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Acoustic decoding of a sheep bell and trotters within a sheep herd

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Abstract: *Time series analysis is used to de-convolve bell and trotter signals within a hired of sheep for the purpose of identifying the sheep's activity: walking to and from grazing pasture and stock pens. A bimodal model of the standing-wave quarter wavelength closed air-column mode is found to represent the frequency response (1-8 kHz) the elliptical shape and composite design of the iron bell that is commonly attached around the sheep neck.*

Keywords: sheep bells, acoustic recoding, time series, overtones and walking gait.

1. Introduction

For centuries percussion instruments in the form of iron bells have been placed around the neck of sheep (also cattle and goats) to let herders know what's going on with the herd while they are doing other things. Indeed to improve awareness of the shepherds to the herd's activity, the loudest bell is placed on the more active bucks. The tranquil melodic bell ring while sheep are grazing has been used to locate herds on pasture, as well as letting the shepherds know that 'all is well'. In contrast the more rapid and louder ring tones have proven to be a good indicator of nearby predators. To the shepherd who has been brought-up to identify these two extremes, the acoustic signatures are easily identified, however it may be argued that the identifying conditions between these two extremes is much more difficult, and for the average person who is not involved in shepherding.

Time series analysis of a series values sampled of regular intervals has been shown to be a power tool in de-convolving complex noise sources such as: turbulent fluid [1], complex information with industrial plants chemical [2], and White Dwarf stars [3]. This paper reports upon the use of time series analysis and mathematical modelling of the acoustic response of iron bells that are attached to three sheep within a healthy herd containing between 27 to 30 healthy adult male and female 'Sfakia' sheep. The aim of this work is to establish if the bell acoustics can be used to identify the sheep's walking gait as

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they move steadily between pastures, rather than the extreme scenarios of grazing and threat of predators. To prevent imparted stress and 'sheep worrying' to a single sheep the acoustic measurements were performed at a distance of 20 m from the herd. The measurements were made in the month of October on the outskirts of the Cretan village of Kástelos in Western Crete. The time of the measurements are both in the morning (8-9 am local time) when the sheep are moved down-hill to pastures and in the evening when they are moved back up-hill to the safety of their stock pens in the evening (6-7 pm). The two groups of acoustics measurements characterises the mood and movement of the sheep: in the morning the sheep are fresh from their rest and are herded down-hill with a slope of 10 degrees and average speed of 2.4 ±0.2 $m.s^{-1}$, whereas in the evening the sheep are tired and herded up-hill at an average speed of 1.2 ±0.2 $m.s^{-1}$. The measurement is made over seven consecutive days. It is found that speeds are in good agreement with the kinetic characteristic of the walking gate of a sheep as measured on a pressure sensing walking way [4].

In the case of the bell, when the clapper is struck against the rim, the metal-on-metal impact imparts energy instantaneously as sound travels through metal at approximately 5130 $m.s^{-1}$ into the bell. At this moment a temporary distortion (hum) of the rim occurs from the where the energy is transmitted throughout the bells to produce a continuous succession of partials resonate tones. It is this time dependent combination of strike tone and partials which gives rise to the timbre [5] of the bell. However and unlike tuned cast metal hand-bells and church–bells, the sheep bell's elliptical shape and composite design imparts boundaries on the transmission of energy throughout the body of the bell due to the stiffness at the two welded acute angles on the major axis and the less stiff regions on the minor axis. In addition the sheep bells perceived timbre also depends on whether the struck region of the rim is damped by the sheep's neck. Thus the mechanical interaction within a sheep bell's timbre is potentially more complex, in both pitch and amplitude, when compared to a tuned cast bell.

2. Experiment

2.1 Sheep bell

The sheep bell studied here is of the composite elliptical open-bell design that is made from two formed iron metal sheet (1 mm thick) that are brazed/welded together to form the elliptical shaped aperture behind which a closed air-column acoustic chamber is formed. The edge dimensions of the aperture are typically 11.5 cm between the welded seams and 16 cm from the rim to the bell node. The clapper is made from 4 mm diameter x 10 cm in length.

Finally the bell's nodal point (minimum vibration point) is attached to the sheep using a leather strap. A photograph of a sheep bell is shown in Fig 1a and a schematic of the aperture of the bell are shown in Fig 1 b.

