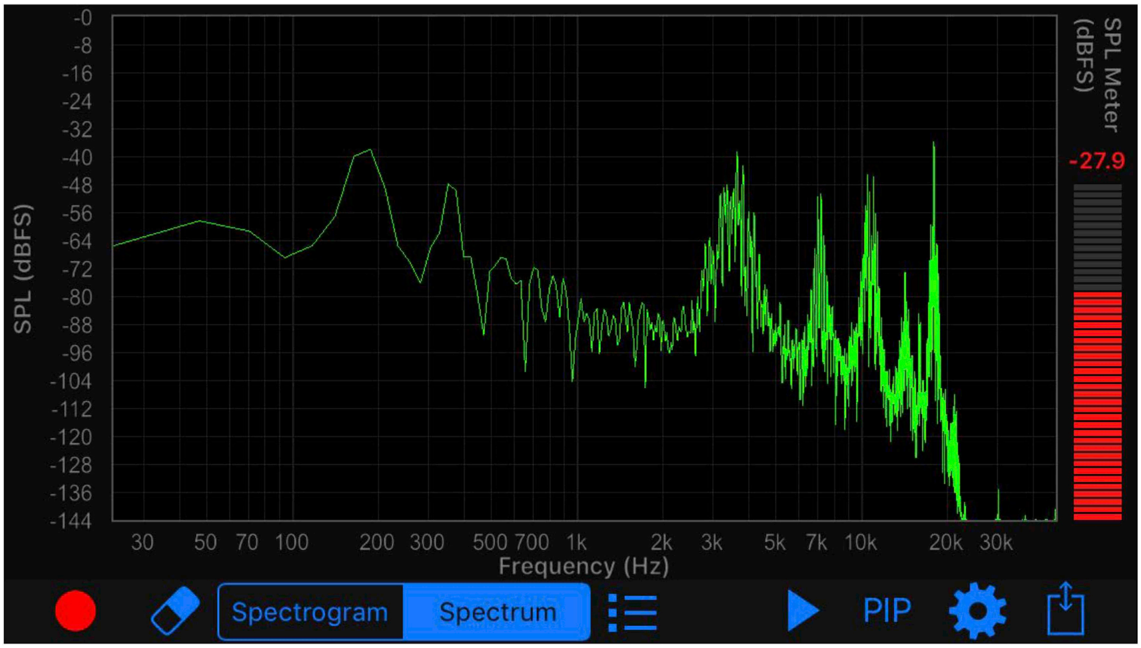


Fig. 18. Spectrum recorded during an IMD experiment playing three ultrasonic tones (25 kHz, 32 kHz, 32.18 kHz).

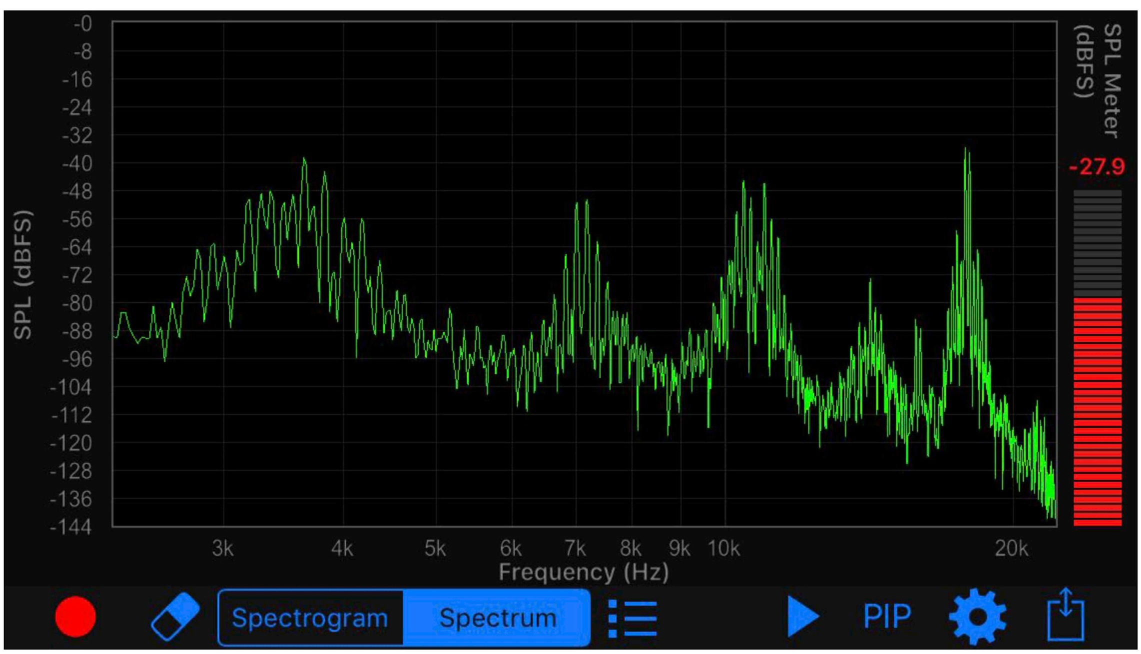


Fig. 19. Magnified spectrum of the signals near 7 kHz during an IMD experiment playing three ultrasonic tones (25 kHz, 32 kHz, 32.18 kHz).

ultrasonic sources.[11] This is because at least two tones are necessary to cause intermodulation distortion from a nonlinear medium such as air or microphone amplification circuitry.

Covertly Exfiltrating a Song with an Ultrasonic Carrier. This is a proof of concept which shows two things: (1) how ultrasound can be used to covertly exfiltrate data (in this example, the audio from a memetastic song serves as a stand-in for eavesdropping on conversation) and (2) how the covert channel becomes audibly overt when a second ultrasonic tone interferes. In this video,[12] there are three microphones, two ultrasonic transmitters, and one audible speaker. The three microphones are: the G.R.A.S. ultrasonic microphone, an audible microphone on the iPhone plotting the FFT, and an audible microphone on the video recording device. The Vifa dynamic ultrasonic speaker inaudibly emits the music modulated on an ultrasonic carrier. A small ultrasonic emitter sends out a single 32 kHz tone. A computer processing the ultrasonic signals from the G.R.A.S. microphone demodulates the signal and plays the resulting data, which is the song, except when IMD causes corruption of the demodulation.

4.5. Discussion of experiments

In the above experiments we reported the spectral measurements from microphone recordings. However, the non-linearity of microphone processing can induce audible components in the recordings; thus the

[11] https://youtu.be/o9jqwk83PSM.
[12] https://youtu.be/w7_J1E5g8YQ.

