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Acoustics • Shock • Vibration • Signal Processing

May 2007 Newsletter

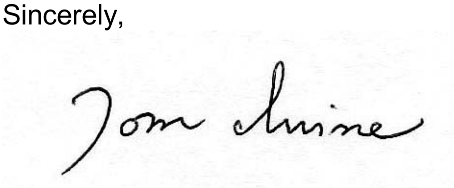
G'Day Mate!

The bullroarer is simple device consisting of a wooden slat and a string. It produces an eerie humming sound when swung overhead. The Australian Aborigines and many other traditional cultures have used this instrument as a conduit for the voices of their gods or in rainmaking rituals.

Despite the bullroarer's simple design, its sound generation mechanism is complicated, necessitating a review of rigid-body dynamics, aerodynamics, and aeroacoustics. Each of these subtopics is included in the first article.

The second article describes a biomechanical vibration technique employed by bumblebees to efficiently extract pollen from tomato blossoms and other types of flowering plants. Insectary-reared bumblebees are becoming the preferred pollination method for growing high-value tomatoes in commercial greenhouses. You are welcome to impress your family and friends with these facts the next time you visit an Italian restaurant.

Sincerely,



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Feature Articles

Figure 1. Lady Swinging Bullroarer

The lady's hand, the string, and the wooden slat effectively sweep out a shallow cone as the slat travels in a complete cycle. The slat is undergoing upward motion due to lift with accompanying backspin in the above image. The slat alternately undergoes downward motion due to negative lift with accompanying topspin. The cone angle is inverted as a result of the downward motion.

Bullroarer Acoustics by Tom Irvine

Introduction

The bullroarer, or turndun, is an ancient, instrument used by the Australian Aborigines in men's initiation ceremonies, tribal councils and in rainmaking rituals.

The bullroarer also provides a means of communicating over extended distances, given the low-frequency content of its humming sound, which is largely a modulated sine function. Messages can be encoded in the resulting sound waves via the modulation.

The bullroarer emits a pulsating, humming sound when swung above a certain rotational rate threshold. The resulting sound may also be described as vibrato, with an accompanying Doppler shift.

Mythology

Some Aboriginal cultures consider the bullroarer's sound to represent the Rainbow Serpent. This mythological being is linked to land, water, life and fertility.

Other Aboriginal groups claim that the sound is the voice of Daramulum, the son of Baiame and his emu-wife Birrahgnooloo.

Many traditional cultures throughout the world use similar instruments.

The Navajo call their version the *groaning stick* (tsin di'ni). The medicine man uses the bullroarer to slice through the air, creating an opening that allows the Yei B'Chei (diety) to enter the physical world, thus driving away evil and illness.

Figure 2. Bullroarer

The slat may be painted with animals or other traditional designs.

Design

The bullroarer consists of a wooden slat that is attached to a length of string through a hole at one end.

The slat size varies. Typical lengths are from 15 to 28 cm (6 to 11 inch). The width varies from about 1.25 cm to 5 cm (0.5 inch to 2 inch).

The slat has an oval shape. The cross-section is such that the slat's maximum thickness is at the middle. The cross-section gradually tapers from the middle to the edges. The resulting cross-section may thus be elliptical. The slat's shape renders it as an airfoil.

The bullroarer is swung lasso-style. The rotational plane may either be horizontal or vertical. Note that the horizontal plane would be overhead.

Aerophones

The bullroarer is a free rotational aerophone. It is also considered as a whirling aerophone.

An aerophone is any musical instrument which produces sound primarily by causing a body of air to vibrate, without any vibration of the instrument itself including any strings or membranes.

The aerophone is one of the four main classes (class 4) of instruments in the original Hornbostel-Sachs scheme of musical instrument classification.

This class is further divided into two categories.

The 41 class includes instruments in which the vibrating volume of air is not contained in the instrument itself. This class includes the bullroarer and free reed instruments such as the harmonica. Car horns, sirens and whips are also members of this group.

The 42 class includes instruments that contain a vibrating column of air. The flute, oboe, trumpet and similar wind instruments are in this class.

The mechanism by which the bullroarer generates sound is rather complex. A brief review of some basic acoustics, dynamics and aerodynamic principles is needed as prelude to the main explanation.

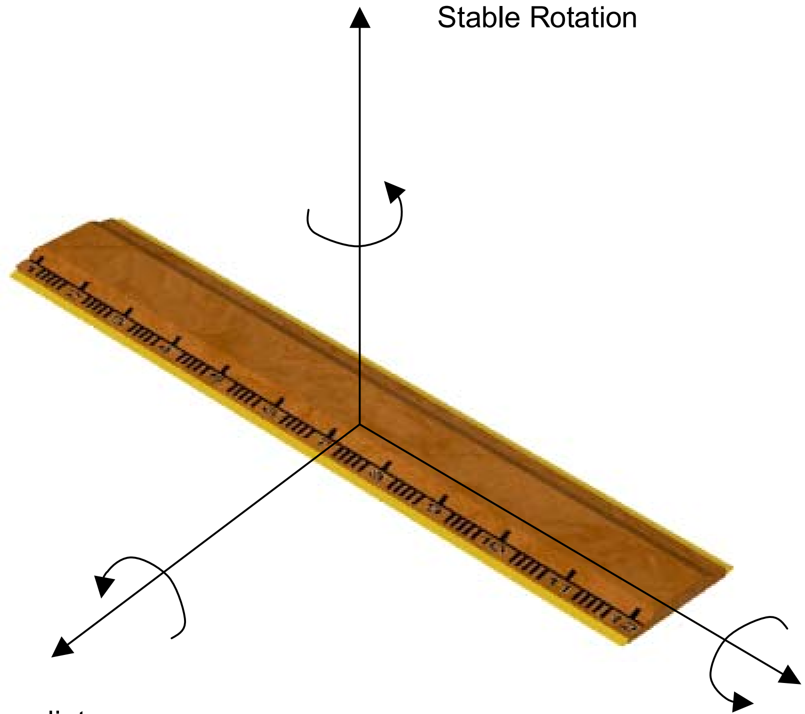

Figure 3.