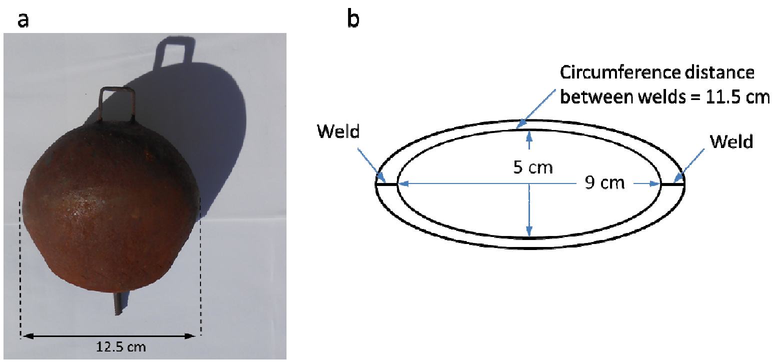


Figure 1a and b: a) photograph of flat side of sheep bell, b) Schematic view of open aperture of sheep bell.

2.1 Acoustic recording

The sound recording and deconvolution analysis used in this study is performed by National instrument LabVIEW 2011 software program running on a Dell laptop. This software has been published elsewhere [6- 10]. The recordings where made using an Omi-directional condenser microphone and sampled at rate of 24000 samples per second with a 24 Bit depth for a period of 1 second. In all cases the measurements were made at a distance of 20 m from the noise source (bell and sheep herd). In order to identify the sheep bells minor and major axis response, a single bell was isolated and freely suspended and the clapper struck using the force of a human hand. The frequency response of a normal healthy human hearing frequency range is defined between 20 Hz to 20 kHz, but is most sensitive in the 1 to 4 kHz range [5]. Therefore it the 20 Hz to 8 kHz range is only considered here. The bell recordings along with a recording of the surrounding acoustic environment (baseline) are used as sound references for subsequent decoding of the sheep traveling upon the road. To standardize the reference measurements with the sheep acoustic recordings a piece-by-piece Savitzky-Golay (SG) [11] moving window of 10 Hz is used smooth the amplitude of the time series data. This digital conditioning of the recordings match the same conditioning process to remove the high frequency sound of the sheep's feet impacting on the concrete road surface.

3. Results

Three sets of 10 bell recordings were made. These sets are reported in sections: 3.1 for a single bell removed from sheep neck and struck by a human hand, 3.2 bells attached to 3 sheep within the herd as the sheep are walking up-hill (evening), and 3.3 as the sheep are herded down-hill in the morning. In all three cases the recording microphone is placed 20 m perpendicular to the direction of the herd movement.

3.1. Sheep bell response (freely suspended)

Figure 2 shows a triplet of reference acoustic spectra for the freely suspended sheep bell. The top spectrum is associated with the clapper striking the bell on the major axis, the middle spectra is associated with the clapper striking on the minor axis and lower spectrum is a measurement of the surrounding area without any strikes (baseline) and is only shown for comparative purpose here.