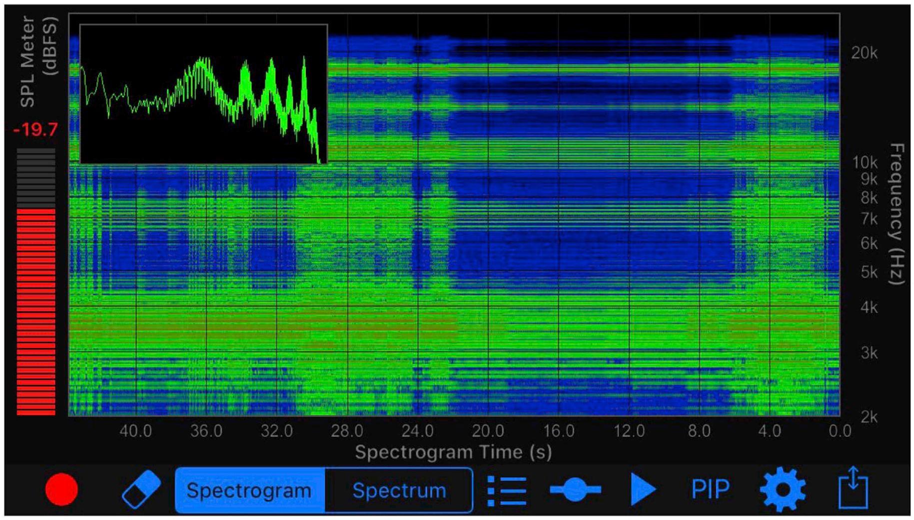


Fig. 20. Waterfall plot during an IMD experiment playing three ultrasonic tones (25 kHz, 32 kHz, 32.18 kHz).

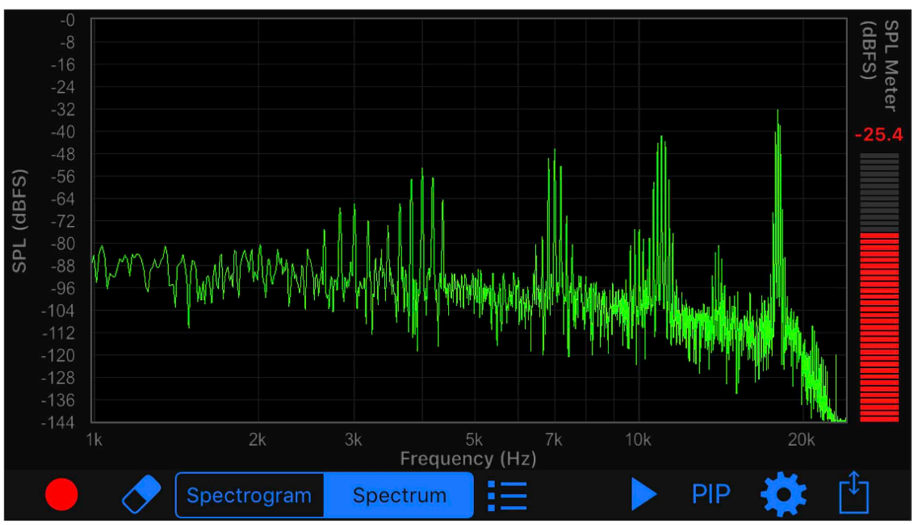


Fig. 21. Spectrum of sounds heard by a smartphone when playing 25 kHz and 180 Hz AM modulated on a 32 kHz carrier. The IMD spectrum resembles the ripples near 7 kHz in the AP news spectrum.

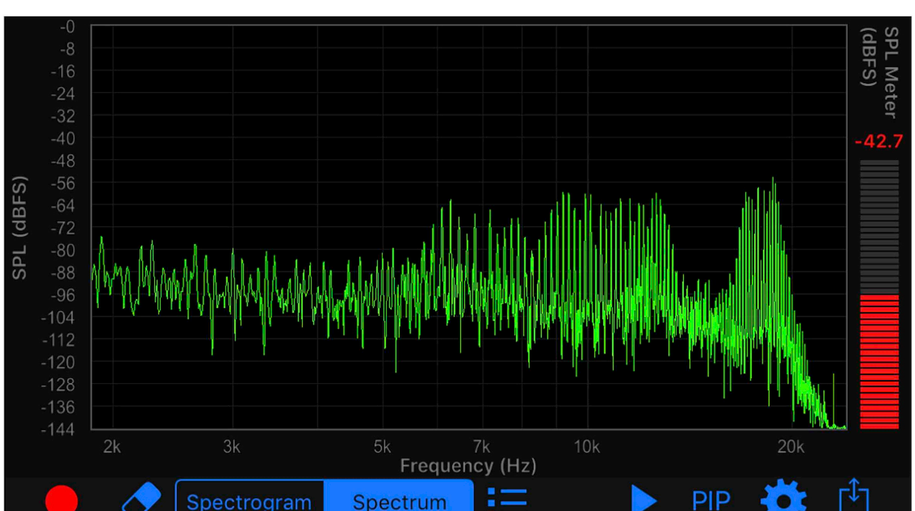


Fig. 22. Spectrum of sounds heard by a smartphone when playing 25 kHz and 180 Hz FM modulated on a 32 kHz carrier.

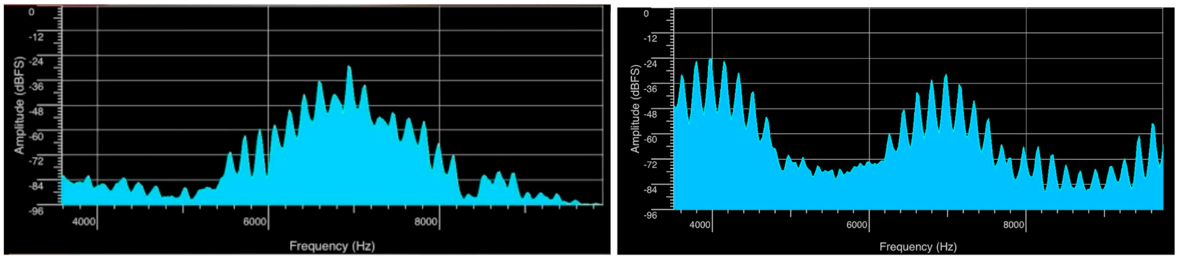


Fig. 23. The spectra from the AP news (L) and one of our experiments (R).

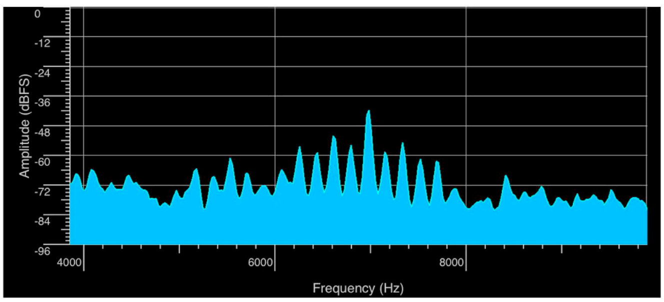


Fig. 24. The spectrum from one of our experiments showing only signals around 7 kHz.