Some Rigid-Body Dynamics

The bullroarer undergoes several types of motion. First, it travels in an overhead circular pattern as it is swung by the string. Second, it twists about the string as it is being swung.

A body is stable for rotations about two of its major axes, through its center of mass. Its rotation is unstable about the axis with the intermediate moment of inertia.

The bullroarer undergoes a stable rotation about its long axis as it is swung overhead.

Some scientists have described this motion as aerodynamic-driven autorotation, somewhat similar to that of the rotor blades on either an autogiro or a helicopter descending in a powered-off landing. This explanation is largely correct, but the bullroarer's motion is more complicated.

The bullroarer does experience a large, net rotational displacement which causes the string to become wound-up in a matter of a few seconds in the slat's backspin direction.

The stretched string also serves as a torsional spring, however. The string undergoes a series of winding and unwinding cycles.

Thus the bullroarer experiences a series of reversals about its long axis during the swinging process. Note that the slat's long axis is collinear with the string.

The respective rotational amplitudes in each direction are unequal. Thus, the slat undergoes a large net rotational displacement, as previously mentioned.

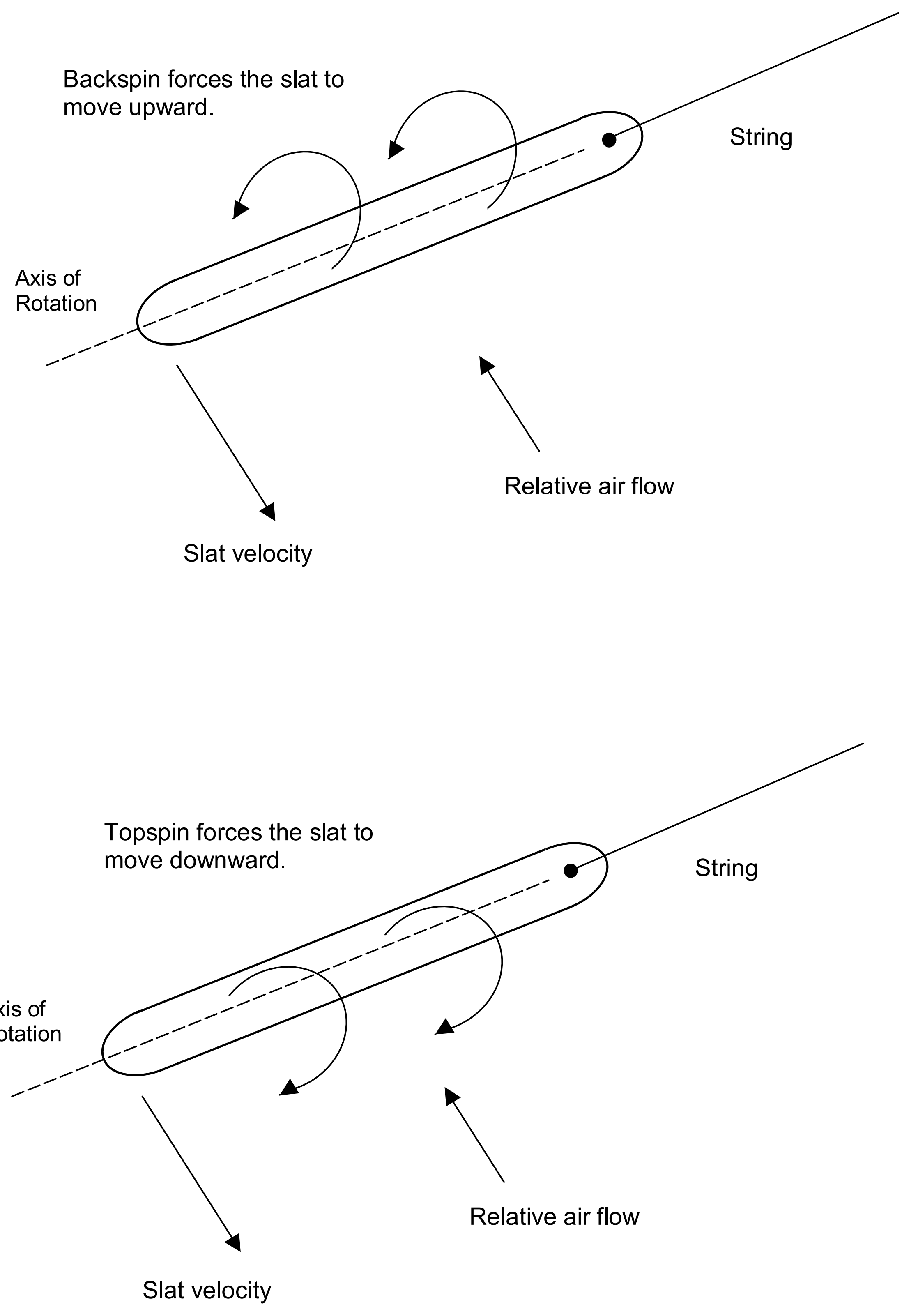

Figure 4. View from Top Looking Down

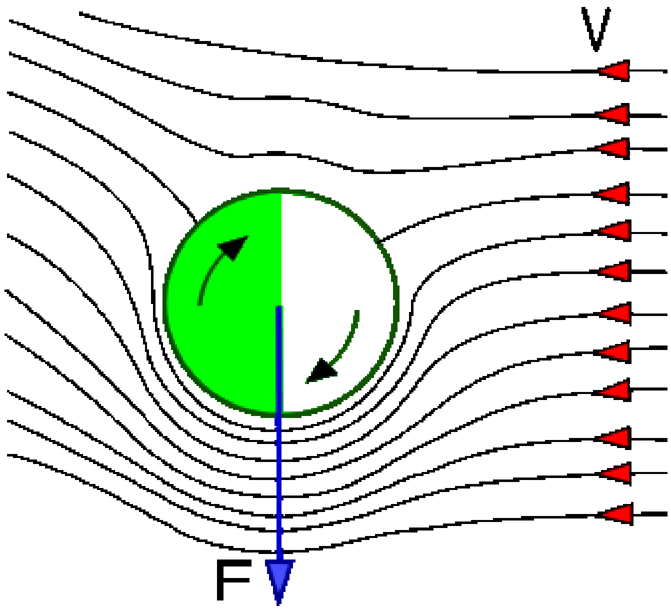

Figure 5. Magnus Effect on a Ball (Image courtesy of Wikipedia)

Some Aerodynamic Principles

The diagrams in Figure 4 show the slat's rotation in the relative air flow causes upward or downward movement.

