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SHORT COMMUNICATION

THE SCALING OF SONG FREQUENCY IN CICADAS

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In male cicadas, sound is generated by a pair of tymbals on the abdomen (Pringle, 1954). The tymbals buckle inwards causing pressure changes in the abdominal cavity, from which sound is radiated through the tympana (Young, 1990). A recent model of sound production in cicadas suggests that the abdominal cavity and tympana act as the components of a Helmholtz resonator that is excited by the drive from the tymbals (Bennet-Clark and Young, 1992). A Helmholtz resonator consists of a cavity open to the outside *via* a hole which has a real or notional neck, and the resonant frequency f_0 is given by the general equation:

$$f_0 = \frac{c}{2\pi}\sqrt{\left(\frac{A}{L \times V}\right)}, \tag{1}$$

where c is the speed of sound in the fluid, taken as $340\,\mathrm{m\,s^{-1}}$ for air, A is the area of the neck, L is the length of the neck and V is the volume of the cavity. Where the resonator has two holes, these terms should be somewhat modified: A is the combined area of the two holes, L is $16/3\pi r$ ($\approx 1.7r$) for a simple hole in a thin-walled vessel and r is the radius of one hole (Seto, 1971). These modifications to equation 1, which include corrections for the acoustic end-effect at either side of a simple hole in the wall of a vessel, are applicable to a model of the male cicada, in which there are two tympana close to the ventral surface of the abdomen.

Simplifying this equation, it can be seen that the resonant frequency of a series of similar cavities scales as:

$$f_0 \propto \sqrt{\left(\frac{A}{L \times V}\right)} \propto \sqrt{\left(\frac{L^2}{L \times L^3}\right)} \propto \frac{1}{L}\,. \tag{2}$$

This relationship should apply to the dominant sound frequency produced by such a system. One might expect song frequency to scale with body size in male cicadas, provided that the sound-producing structures are of similar design in different species.

Key words: cicada, sound production, (Helmholtz) resonator, scaling.

The majority of male cicadas do appear to have a similar anatomy and similar relative body dimensions, even though their body lengths range from below 15 mm to over 50 mm. We may refer to these as 'typical' cicadas, following Young (1990). There are a few notable exceptions to this common design, such as the bladder cicada *Cystosoma saundersii*, which has a distended thin-walled abdomen (Simmons and Young, 1978).

Bennet-Clark and Young (1992) found that the dimensions of the abdominal cavity and of the tympana of three species of cicada, *Cyclochila australasiae*, *Macrotristria angularis* and *Magicicada cassini*, when applied to equation 1, give resonant frequencies that agree well with the song frequencies measured for these species. However, the cicada *Magicicada septendecim*, which has anomalously thick tympana, did not fit the model well. We now report the relationship between body length and the dominant song frequency for a series of typical cicadas.

For several species studied by Young and Josephson (1983*a*), we used tape recordings and specimens from that earlier work. For *Cicadetta quadricincta*, we used recordings made by H.C.B.-C. on a Sony V90 camcorder using its own microphone. These records were analysed using a Kay DSP Sonagraph model 5500; the song frequency is taken as that at which the peak energy is seen. Body length was measured from dried preserved specimens of each species; these may be slightly shorter than live insects in the singing posture (Young, 1990) but, since the body lengths quoted by others have been measured in the same way, the various data may reasonably be regarded as comparable.

For the other species, data for carrier frequency and/or body dimensions have been obtained from the literature (Pierce, 1948; Pringle, 1954; Popov, 1989, 1991), supplemented by measurements of museum specimens. Some of the older published measurements of song carrier frequency were made by direct measurement from oscillograms and so they may be slightly less precise than those made using more recent methods of analysis.

The data for the dominant song frequency and body length for 16 cicada species are shown in Table 1. From these data, a plot of the reciprocal of body length against song frequency is shown in Fig. 1. The correlation coefficient of the calculated linear regression given on Fig. 1 is 0.875 (r^2=0.766, 30 d.f.), which is highly significant (P<0.001). Such a correlation suggests that body size is acting as a constraint on the sound frequencies that are produced by typical cicadas. This is perfectly understandable if all, or nearly all, these species are employing a similar type of Helmholtz resonator as an acoustic load for their sound-generating tymbals. The dominant song frequency will then be an inevitable consequence of the dimensions of their abdominal cavities and tympana, as indicated in equations 1 and 2.

Another consequence of employing this common design of resonant structure in different species is that the system allows similar insect to air impedance matching at all sizes. The physical acoustics of sound production would suggest that, for good impedance matching, the linear dimensions of the sound-radiating structure should vary in direct proportion to the sound wavelength (see, for example, Olson, 1957; Seto, 1971). In cicadas which are known to radiate sound through the tympana (*Cyclochila australasiae*, *Macrotristria angularis*), this sound source is evidently large enough to provide good impedance matching between the insect and the surrounding air. Since it appears that the

Table 1. *Body length, reciprocal of body length and dominant song frequency for male cicadas*