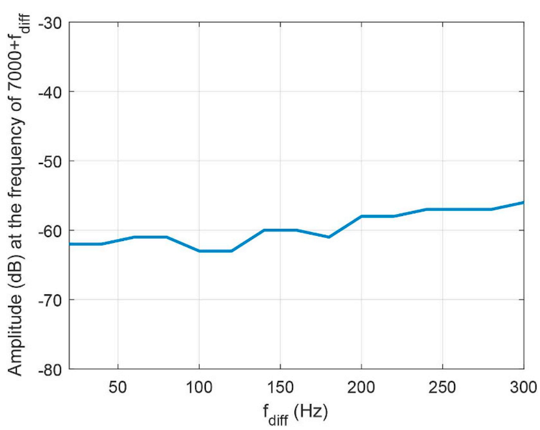


Fig. 25. The amplitude of IMD product at different frequencies.

recordings may be different from what a human could hear. To necessarily substantiate the audible perception with our ears, our experiments were carried out in a lab at extremely low amplitudes to ensure the safety of the researchers. We confirm that our ultrasonic experiments create small, focused areas where one can perceive the audible sounds, and only where the ultrasonic beams cross do the sounds become perceptible. Moving even a few inches from the beam can change the pitch, intensity, and sensation.

Running the SpectrumView application, we were able to obtain spectra similar to the AP news, as shown in Fig. 23. The IMD products generated in our lab differ from the AP news recording in that we notice a set of tones at 4 kHz. While the student carrying out the experiment did hear the 7 kHz tone with his own ears, he could not hear the 4 kHz tone. We suspect that nonlinearities in our microphones created this additional 4 kHz IMD, and differences of nonlinearity between microphones can lead to different recordings of IMD. This observation is consistent with IMD that we have found in other microphones from our previous research on ultrasonic cybersecurity [14]. Nevertheless, by adjusting the transmitter's power and position, we were able to change the spectral characteristics and reduce the 4 kHz component (Fig. 24). This again suggests that IMD results can be affected by various factors, and it is difficult for us to fully replicate the AP recordings since the actual equipment, approach, and environment involved in the recording from AP news are unknown to us.

5. Quantification experiments

After validating the feasibility of obtaining a similar recording with ultrasounds, we consider the robustness of intermodulation distortion with regard to frequency, and investigate factors that may affect the intermodulation distortion results with high-power ultrasound emitters.

5.1. Robustness of IMD

A natural question concerning the robustness of IMD is, will IMD always transpire between ultrasounds of all frequencies? A complete answer to this question would require a comprehensive study, which is beyond the scope of this paper. Nevertheless, we study the robustness of IMD in our choice of frequencies, i.e., will small changes in frequency lead to changes in the IMD products? Previously in Section 4.2, we choose the frequency difference f_{diff} between the two 32 kHz transducers to be 180 Hz, corresponding to the AP spectral characteristics. We alter f_{diff} from 20 Hz to 300 Hz, and measure the amplitude of the IMD product at a frequency of $(7000 + f_{diff})$ Hz. Fig. 25 shows that the amplitude of IMD product does not change greatly with frequency. It suggests that IMD is a constant phenomenon that is insensitive to small frequency changes.

5.2. High-power ultrasound emitters

Since IMD typically transpires when ultrasounds are at high amplitudes, it is worthwhile to study the phenomenon with high-power ultrasound emitters and investigate the factors that influence realistic scenarios. We constructed two arrays of ultrasonic transducers of 25 kHz and 32 kHz, shown in Fig. 26. Each array consists of 40 transducers which are connected in parallel. We drove the arrays with two signal generators and a power amplifier, and analyzed the generated sound with a smartphone. We studied the IMD from the two arrays by quantifying the amplitude change at 7 kHz under different powers, distances, and angles.

Power. We gradually increased the emitting power of the two arrays, and measure the amplitude of IMD at 7 kHz with a smartphone at a distance of 1 m. As shown in Fig. 27, the amplitude of IMD increases with the power. Therefore, it is evident that higher power ultrasounds can cause louder audible IMD sensations.

Distance. We fixed the emitting power at 1.2 W, and altered the distance between the arrays and the recording smartphone. The results, noted in Fig. 28, show that as the distance increases, sounds from the IMD show an amplitude pattern specific to the distance. The IMD sounds do not attenuate exponentially, as do sounds from traditional speakers. We believe that this pattern is caused by the nonlinear propagation of ultrasounds in air, and is affected by the radiation pattern of the ultrasonic arrays.

Angle. We measured the radiation pattern of the ultrasonic arrays in terms of the amplitude of IMD at 7 kHz, and compared with that of a traditional speaker playing a 7 kHz tone. We show the results with polar

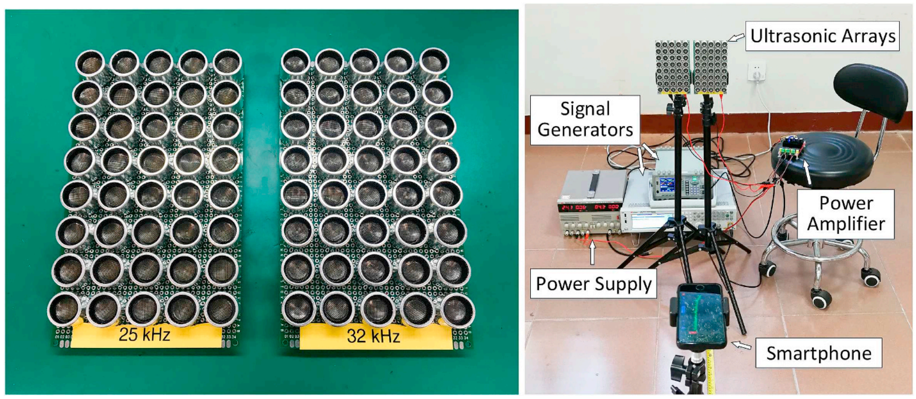


Fig. 26. The ultrasonic transducer arrays (L) that are capable of transmitting high-power ultrasounds at 25 kHz and 32 kHz, and the experiment setup (R) with the arrays.

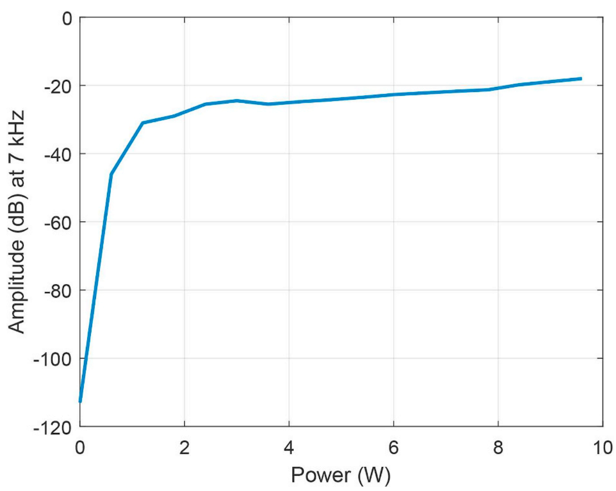


Fig. 27. The amplitude of the IMD product at 7 kHz with different emitting powers.