The force causing the upward motion is called lift. The force causing the downward motion is called negative lift.

The upward and downward motion is known as the Magnus effect. It is a product of various phenomena, including the Bernoulli principle, and the formation of boundary layers in the medium around moving objects.

As air flows around an object, the side with the greater air velocity will experience the lower pressure and thus lift.

A basketball player making a long-distance, arching shot utilizes these principles as he or she applies backspin to the ball.

Recap of the Aerodynamic Forces on the Slat

The air follows the topside more rapidly, as the slat spins with a backspin into the oncoming air flow; while the slat's underside works against the air passing over it, causing more friction.

Thus, the pressure against the topside is lower than that against to the bottom. The resulting lift force causes the slat to rise.

As a final note, a drag force and aerodynamic moment also act upon the bullroarer, but a discussion of these forces is omitted for brevity.

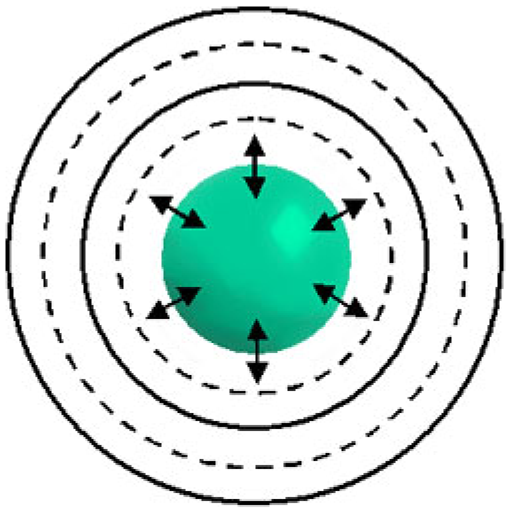

Figure 6. Acoustic Monopole

All points move in phase.

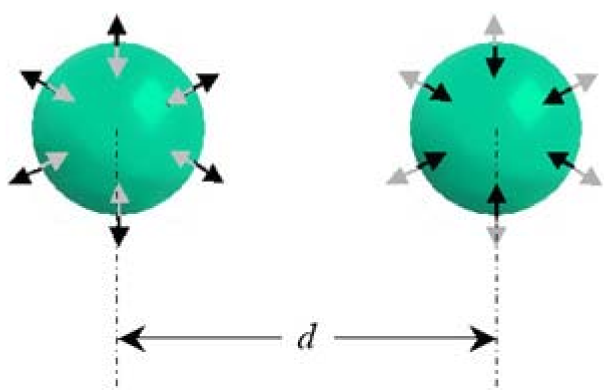

Figure 7. Acoustic Dipole

The two spheres oscillate 180° out-of-phase.

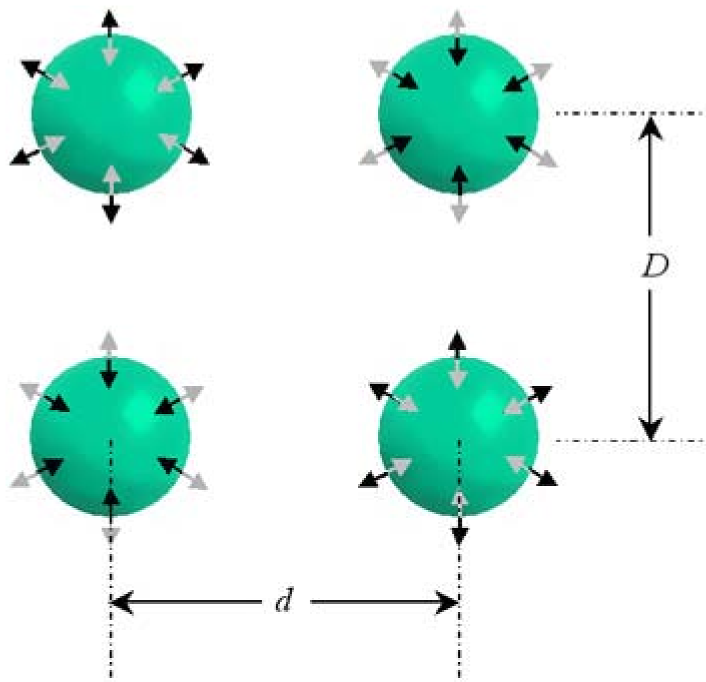

Figure 8. Acoustic Lateral Quadrupole

The quadrupole's monopoles are arranged at the vertices of a square.