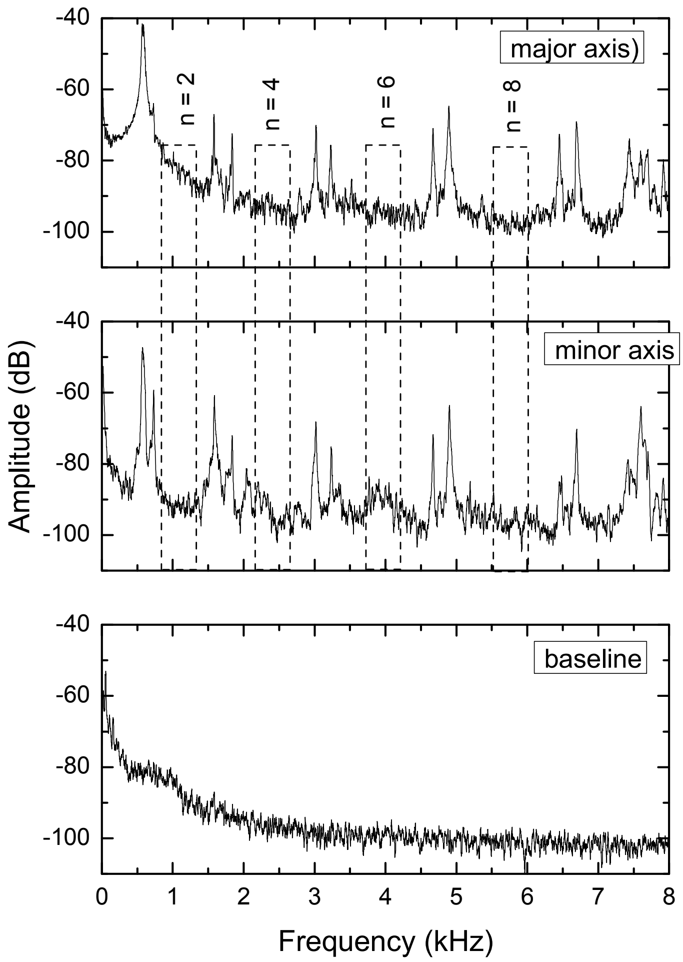


Figure 2: Frequency response of sheep bell as struck on the major, minor axis using a human hand and basline measurement.

Upon comparison of the spectra's, there a number of features of note: Firstly the strike tone is seen to be formed from doublet peak with frequencies of 600 Hz 740 Hz which is followed by harmonic related overtones/partials that exhibit doublets also. The overtones/partials frequencies in the major axis spectra appear to have a strong odd harmonic relationship to the strike tone. For example n = 3, 5, 7, 9, whereas both even overtones/partial frequencies (n = 2, 4, 6, 8 etc.) and odd overtones appear in the minor axis spectra. The disparity that appearance the between odd and odd plus even overtones leads the minor axis spectra having a richer timbre which may be expressed by the normalised mean amplitude (centred around ±200 Hz) of the even overtones/partials to the strike tone amplitude as denoted using the standard notation of loss to the carrier (dBc), see the annotated dashed box for n = 2, 4, 6 and 8 in figure 2 and measured mean values in table 1. In table 1 it can be seen that the loss to the strike tone (carrier) for n = 4, 6, 8 is greater for the major axis typically 52.6 dB as compared to typically 41.6 dB for the minor axis. The lost however at n = 2 is reversed but only by 3 dB.

Table 1. Strike tone amplitude and dBc values centred (±200 kHz) around even overtones/partials for both major and minor axis.

Axis	Strike tone (dB)	n = 2 (dBc)	N = 4 (dBc)	n = 6 (dBc)	n = 8 (dBc)
Major axis	-41	-44	-50	-52	-56
Minor axis	-47	-48	-43	-37	-45

To a first approximation (predict single rather doublets), the strike tone frequency (f_o) and the odd overtone/partials frequencies (f_n) may be represented mathematically using a single standing-wave quarter wavelength closed air-column model [5-9] as shown Equation (1).

$$f_n \approx \frac{nc}{4L} \qquad (1)$$

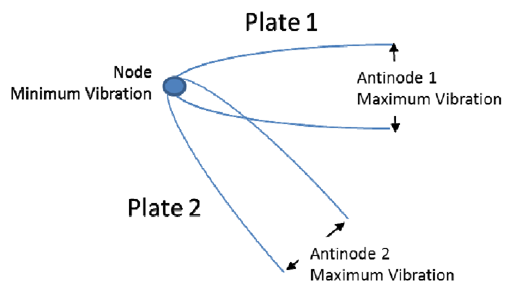
In equation (1), n is modulo frequency number, L is the physical length of resonator and c *is the* sound velocity at 20 ^{o}C (air: ~346 m.s^{-1}; iron: ~5130 m.s^{-1}). For a closed air-column, the bell aperture defines the antinode (maximum pressure vibration) and the node point defines the minimum vibration point. Thus using equation (1), the bells 600-800 Hz strike tones equates to L = 11.4 to 11.8 cm. Using the bell's geometric information proved in figure 1 the computed value of L approximates to the bell's major axis and either side of the apertures surface length which would suggest the twin peaks in the strike tone originate from the aperture volume and the metal rim, Given this configuration, odd overtones/partials are readily supported and even overtones/partials are suppressed. To predict both even and odd overtones/partials resonances equation 1 needs to modified by replacing the 4 the denominator with 2 thus making equation 1 to represent a half wavelength resonator.