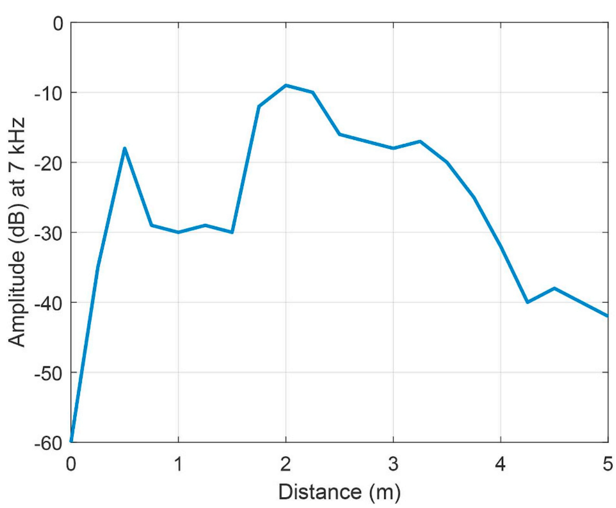


Fig. 28. The amplitude of the IMD product at 7 kHz at different distances.

plots in Fig. 29. It is clear that the ultrasonic arrays are more directional, as compared with a traditional speaker.

Discussion of high-power ultrasound emitters. For safety concerns, our experiments were carried out in a closed room, and all researchers wore protective ear muffs during the entire process of experiment when human involvement was necessary. Intermodulation distortion is a prominent phenomenon when ultrasounds are emitted at a high power, and its amplitude can be greatly affected by the location (distance and angle) where the sound is perceived.

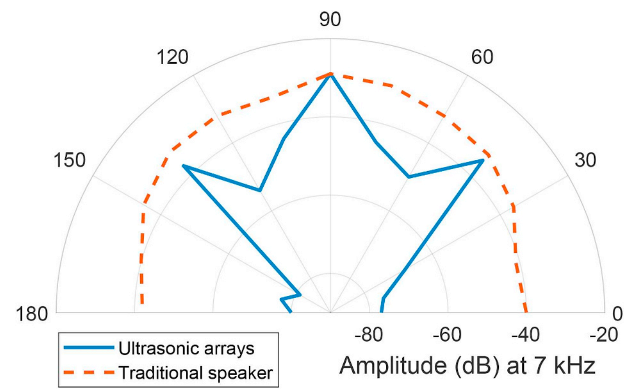


Fig. 29. The amplitude of the IMD product at 7 kHz and a sound played by a traditional speaker at different angles.

6. Safety and neurological implications

There are two important questions that pertain to human health. They are: what types of ultrasound can lead to hazardous situations or harm, and what are the neurological effects on humans?

Safety: Hazards, Hazardous Situations, Harm. We found little consensus on the risks of human exposure to airborne ultrasound [17,18]. Airborne ultrasonic waves are not necessarily harmful in and of themselves, but may become harmful at high intensities, or when an individual comes in direct contact with a vibrating source. Ultrasound can cause thermal injuries during direct contact exposure [18]. OSHA warns of the potential harm from subharmonics of ultrasound [19], and appears to set a safety threshold in an abundance of caution. Health Canada [18] sets stricter safety requirements for the intensity of airborne ultrasound, based on plausible risks of heating and cavitation as well as auditory and subjective effects. Canada sets a conservative 110 dB safety limit on emissions of airborne ultrasound.

According to a news article [1], “The AP reported last month that some people experienced attacks or heard sounds that were narrowly confined to a room or parts of a room.” Such a sensation is typical for ultrasound, because it is more directional as compared with audible sound and infrasound. Ultrasound can be focused on a certain area. Therefore, ultrasound can match the realized symptoms of discomfort.

Neurological Effects of Ultrasound. Researchers analyzed the effects of intense sounds on humans, but we find that the outcomes include large safety margins to make up for a lack of consensus [20]. The *Handbook of*

Table 1
A summary of alternative hypotheses to explain symptoms reported by diplomats in Cuba. Determining a cause with absolute certainty is unlikely without a control trial and baseline data.

Theory	Localized	Audible	Neurological Damage	Able to Record Audio	Experimentally Confirmed
Airborne Ultrasound	√	√	?	√	√
Microwave	√	√	√	?	×
Virus	?	?	√	×	×
Toxin/Poison	?	?	√	×	×
Sonic Weapon	√	√	?	√	×
Pre-existing Condition	?	?	?	×	×
Psychosomatic	?	?	√	×	?

Human Vibration [21] and an ISO standard [22] explore the physiological effects of low frequency vibrations and sounds. We have found little in the way of reproducible control trials for ultrasonic vibrations, aside from folklore. Neurologists who examined the injured diplomats published their findings in JAMA [8], and suggest that the neurological damage is real. However, there are limitations to the retrospective study [9], namely, causality is difficult to establish without a control trial or elimination of other null hypotheses. Our report does not itself contribute any new findings on neurological harm.

7. Alternative explanations

While our results do not rule out other potential causes, the results suggest that ultrasound without harmful intent could have led to accidental harm to diplomats in Cuba.

We originally suspected subharmonics of ultrasound as the cause, but this hypothesis would not align well with the spectral analysis provided by the AP news. Rather than evenly spaced ripples in the frequency domain, we would expect to see frequencies at $1/n$ submultiples of the fundamental frequency for integers n, if subharmonics were responsible for the observed patterns.

180 Hz is at the high end of the fundamental frequencies of average male conversational voices. It may be coincidence that the tones are 180 Hz apart, but this could also indicate a type of voice eavesdropping modulated over ultrasound and gone awry.

While the mathematics leads us to believe that intermodulation distortion is a likely culprit in the Cuban case, we haven't ruled out other null hypotheses that may account for the discomfort that diplomats felt. For example, perhaps the tones heard by personnel didn't cause their symptoms but were yet another symptom, which may be indicative of the actual cause. Or perhaps the sounds had a non-auditory effect on hearing and physiology, via bone conduction or some other phenomenon. Microwave radiation is another possible source of the health effects [23]. Pulsed radio frequency energy can cause an auditory response within the human head due to the thermoelastic expansion of portions of the auditory apparatus [24]. However, a remaining question is whether microwaves could have produced the high-pitched sounds recorded by the smartphone in the AP news video. We compare the alternative hypotheses in Table 1.