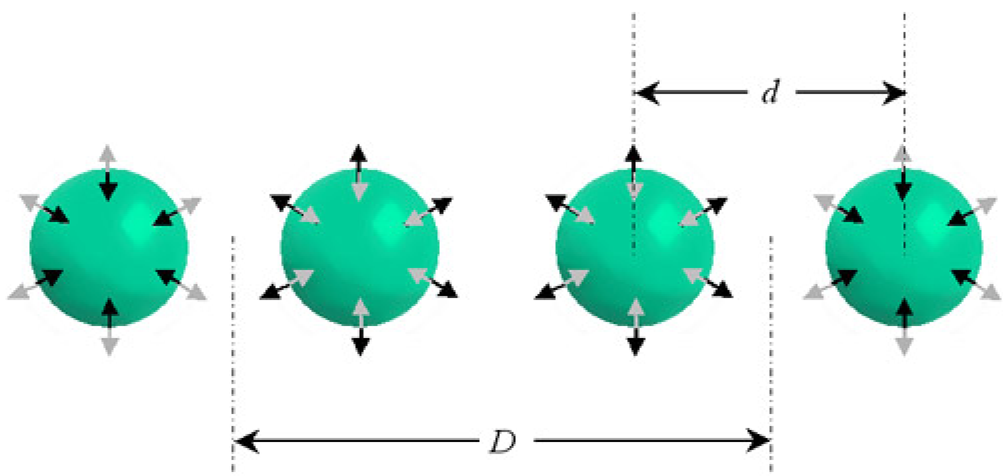

Figure 9. Acoustic Longitudinal Quadrupole

The quadrupole is arranged in a line with alternating phase.

Figures 6 through 9 are courtesy of: http://www.diracdelta.co.uk

Slat and String Rotation

The slat rotation is affected by two forces. One is the restoration moment in the wound string. The other is tension in the string induced by lift in either the upward or downward directions.

The slat's backspin causes the string to wind in the backspin direction, thus increasing the tension in the string. The string acts as a torsional spring.

Furthermore, the lift motion in the upward direction increases the tension in the string. The string becomes stretched, increasing the opposing torsional moment.

The stretched, wound string gradually slows the backspin rotation until it reverses the spin direction altogether.

The slat next experiences topspin resulting in negative lift with downward motion. The string tension is relieved until the slat passes through an equilibrium plane at which the cone angle is zero.

The slat continues to move downward past this plane due to the slat's inertia. The string's tension again increases, until it is sufficiently large to cause another spin reversal.

The cycle then repeat itself, but eventually the string become so wound up that the player must stop swinging the slat so that the string can unwind.

Motion Summary

In summary, the slat undergoes three types of motion:

1. Rotation in a large circle about the player's hand, which serves as the pivot point.
2. Twisting or spinning cycles about the axis collinear with the string. (This is also called proper rotation).
3. Alternate upward and downward motion due to positive and negative lift effects.

Some Aeroacoustic Theory

The Ffowcs Williams and Hawkings acoustic analogy uses equivalent moving sources to represent disturbed flows induced by body motion and by the body itself. These equivalent sources radiate as if the air were unbounded and perfectly at rest. These sources are represented by monopoles, dipoles and quadrupoles.

An acoustic monopole is a pulsating sphere of gas particles that radiates sound.

A dipole is two closely-spaced monopoles with equal strength that oscillate 180° out-of-phase. A dipole is also called an acoustic doublet.

A quadrupole consists of four monopoles in either a lateral or longitudinal pattern.

Monopole Sound Generation

There is a monopole due to thickness noise.

The slat has a low Mach number. The monopole is negligible for low Mach numbers and especially for a flat body in unsteady aerodynamics.

Dipole Sound Generation

The bullroarer's sound production is largely due to generation of an oscillating-rotating dipole across the slat, according to References 1 and 2.

The slat undergoes autorotation which yields fluctuating lift and drag forces. These forces act as equivalent acoustic dipoles.

The dipole thus results from loading noise.

Furthermore, the dipole's maximum value occurs when the slat is oriented broadside relative to its motion through the air.

Quadrupole Sound Generation

Quadrupoles correspond to flow noise. Quadrupoles are only efficient sources at higher Mach numbers.

Again, the slat's Mach number is low, typically less than 0.1.

Some Formulas

Aerophones have three characteristic periods.

The whirl period T_o imposed by user is

$$T_o = 2\pi / \Omega_o \quad (1)$$

where Ω_o is the whirl angular velocity.

The proper period T_r is

$$T_r = 2\pi / \Omega \quad (2)$$

where Ω is the proper angular velocity.

Again, proper rotation is twisting or spinning about the axis collinear with the string.

T_S is the inversion period of the proper rotation.

Note that

$$T_S > T_o >> T_r \quad (3)$$

Equations (1) through (3) are taken from Reference 2.

Furthermore, the acoustic frequency is twice the axial or proper rotation speed due to the twofold rotation symmetry of the slat, per Reference 1. The acoustic frequency is modulated in synchrony with the arm rotation.

Doppler Shift

The apparent frequency increases as the bullroarer slat moves toward the listener or the microphone. It decreases as it moves away. This has the effect of broadening the peaks in the spectral magnitude plot. The change in pitch becomes greater in proportion to the slat's velocity.

Further information about Doppler shifts is given in the Vibrationdata June 2003 Newsletter.

Vortex Shedding

Vortex shedding has only a minor affect in sound generation according to Reference 1.

Experimental Data

A sound recording was made of the bullroarer in Figure 10. The recorder was an EDIROL R-09.

The full time history is shown in Figure 11. A close-up view is shown in Figure 12. The envelope is modulated at 3.5 Hz which is twice the hand whirl rate.

The proper rotation occurs at 36 Hz, as shown in the spectral plot in Figure 13. This rotation generates a 2X acoustical peak at 72 Hz, with energy smeared to adjacent frequencies due to Doppler shifting and other effects.

The results are somewhat similar to those in Reference 2.