The physical constriction of the welded iron bell leads the proposition of a double standing-wave quarter wavelength closed air-column model as shown in

Equation (2) and (3). In these two equations the single (′) and double (″) represents the first and second frequency within the doublet frequency of the bell and also the length of the first and second plates of the bell.

$$f_n^{'} \approx \frac{nc}{4L^{'}} \quad (2)$$

$$f_n^{"} \approx \frac{nc}{4L^{"}} \quad (3)$$



Schematic of the doublet bell model

3.2. Sheep bell response as the herd is moving up-hill

Figure 3 shows a representative acoustic frequency spectrum of the 10 recordings of 3 similar bells (with a major axis of 10 cm) attached to 3 individual sheep within the herd. The herd are being walked up-hill at an average speed of 1.2 $m.s^{-1}$. The acoustic spectrum shows a clear strike tone at 750 Hz followed by a series of harmonically grouped overtone/partials at 2.3 to 2.66 kHz, 4.08 to 4.85 kHz. The dispersion frequency spans of these of these groups are of the order of 1 kHz.

The frequency position of the overtones/partials reveal two features of note. Firstly it is known that sonic energy travels approximately 14 times faster through ion when compared to air, which will result partials having a different harmonic relationship to the strike tone. Secondly, the odd harmonic relationship of the reference bell, as discussed in section 3.1, is observed; in that they have an odd harmonic relationship (n = 3 (2.55 kHz); n = 5 (4.25 kHz); and n = 7 (5.95 kHz) to the strike tone. Using equation 1 the frequency of the strike tone corresponds to the characteristic bell length of 10 cm. However, the overtones appear to have twice the bandwidth (~1 kHz) as compared to the reference iron bell (~0.5 kHz).

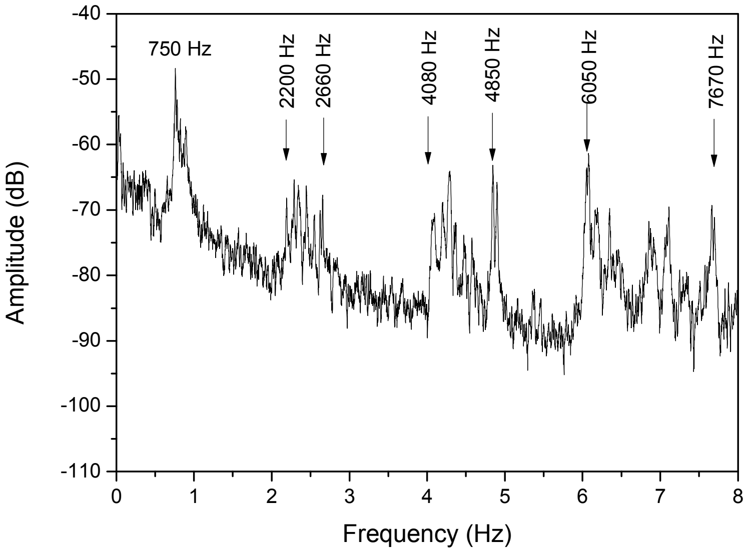


Figure 3: Frequency response of sheep herd walking up-hill at 1.2 m.s^{-1}.

3.3. Sheep bell response as the herd is moving down-hill

Figure 4 shows a representative frequency signature of the 10 acoustic recordings of the same herd with three bells, but as they are walking down-hill in the morning at an average speed of 2.4 m.s^{-1}. When compared to the sheep walking up-hill spectrum (figure 3) the recorded spectrum shows that the strike tone, a 425 Hz tone and overtones/partials are present but there is a significant increase in the number of discrete and irregular frequency spaced (10 to 100 Hz) noise (14 to 20 dBc) peaks between the bell's strike tone and the 3rd overtone/partial without altering the frequency dependent noise floor level at the even harmonics (n = 2 (1.7 kHz); n = 4 (3.4 kHz); and n = 6 (5.1 kHz)) locations.