8. Related work

The notion of using audible and inaudible sound to cause auditory and sensory illusions is not new. Our results build upon the following research.

Research from the music community used AM modulation on ultrasound to generate focused audible sound [25]. This research evolved so that a company called Holosonics[13] was formed with a product called Audio Spotlight for music, as well as personalized sound, and museum exhibits, among other artistic applications. Projects such as Soundlazer[14] enable the hobbyist engineer to investigate the ultrasonic generation of audible tones. Companies such as the LRAD Corporation[15] produce products that deliver higher intensity sounds with military application, such as crowd control and long-distance hailing at sea. However, modern LRADs use audible parametric sound rather than ultrasound. Musicians have also used intermodulation distortion of *audible* tones to synthesize additional audible tones from nonlinearities of the inner ear [26]. Campbell describes his realization of hearing synthesized combination tones (also known as intermodulation distortion) while listening to a movement in Sibelius's Symphony #1 [27].

Several researchers use ultrasound to fool sensors such as microphones. The BackDoor paper from Illinois [13] uses ultrasound and intermodulation distortion to jam eavesdropping microphones and watermark music played at concerts. A team from Korea uses both audible and ultrasonic tones to cause malfunctions in flight stability control of drones by acoustic interference at the resonant frequency of MEMS gyroscopes [28].

Our previous work [14,29,30] provides an important perspective on how ultrasound causes audible byproducts. In our past research, we use audible and ultrasonic tones to test the cybersecurity of computer systems. The DolphinAttack paper [14] uses ultrasound and intermodulation distortion to inject inaudible, fake voice commands into speech recognition systems including Siri, Google Now, and Alexa. The Walnut paper [29] exploits nonlinear amplifiers, permissive analog filters, and signal aliasing with sound waves to adulterate the output of MEMS accelerometers in applications such as Fitbits, airbags, and smartphones.

We have urged more attention to be paid to the physics of cybersecurity [31], and the events in Cuba provide more evidence of the need to understand the causal relationships between physics and cybersecurity.

9. Discussion

9.1. Source of non-linearity

To hear the intermodulation products of ultrasounds with human ears, the non-linearity transmission of sound through air produces audible sounds [32]. When sound waves have sufficiently large amplitudes, their propagation through the air can no longer be modeled by the traditional linearization of fluid dynamics equations. Due to the nonlinearity effect of the air, sound waves are distorted as they travel, and the inaudible ultrasounds can generate audible sounds. Although human hearing is also reported to be non-linear [33], it is difficult to quantify the extent that non-linearity of the ear contributes to the sensation of intermodulation products, particularly when human ears receive ultrasound with difficulty. Therefore, we tend to assume the non-linearity of the air is mostly responsible for the audible sensation of ultrasounds in human ears. For microphone recordings, the non-linearity of both the air and the microphone are involved in the transformation process. Thus, there is a finite difference between the AP news audio and the sound that the diplomats actually heard.

9.2. Unresolved questions

Our report shows how simple ultrasonic tones and intermodulation distortion can provide an explanation for the reported symptoms of hearing loss, localized sound, spectral patterns, and the ability for a

[13] https://www.holosonics.com/.
[14] http://www.soundlazer.com/.
[15] https://www.lradx.com/.

diplomat to record the sounds. Our approach differs from other hypotheses, in that we implemented hypothesis-testing experiments, and we supposed accidental harm rather than intentional harm when developing our test system. This allowed us to consider the effects of high-power ultrasonic transmissions from *within* a diplomat's home rather than the more difficult question of how to beam ultrasound *into* a home from a great distance. However, our experiments do not eliminate other hypotheses. In particular, several mysteries remain:

- How could ultrasound penetrate walls into homes and offices? Could an emitter be outside the premises or planted inside? Was it primarily airborne, or did it originate as a contact vibration?
- At what level of intensity could IMD products cause harm to humans? We know of no non-trivial lower bounds. Based on our reading of various safety documents, we believe most countries set conservative thresholds for airborne ultrasound out of an abundance of caution and to compensate for uncertainty. While there are anecdotes and folklore concerning harm from airborne ultrasound, we have found no primary sources that confirm this, aside from stories about extremely intense sounds above 155 dB.
- What about standoff distance? Our report does not investigate distance beyond 5 m. We do not have a facility to safely test high intensity ultrasound, but might consider it in the future if facilities are available to do so.
- Could audible tones be a symptom or cause? Without a controlled study, it would be difficult to distinguish a cause from a symptom. It is possible that the audible sensations are byproducts from contact vibration or some other ultrasonic source.

10. Conclusion

Two inaudible ultrasonic tones from one or more mixing signals traveling in a nonlinear medium could easily lead to an audible intermodulation distortion product. Although little is known about how audible sound waves can cause neurological damage, rather than merely be correlated with neurological damage, the safety community has studied the mechanism by which certain audible sounds can cause pain and hearing damage. Ultrasonic intermodulation distortion can produce harmful, audible byproducts. The safety warnings on audible frequencies and intensities would apply to these byproducts.

While our experiments do not eliminate the possibility of malicious intent to harm diplomats, our experiments do suggest that whoever caused the sensations may have had no intent for harm. The emitter source remains an open question, but could range from covert ultrasonic exfiltration of modulated data to ultrasonic jammers, or even perhaps the presence of ultrasonic pest repellents. It is also possible that someone was trying to covertly deliver data into a localized space using ultrasound to say, activate a sensor or other hidden device. Our experiments suggest that tones modulated on an ultrasonic carrier by one or more parties could have collided invisibly to produce audible byproducts. These audible byproducts can exist at frequencies known to cause annoyance and pain. Another possibility would be that solid vibration (e.g., unwittingly standing on a covert transmitter) at ultrasonic frequencies for prolonged periods—leading to bodily harm. In such a case, audible intermodulation distortion could represent a harmless side effect rather than the cause of harm. Although our tests focus on frequencies rather than amplitudes or distances, we believe that high amplitude ultrasonic signals could easily produce high amplitude audible signals as unintentional byproducts, capable of harm to hearing.

Conflicts of interest

None Declared.

Acknowledgments

This research is supported by NSFC-61472358 and NSF CNS-1330142. The views and conclusions contained in this paper are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of NSFC or NSF.