Figure 10. Bullroarer used in Experiment

Slat Length	11.5 inch	29.2 cm
Maximum Width	2.75 inch	7.0 cm
String Length	25.5 inch	64.8 cm
Mass	3.8 oz	108 grams
Whirl Speed	1.75 Hz	105 rpm

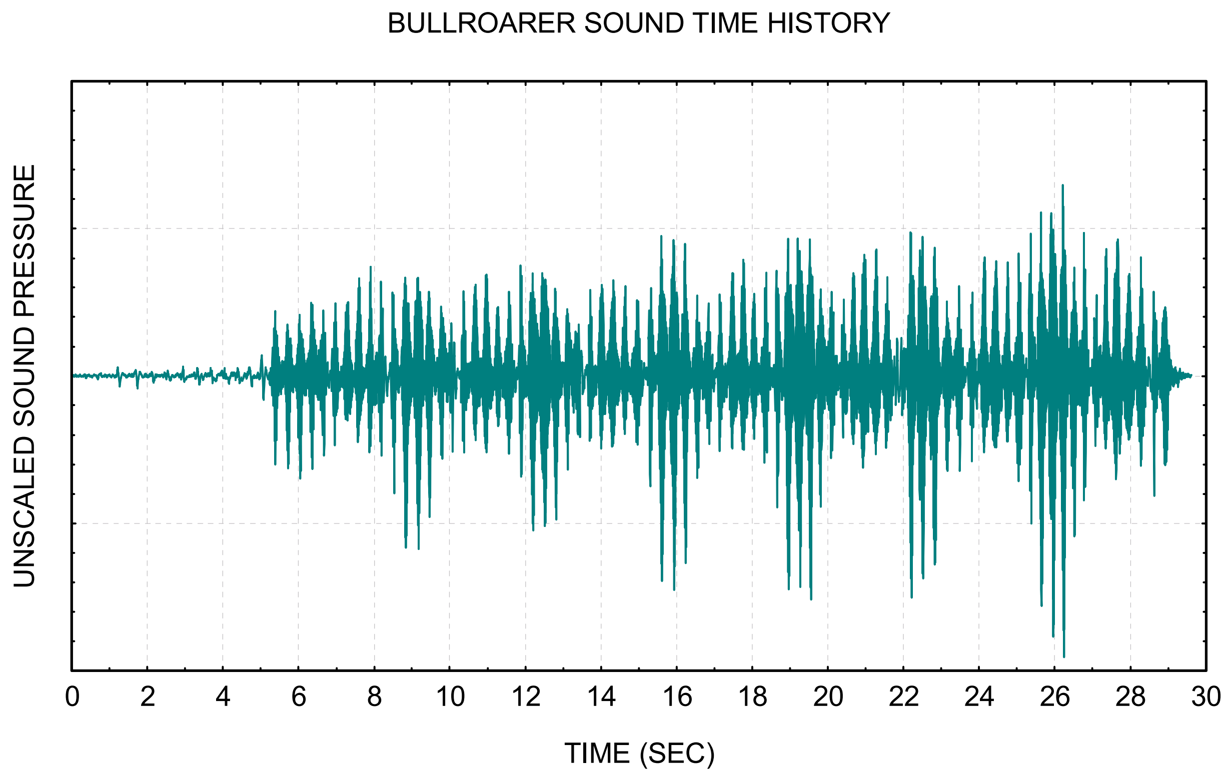

Figure 11.

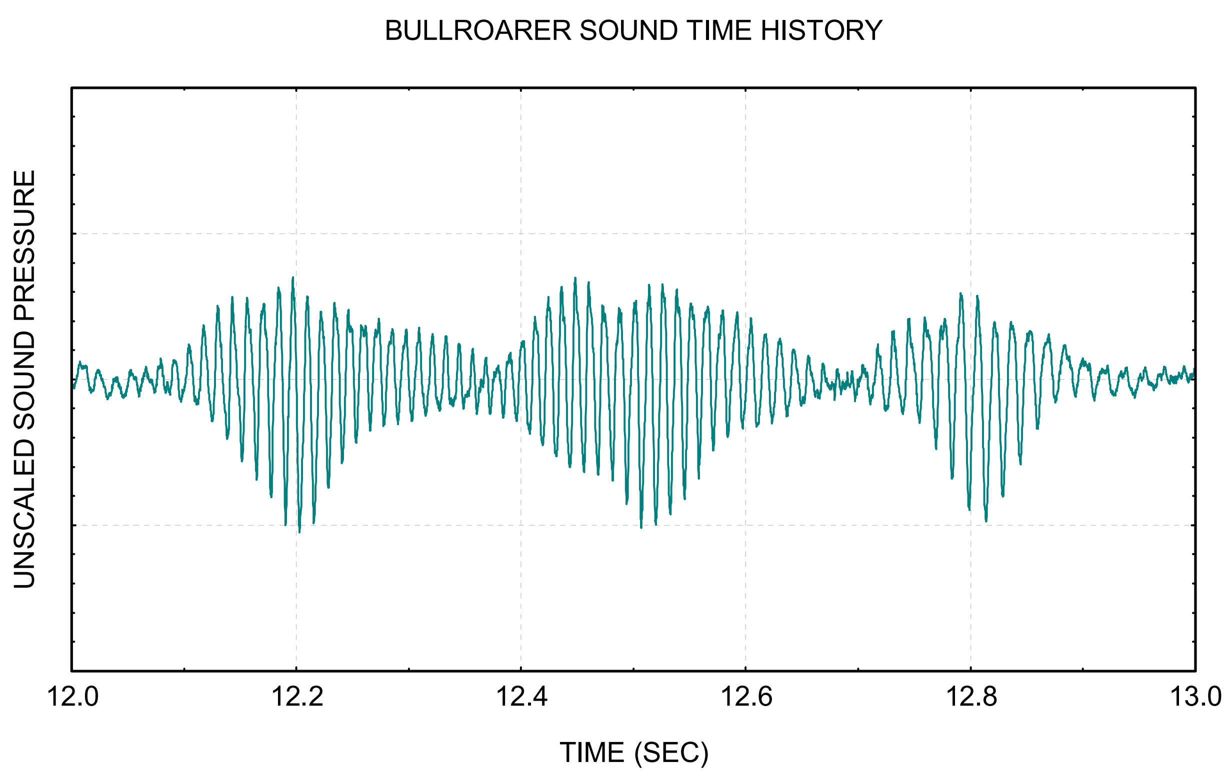

Figure 12.