It is known that when quadrupeds such sheep change their forward speed from walk to trot their gait cycle duration (beat-to-beat per limb) changes dramatically from 0.8 to 0.1s Thus for a herd of 30 quadrupeds (of mixed age, size and health) moving at a trot speed of 2.5 m/s, we might expect a mean acoustic frequency response of 1.2 kHz. . Given the factor of 2 increase in herd speed between the up-hill (figure 3) and down-hill (figure 4) recordings, the additional irregular peaks may originate from the impact of the sheep’s trotters. Our Measurements show that the statistical variance for the same herd can be ± 0.8 kHz

To analysis the sheep gait, an audio-visual movie was made for both the upward and downward directions of the herd. It was found that the sheep have a two-beat diagonal gait (trot) where the diagonal pairs of legs move forward at the same time in the down-hill case (2.4 m.s^{-1}). In the up-hill case (1.2 m.s^{-1}) the sheep tend to move one leg at time. This result is in good agreement with the work of J. Kim and G. Breur who used a pressure sensing walkway to measure the gait of Suffolk-mix sheep [4]. In their work it was reported that the walking trot gait imparted 50-56% of the sheep's body weight to the synchronised diagonal forward and hind limb with a disparity of 59% to 41% in favour of the forward limb. This would imply the loudness of the sheep trot signature would be greater than the up-hill walking gait where one limb is moved at a time. It is presumed that in our case the loudness (noise) of the sheep walking up-hill gait is not observed due to the noise floor of the acoustic measurement.

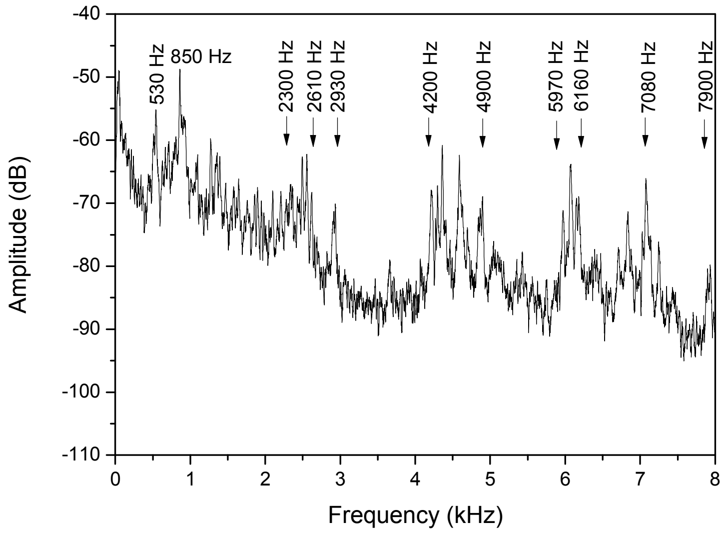


Figure 4: Frequency response of sheep herd walking down-hill at 2.4 m.s^{-1}.

4. Conclusion

Acoustic recordings of iron composite bells have been made in the frequency range of 0 to 8 kHz. The acoustic signature of single (and isolated) reference bell is used to identify the bells strike tone and overtones/partials response when the clapper struck against the metal rim. It is found the bell supports doublets strike tone and doublets of odd overtones/partials and abates the even overtones/partials. A single quarter wavelength closed air column is used to model the acoustic response. However the single model it is not suffienelty detailed to provide the true doublet response on the composite ion bell. Therefore a double quarter-wave model is proposed. Given new model the recordings are then used as a reference to decode the frequency dependent acoustic signature of bells attached to 3 sheep within a herd of 27 to 30 healthy male and female Sfakia sheep as they are walked up-hill and down-hill on an inclined (10%) concrete road at a pace of 1.2 and 2.4 m.s^{-1}, respectively.

Time series analyses of the acoustic recordings of the herd indicate that there is significant difference in the up-hill and down-hill. The difference in acoustic signature is attributed to the change in the walking gait of the sheep: from one-beat-to-beat impact as the sheep alter their gait from a walk to a trot.

Acoustically the difference occurs in the 850 Hz to 2 kHz frequency range which is the sensitive hearing range of the human ear.

It is concluded that the movement behaviour of a sheep herd that lay between the extremes of grazing and predator threat can be discriminated using the non-obtrusive and non-worrying technique of acoustic recording.

Acknowledgements

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