Appendix A. Simulation of Intermodulation Distortion

Appendix A.1Calculation of IMD of Two Tones

We model a nonlinear system as the following polynomial equation:

$$s_{out} = a_1 s_{in} + a_2 s_{in}^2 + a_3 s_{in}^3 + \cdots + a_n s_{in}^n$$

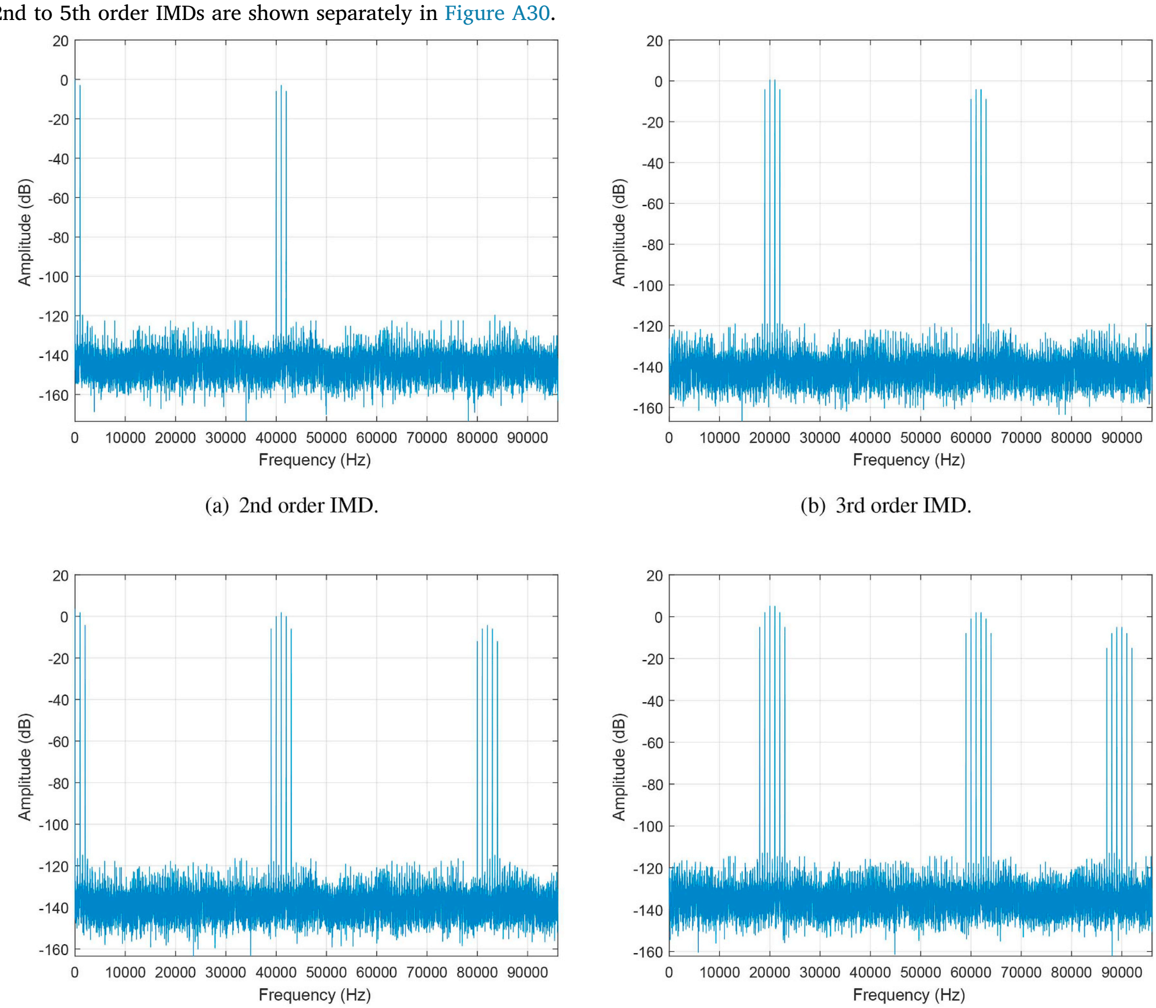
where s_{in} is the system input and s_{out} is the system output. When the input s_{in} is a mixture of two tones at different frequencies, i.e., $s_{in} = \sin(2\pi f_1 t) + \sin(2\pi f_2 t)$, the output s_{out} contains new frequency components (other than f_1 and f_2) that are introduced by the nonlinear polynomials $a_n s_{in}^n (n > 1)$. We show the equation of the 2nd and 3rd order IMDs as follows.

$$\begin{aligned} s_{imd(2)} &= a_2 s_{in}^2 \\ &= a_2[\sin(2\pi f_1 t) + \sin(2\pi f_2 t)]^2 \\ &= a_2[\sin^2(2\pi f_1 t) + \sin^2(2\pi f_2 t) + 2\sin(2\pi f_1 t)\sin(2\pi f_2 t)] \\ &= a_2\left\{\frac{1}{2}[1 - \cos(2\pi(2f_1)t)] + \frac{1}{2}[1 - \cos(2\pi(2f_2)t)] + \cos(2\pi(f_1 - f_2)t) - \cos(2\pi(f_1 + f_2)t)\right\} \\ &= a_2\left[1 - \frac{1}{2}\cos(2\pi(2f_1)t) - \frac{1}{2}\cos(2\pi(2f_2)t) + \cos(2\pi(f_1 - f_2)t) - \cos(2\pi(f_1 + f_2)t)\right] \end{aligned}$$

$$
\begin{aligned}
s_{imd(3)} &= a_3 s_{in}^3 \\
&= a_3[\sin(2\pi f_1 t) + \sin(2\pi f_2 t)]^3 \\
&= a_3\{\sin(2\pi f_1 t)[\sin(2\pi f_1 t) + \sin(2\pi f_2 t)]^2 + \sin(2\pi f_2 t)[\sin(2\pi f_1 t) + \sin(2\pi f_2 t)]^2\} \\
&= a_3[\sin(2\pi f_1 t) - \tfrac{1}{2}\cos(2\pi(2f_1)t)\sin(2\pi f_1 t) - \tfrac{1}{2}\cos(2\pi(2f_2)t)\sin(2\pi f_1 t) \\
&\quad + \cos(2\pi(f_1 - f_2)t)\sin(2\pi f_1 t) - \cos(2\pi(f_1 + f_2)t)\sin(2\pi f_1 t) + \sin(2\pi f_2 t) \\
&\quad - \tfrac{1}{2}\cos(2\pi(2f_1)t)\sin(2\pi f_2 t) - \tfrac{1}{2}\cos(2\pi(2f_2)t)\sin(2\pi f_2 t) + \cos(2\pi(f_1 - f_2)t)\sin(2\pi f_2 t) \\
&\quad - \cos(2\pi(f_1 + f_2)t)\sin(2\pi f_2 t)] \\
&= a_3\{\sin(2\pi f_1 t) - \tfrac{1}{4}[\sin(2\pi(3f_1)t) - \sin(2\pi f_1 t)] - \tfrac{1}{4}[\sin(2\pi(2f_2 + f_1)t) - \sin(2\pi(2f_2 - f_1)t)] \\
&\quad + \tfrac{1}{2}[\sin(2\pi(2f_1 - f_2)t) + \sin(2\pi f_2 t)] - \tfrac{1}{2}[\sin(2\pi(2f_1 + f_2)t) - \sin(2\pi f_2 t)] + \sin(2\pi f_2 t) \\
&\quad - \tfrac{1}{4}[\sin(2\pi(2f_1 + f_2)t) - \sin(2\pi(2f_1 - f_2)t)] - \tfrac{1}{4}[\sin(2\pi(3f_2)t) - \sin(2\pi f_2 t)] \\
&\quad + \tfrac{1}{2}[\sin(2\pi f_1 t) + \sin(2\pi(2f_2 - f_1)t)] - \tfrac{1}{2}[\sin(2\pi(2f_2 + f_1)t) - \sin(2\pi f_1 t)]\} \\
&= a_3[\tfrac{9}{4}\sin(2\pi f_1 t) + \tfrac{9}{4}\sin(2\pi f_2 t) + \tfrac{3}{4}\sin(2\pi(2f_1 - f_2)t) + \tfrac{3}{4}\sin(2\pi(2f_2 - f_1)t) \\
&\quad - \tfrac{3}{4}\sin(2\pi(2f_1 + f_2)t) - \tfrac{3}{4}\sin(2\pi(2f_2 + f_1)t) - \tfrac{1}{4}\sin(2\pi(3f_1)t) - \tfrac{1}{4}\sin(2\pi(3f_2)t)]
\end{aligned}
$$