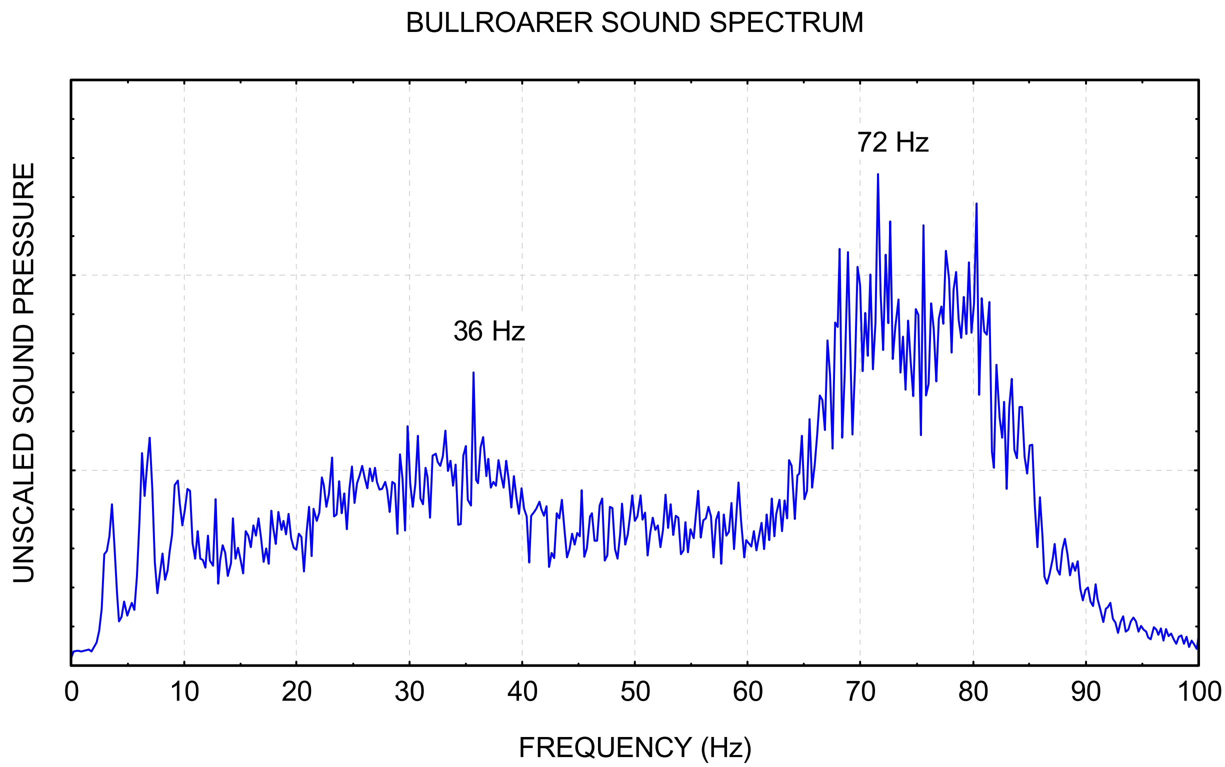

Figure 13.

Human Hearing

The ability to hear sounds at different frequencies depends on an individual's age, previous noise exposure and myriad other variables. The typical domain for an individual with good hearing is 20 to 20,000 Hz.

The bullroarer generates low frequency sound, with some spectral components below 20 Hz, which correspond to inaudible infrasound.

References

1. N. H. Fletcher, A. Z. Tarnopolsky and J. C. S. Lai; Rotational aerophones, J. Acoust. Soc. Am., Vol. 111, No. 3, March 2002.

2. M. Roger and S. Aubert, Autorotation and the Theory of Bullroarer Sound, AIAA Paper 99-1827, 1999.

3. K. Elsner, The Australian Bullroarer, The Physics Teacher, April 1994.

Figure 1. Bumblebee Latched to a Tomato Blossom

Buzz Pollination by Tom Irvine

Some Birds and Bees

Flowers contain reproductive organs.

The stamen is the male organ. The stamen has a filament stock. An anther mounted on top of each stamen typically contains four pollen sacs.

The female organ consists of the stigma, pistil and ovary. The stigma is the receptor of the pollen. The stigma is typically coated with sticky hairs for this collection purpose.

The anther's pollen is spread by the wind, insects and birds. Butterflies, bees and other insects are attracted, according to their own species, to certain types of flowers. The same is true for hummingbirds.

The pollination of many types of agricultural crops depends particularly on bees.

Female bees fly from one flower to the next gathering pollen. The bees carry the protein-rich pollen on their hind legs back to the hive. The pollen is then mixed with nectar to feed the underground brood cells.

Most blossoms have anthers that readily give up their pollen to the bees, but this process is more difficult for other flower species.

Figure 2. Buffalobur Nightshade

Plants with Apical Pores Anthers

About 8% of the world's 250,000 species of flowering plants (angiosperms) have tubular anthers with small apical pores which hold tiny pollen grains. Extraction of these microscopic grains requires a great deal of effort from the bees.

The Buffalobur Nightshade or Buffalo Burr (*solanum rostratum*) is an example of a plant with apical pores. Common crop plants in this category include: blueberries, cranberries, chili peppers, eggplants, kiwi fruits and tomatoes.

The flowering plants in this group have stamens which are like salt shakers in some sense, as explained in the next section. Note that these flowers are referred to as “buzz blossoms” in the remainder of this article.

Bumblebees

Bumblebees (*Bombus spp*.) have a unique method of extracting pollen from buzz blossoms, which honeybees (*Apis mellifera*) lack.

A bumblebee latches onto the flower with her feet and jaws. She decouples her flight muscles from her wings. She then moves her flight muscles rapidly, causing the flower and anthers to vibrate, dislodging the pollen.

The bumblebee, by analogy, shakes the salt out of its container. This is called buzz pollination or sonification.

The bumblebee’s muscle contractions occur at frequencies between 320 and 410 Hz per Reference 1.

Furthermore, the bumblebees may use a single buzz on a flower if the blossom is nearly empty or a long train of multiple buzzes on a previously unvisited blossom.