Species	Body length (mm)	Reciprocal body length (mm^{-1})	Dominant song frequency (kHz)	Source
Abricta curvicosta Germar	28.2	0.036	9.6	Original, D.Y.
Cicadatra cataphractica Popov	25.4	0.039	5.5	Popov (1989)
Cicadatra querula Pall.	22.7	0.044	8.0	Popov (1989)
Cicadetta inserta Horv.	15.0	0.067	15	Popov (1991)
Cicadetta petrophila Popov	15.2	0.066	10.5	Popov (1991)
Cicadetta quadricincta Walker	16.2	0.062	11	Original, H.C.B.-C.
Cyclochila australasiae Donovan	45.3	0.022	4.3	Young (1990)
Okanagana rimosa (Say)	23	0.043	8.1	Pierce (1948)
Okanagana vanduzeei Distant	19.6	0.051	10.5	Original, D.Y.
Macrotristria angularis Germar	44.5	0.022	4.0	Young (1990)
Magicicada cassini Fisher	23.8	0.042	6.0	Young and Josephson (1983*b*)
Platypleura octogutta Fabre	29	0.035	5.5	Pringle (1954)
Psaltoda claripennis Ashton	28.8	0.035	6.4	Original, D.Y.
Terpnosia stipata Walker	35	0.029	5.2	Pringle (1954)
Tamasa tristigma Germar	18.8	0.054	8.6	Original, D.Y.
Tibicen canicularis Harris	30	0.033	7.4	Pierce (1948)

The source of the data is shown; where original data have been used, this is indicated. Body length for *M. cassini* was measured by us from preserved specimens.

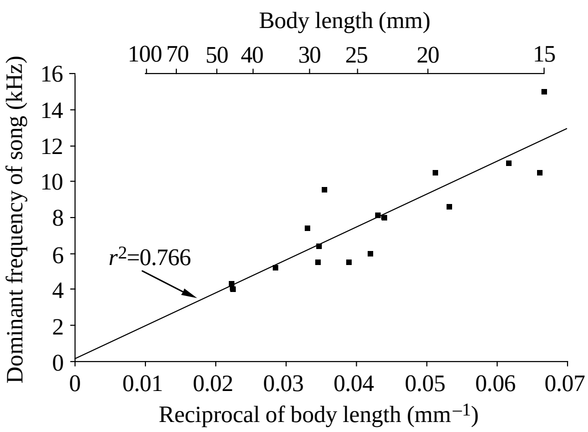

Fig. 1. Graph of dominant frequency in the song *versus* the reciprocal of body length for the 16 cicada species listed in Table 1, with the calculated linear regression of the data. For reference, the insects' body length is also shown.

wavelength of the song of cicadas scales with body length, good matching should also be possible for smaller species. Certainly, cicadas are, for their size, extremely noisy.

There is a further possible consequence of design similarity in the system. A useful dimensionless parameter of a resonant system is its quality factor or Q, which is a measure of the sharpness of its tuning, given by:

$$Q = \frac{\text{resonant frequency}}{\text{bandwidth at } -3\,\text{dB}}\,. \tag{3}$$

Thus, a sharply tuned resonator has a high Q.

For a Helmholtz resonator, the quality factor Q is given by (Seto, 1971):

$$Q = 2\pi\sqrt{\left(\frac{L^3 \times V}{A^3}\right)}. \tag{4}$$

Simplifying this, it can be seen that Q scales as:

$$Q \propto \sqrt{\left(\frac{L^3 \times V}{A^3}\right)} \propto \sqrt{\left(\frac{L^3 \times L^3}{L^6}\right)} \propto L^0. \tag{5}$$

In other words, Q does not scale and is a constant of the design. Hence, a similar sharpness of tuning is potentially available at all sizes and size is not a constraint in this respect.

References

BENNET-CLARK, H. C. AND YOUNG, D. (1992). A model of the mechanism of sound production in cicadas. *J. exp. Biol.* **173**, 123–153.

OLSON, H. F. (1957). *Acoustical Engineering.* Princeton, NJ: Van Nostrand.

PIERCE, G. W. (1948). *The Songs of Insects.* Harvard University Press.

POPOV, A. (1989). Species of singing cicadas revealed on the basis of peculiarities of acoustic behavior. I. *Cicadatra cataphractica* Popov. (ex gr. *querula*) (Homoptera, Cicadidae). *Ent. Rev.* **68**, (6) 62–78. (English translation of 1989 Russian original).

POPOV, A. (1991). Species of singing cicadas revealed on the basis of peculiarities of acoustic behavior. II. *Cicadetta petrophila* Popov. (ex gr. *inserta*) (Homoptera, Cicadidae). *Ent. Rev.* **70**, (4) 17–24. (English translation of 1990 Russian original).

PRINGLE, J. W. S. (1954). A physiological analysis of cicada song. *J. exp. Biol.* **32**, 525–560.

SETO, W. W. (1971). *Theory and Problems of Acoustics.* New York: McGraw-Hill.

SIMMONS, P. AND YOUNG, D. (1978). The tymbal mechanism and song patterns of the bladder cicada, *Cystosoma saundersii*. *J. exp. Biol.* **72**, 43–55.

YOUNG, D. (1990). Do cicadas radiate sound through their ear-drums? *J. exp. Biol.* **151**, 41–56.

YOUNG, D. AND JOSEPHSON, R. K. (1983*a*). Mechanisms of sound production and muscle contraction kinetics in cicadas. *J. comp. Physiol*. **152**A, 183–195.

YOUNG, D. AND JOSEPHSON, R. K. (1983*b*). Pure tone songs in cicadas with special reference to the genus *Magicicada*. *J. comp. Physiol*. **152**A, 197–207.