Appendix A.2Simulation of 20 kHz and 21 kHz IMD

We simulate the nonlinear system and intermodulation distortion in MATLAB with $a_n = 1$. When the two tones are (f_1, f_2)= (20 kHz, 21 kHz), the simulated 2nd to 5th order IMDs are shown separately in Figure A30.



(a) 2nd order IMD.

(b) 3rd order IMD.

(c) 4th order IMD.

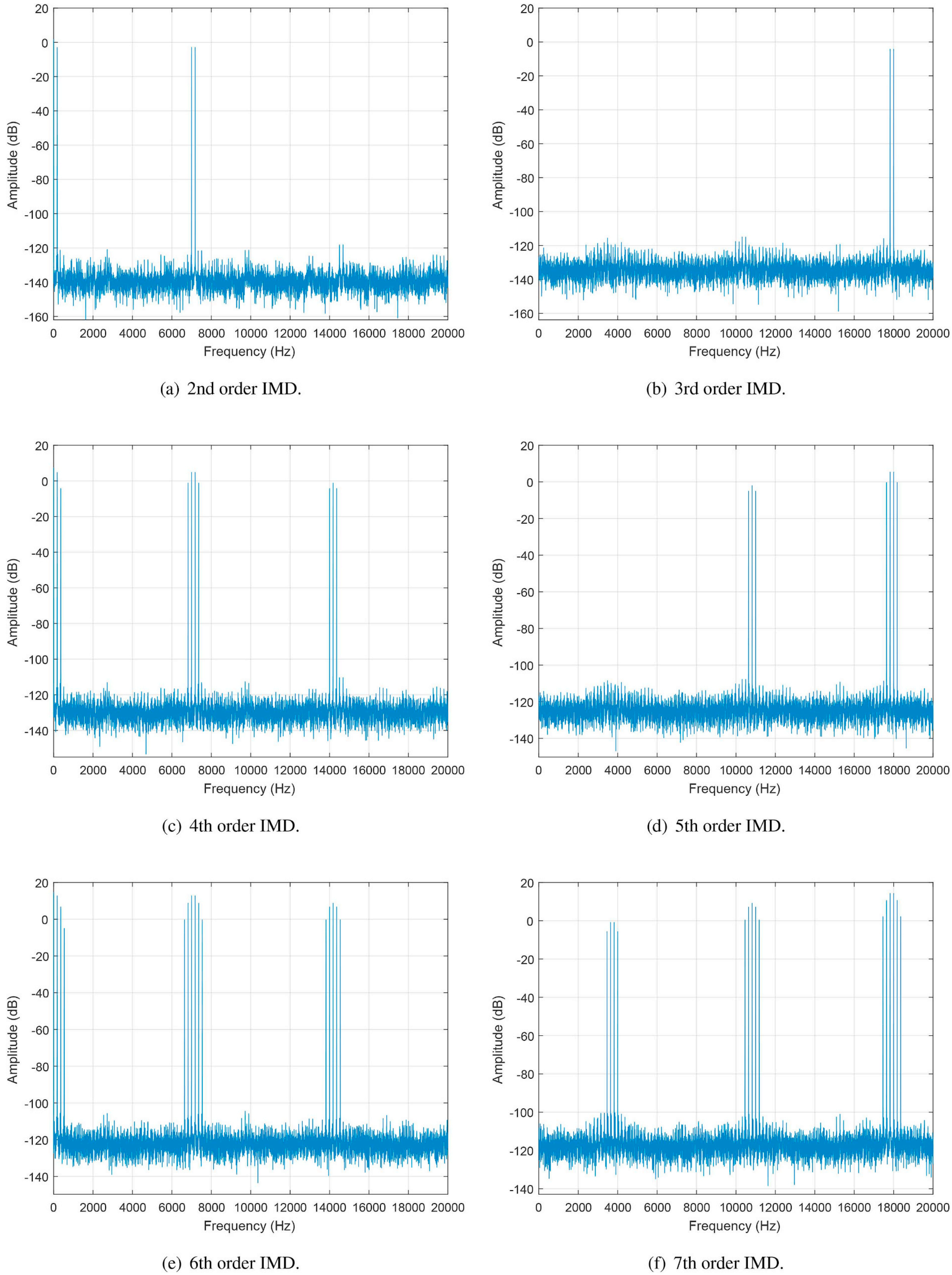
(d) 5th order IMD.

Figure A.30. Simulated spectrum of the 2nd to 5th order IMD for (f_1, f_2)= (20 kHz, 21 kHz).

The simulation results are consistent with our mathematics. For example, the 2nd order IMD introduces DC and {1, 40, 41, 42} kHz, and the 3rd order IMD introduces {19, 20, 21, 22, 60, 61, 62, 63} kHz. Note that higher order IMDs (e.g., 4th) cover the lower order ones (e.g., 2nd), but the even and odd order series are separate from each other.

Appendix A.3Simulation of IMD of Three Ultrasonic Tones

We simulate the intermodulation distortion of three tones at 25 kHz, 32 kHz, and 32.18 kHz in Figure A31, with a focus on the audible spectrum ($f < 20$ kHz).



(a) 2nd order IMD. (b) 3rd order IMD.

(c) 4th order IMD. (d) 5th order IMD.

(e) 6th order IMD. (f) 7th order IMD.