The vibration is transmitted throughout the hollow pollen-containing anthers, releasing clouds of golden pollen. The bumblebee’s body fuzz captures this airborne pollen.

The bumblebees distribute some of this pollen to nearby flowers, thereby guaranteeing a new crop. The remainder of this pollen is gathered into “pollen baskets” on the bumblebee's hind legs, for delivery to the hive.

Figure 3. Bumblebee Returning to her Hive (*Bombus impatiens)*

Note the dark yellow or orange-colored pollen that she is carrying on each of her hind legs. The hive box is located in the author's backyard.

Bees need to extract both nectar and pollen from flowers. Flowers produce nectar to attract the pollinators. The buzz blossoms, however, usually supply pollen only. The bumblebees are willing to forgo the nectar reward, but the honeybee usually avoids the buzz blossoms.

As an aside, the following species also perform sonification on buzz blossoms:

1. Large Carpenter Bee (*Xylocopa spp.*)
2. Wild Halictid Bee (*Augochloropsis spp.*)
3. Blue Banded Bee (*Amegilla spp.)*

Figure 4. Bumblebee (Image courtesy of Wikipedia)

Greenhouses

Growing tomatoes in greenhouses has been a challenge over the years. Pollination required human workers to use electrical vibrators to extract the pollen from the tubular anthers.

Bumblebees are becoming the preferred method of pollination, because they do so more efficiently and at less cost than humans.

Additional Bumblebee Facts

The bumblebee is not aggressive and only stings if its hive is threatened.

A bumblebee's buzz is created by air forced through holes in its abdomen as it flaps its wings.

Bumblebees form colonies. Their colonies are usually much smaller than those of honeybees. Bumblebee hives are also less tidy than honeybee hives.

The agricultural use of bumblebees is limited to pollination. Bumblebees do not maintain the entire colony over winter, so they do not stockpile honey.

The last generation of summer includes a number of queens. In the autumn, young queens mate with male drone bees and hibernate over the winter in a sheltered area.

The queens can live up to one year, possibly longer in tropical species.

Bumblebee workers are sterile females. Each worker forages independently.

Honey is essentially concentrated nectar. Nectar is mainly a mix of different sugars that are secreted from flowers into their nectaries. The bees suck up the nectar using their tongues. The tongue is long and feathery at the end.

Bumblebees are warm-blooded insects. The nest temperature is regulated to about 86 °F (30 °C). Furthermore, a bumblebee cannot fly if its muscle temperature drops below this temperature.

Bumblebees maintain the hive temperature themselves by producing body heat without wing movement.

Bumblebees radiate heat from their bodies for cooling as needed. In addition, they use wing fanning to provide air circulation.

Bumblebees have a division of labor. Some workers tend the hive and regulate its temperature. Others forage for pollen and nectar.

There are 239 species of bumblebees worldwide, according to Reference 2. Bumblebee species include the following:

Bombus hortorum
Bombus impatiens
Bombus lapidarius
Bombus lucorum
Bombus pascuorum
Bombus pratorum
Bombus sonorus
Bombus terrestris

The Bombus impatiens species is sold commercially for greenhouse and garden pollination.

Aerodynamic analysis shows that the bumblebee can fly because its wings encounter dynamic stall in every oscillation cycle. This stall consists of airflow separation above the wing with a large vortex, which briefly produces several times the lift of the aerofoil in regular flight.

Spectral Analysis

A spectral plot of the sound made by bumblebees flying inside their hive box is shown in Figure 5. The box is the same at that show in Figure 3.

A spectral plot of the sound made by a *Bombus terrestris* buzz pollinating a tomato blossom is given in Figure 6. The sound file is courtesy of David Lang from Bio-Bee in Israel.

References

1. http://www.cerrilloshills.org/nature/insects.html

2. J. Schmidt and R. Jacobson, Refugia, Biodiversity, and Pollination Roles of Bumble Bees in the Madrean Archipelago, USDA Forest Service Proceedings, RMRS-P-36, 2005.

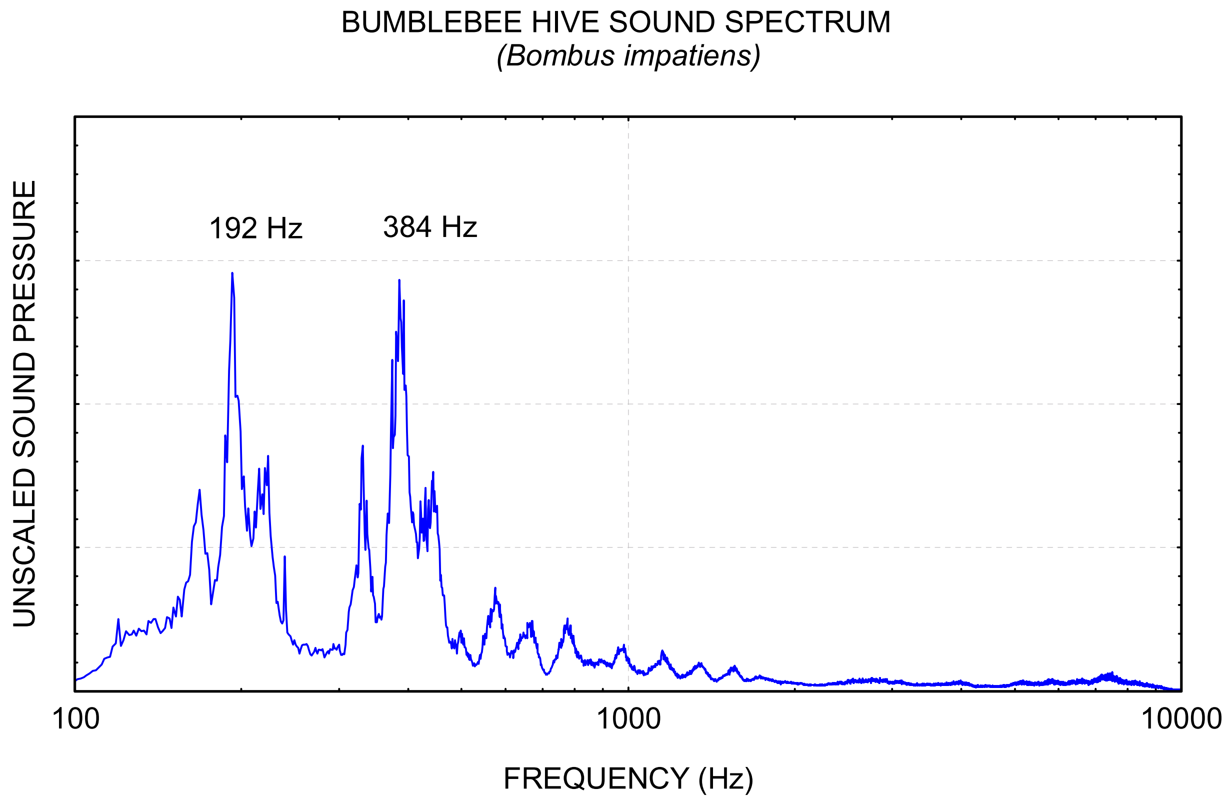
BUMBLEBEE HIVE SOUND SPECTRUM
(Bombus impatiens)
UNSCALED SOUND PRESSURE
192 Hz
384 Hz
100
1000
10000
FREQUENCY (Hz)

Figure 5.

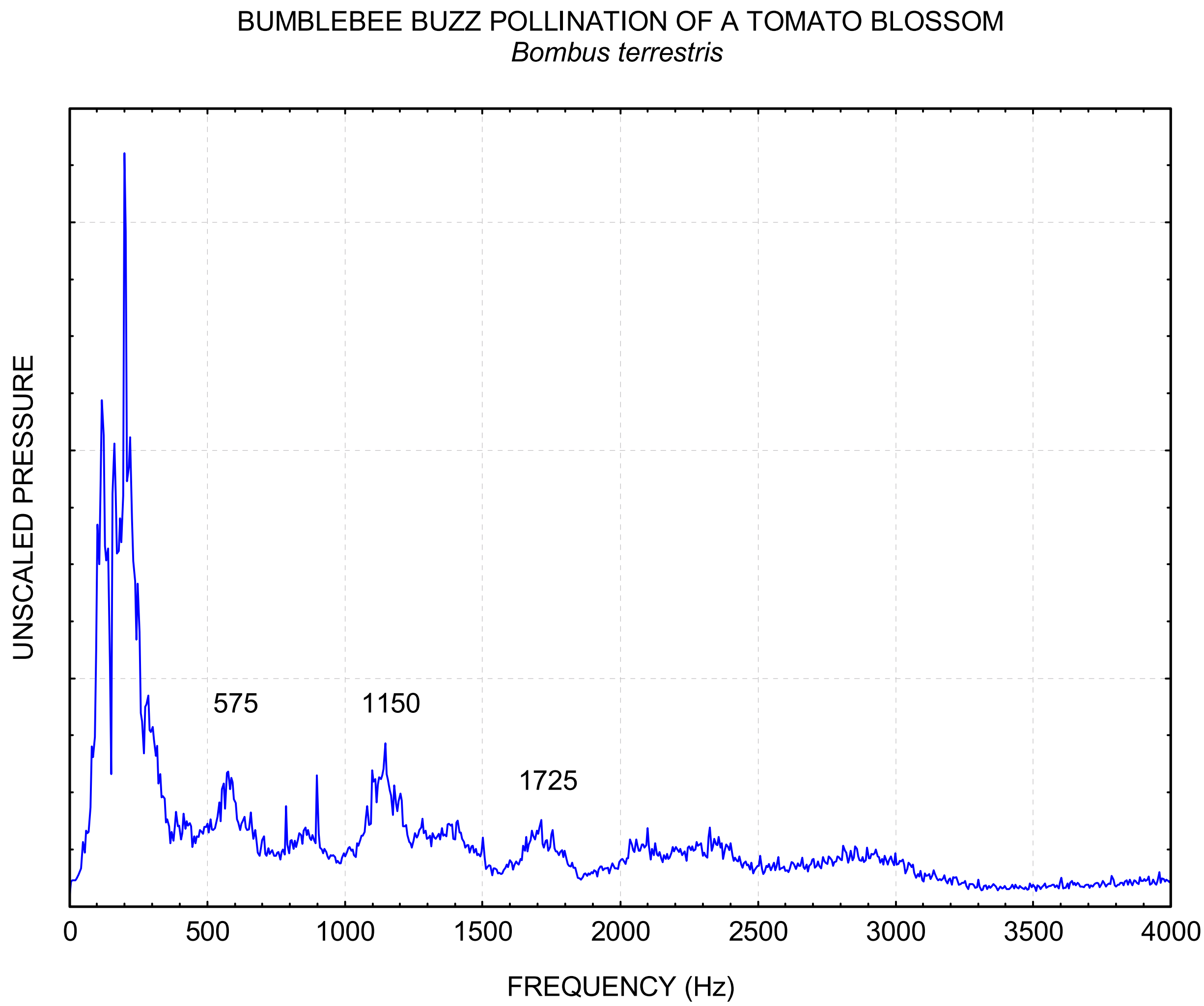

Figure 6.

The energy below 300 Hz is due to ambient noise unrelated to the buzz pollination.

The fundamental sonication frequency is 575 Hz with integer multiples at 1150 and 1725 Hz.

The 575 Hz frequency in Figure 6 is higher than that expected from Reference 1. Additional research is needed to identify frequency variation between subspecies, individuals, blossom types, etc.

Note that the buzz pollination frequencies are higher than those generated by the bees during flight. The sonication frequencies are also higher than those made by the bees as their flap their wings to circulate air about the hive. This can be shown by comparing Figures 5 and 6, even though each figure represents a different subspecies.