Figure A.31. Simulated audible spectrum of the 2nd to 7th order IMD for 25 kHz, 32 kHz, and 32.18 kHz tones.2

References

[1] J. Lederman, M. Weissenstein, Dangerous Sound? what Americans Heard in Cuba Attacks, AP News, Oct. 2017, https://www.apnews.com/88bb914f8b284088bce48e54f6736d84.
[2] R. Stone, Stressful conditions, not 'sonic weapon,' sickened U.S diplomats, Cuba panel asserts, Science 362 (6418) (Dec. 2017), https://www.sciencemag.org/news/2017/12/stressful-conditions-not-sonic-weapon-sickened-us-diplomats-cuba-panel-asserts.
[3] E. Waltz, IEEE Spectrum, (Dec. 2017) Was a Sonic Weapon Deployed in Cuba https://spectrum.ieee.org/the-human-os/biomedical/devices/acoustic-weapon-deployed-in-cuba-not-likely.
[4] G. Harris, U.S. To Open Formal Inquiry on Americans Sickened in Cuba, The New York Times, Jan. 2018, https://www.nytimes.com/2018/01/09/us/politics/us-cuba-attacks-sick.html.
[5] G. Harris, Tillerson Suggests Cuba Could Have Stopped 'Targeted Attacks' on U.S. Diplomats, The New York Times, Dec. 2017, https://www.nytimes.com/2017/12/06/us/politics/tillerson-cuba-attacks-diplomats.html.
[6] G. Harris, J.H. Davis, E. Londoño, U.S. Expels 15 cuban diplomats, Latest Sign Détente May Be Ending, The New York Times, Oct. 2017, https://www.nytimes.com/2017/10/03/world/americas/us-cuba-diplomats.html.
[7] G. Harris, A. Goldman, Illnesses at U.S. Embassy in Havana Prompt Evacuation of More Diplomats, The New York Times, Sep. 2017, https://www.nytimes.com/2017/09/29/us/politics/us-embassy-cuba-attacks.html.
[8] R.L. Swanson II, S. Hampton, J. Green-McKenzie, R. Diaz-Arrastia, M.S. Grady, R. Verma, R. Biester, D. Duda, R.L. Wolf, D.H. Smith, Neurological manifestations among US government personnel reporting directional audible and sensory phenomena in Havana, Cuba, J. Am. Med. Assoc. (2018) 1–9.
[9] C.C. Muth, S.L. Lewis, Neurological symptoms among US diplomats in Cuba, J. Am. Med. Assoc. (2018) 1–3.
[10] G. Kolata, Diplomats in Cuba Suffered Brain Injuries. Experts Still Don't Know Why, The New York Times, Feb. 2018, https://www.nytimes.com/2018/02/15/health/cuba-diplomats-attack-concussions.html.
[11] A.C. Madrigal, The Case of the Sick Americans in Cuba Gets Stranger, (Feb. 2018) The Atlantic https://www.theatlantic.com/technology/archive/2018/02/what-happened-to-american-diplomats-in-cuba-nobody-knows/553343/.
[12] T. Golden, S. Rotella, The Sound and the Fury: inside the Mystery of the Havana Embassy, Pro Publica, Feb. 2018, https://www.propublica.org/article/diplomats-in-cuba.
[13] N. Roy, H. Hassanieh, R. Roy Choudhury, BackDoor: making microphones hear inaudible sounds, Proceedings of the ACM International Conference on Mobile Systems, Applications, and Services (MobiSys), ACM Press, 2017, pp. 2–14.
[14] G. Zhang, C. Yan, X. Ji, T. Zhang, T. Zhang, W. Xu, DolphinAttack: inaudible voice commands, Proceedings of the ACM Conference on Computer and Communications Security, CCS, 2017, pp. 103–117.
[15] Lighting Research Center, Specifier Reports: Occupancy Sensors, (1998) https://www.lrc.rpi.edu/programs/NLPIP/PDF/VIEW/SROS2.pdf.
[16] dwkcommentaries, American Teens Hear Strange High-pitched Sound at Havana Airport, (2018) https://dwkcommentaries.com/tag/zoonic-device/.
[17] B. Smagowska, Effects of ultrasonic noise on the human body—a bibliographic review, Int. J. Occup. Saf. Ergon. 19 (2).
[18] Health Canada, Guidelines for the Safe Use of Ultrasound: Part II Industrial and Commercial Applications, (1991), pp. 1–43.
[19] OSHA Technical Manual: Noise: Appendix C Ultrasound (2013) vols. 1–3.
[20] C.H. Allen, I. Rudnick, H. Frings, Some biological effects of intense high frequency airborne sound, J. Acoust. Soc. Am. 20 (2) (1948) 221–221.
[21] M.J. Griffin, Handbook of Human Vibration, Academic Press, 2012.
[22] ISO Standard 2631-1, Mechanical Vibration and Shock: Evaluation of Human Exposure to Whole-body Vibration, (1997), pp. 1–7.
[23] J.C. Lin, Strange reports of weaponized sound in Cuba [health matters], IEEE Microw. Mag. 19 (1) (2018) 18–19.
[24] J.C. Lin, Z. Wang, Hearing of microwave pulses by humans and animals: effects, mechanism, and thresholds, Health physics 92 (6) (2007) 621–628.
[25] F. J. Pompei, The use of airborne ultrasonics for generating audible sound beams, J. Audio Eng. Soc. 47 (9).
[26] G.S. Kendall, C. Haworth, R.F. Cádiz, Sound synthesis with auditory distortion products, Comput. Music J. 38 (4) (2014) 5–23.
[27] M. Campbell, C. Greated, The Musician's Guide to Acoustics, OUP, Oxford, 1994.
[28] Y. Son, H. Shin, D. Kim, Y. Park, J. Noh, K. Choi, J. Choi, Y. Kim, Rocking drones with intentional sound noise on gyroscopic sensors, Proceedings of the 24th USENIX Security Symposium, USENIX Security, 2015, pp. 881–896.
[29] T. Trippel, O. Weisse, W. Xu, P. Honeyman, K. Fu, WALNUT: waging doubt on the integrity of MEMS accelerometers with acoustic injection attacks, Proceedings of the IEEE European Symposium on Security & Privacy, 2017, pp. 3–18.
[30] C. Bolton, S. Rampazzi, C. Li, A. Kwong, W. Xu, K. Fu, Blue note: how intentional acoustic interference damages availability and integrity in hard disk drives and operating systems, Proceedings of the 39th Annual IEEE Symposium on Security and Privacy, 2018.
[31] K. Fu, W. Xu, Inside risks: risks of trusting the physics of sensors, Commun. ACM 61 (2) (2018) 20–23.
[32] M.F. Hamilton, D.T. Blackstock, et al., Nonlinear Acoustics vol. 1, Academic press, San Diego, 1998.
[33] F.A. Everest, Master Handbook of Acoustics, ASA, 2001.