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Infrasound and the ear

Geoff Leventhall Acoustical Consultant Ashtead Surrey UK.

geoff@activenoise.co.uk

Summary

In an earlier critique of the Wind Turbine Syndrome, the author described how the abdomen was rich in sounds at infrasonic frequencies, originating in the heart beat, muscle contractions, fluid movements etc. (Leventhall 2009). This has now been extended to consider infrasound within the inner ear, infrasound which has also originated in normal body processes. The inner ear is connected through the cochlear aqueduct to the cerebrospinal fluid, which picks up pulsations from the heartbeat and breathing. Typical frequencies are: heartbeat ~I.0Hz and harmonics, breathing ~0.3Hz. Pulsations are transmitted to the inner ear fluid (perilymph) through the cochlear aqueduct at sufficient level to drive the ear in reverse, in a similar manner to otoacoustic emissions. Measurement of the resulting pressure in the occluded ear canal permits estimation of the deflection of the tympanic membrane due to the reverse transmission of internally generated infrasound. Earlier work on this, by others, is described and developed to estimate the external infrasound which would produce similar pressures in the inner ear to that produced by internal infrasound. The result is compared with the levels of infrasound from wind turbines in the same frequency range as the internally generated infrasound.

1 Hearing at low frequencies.

The pure tone hearing threshold has been measured in a chamber down to 4Hz (Watanabe and Møller 1990) and to lower frequencies using earphones (Yeowart and Evans 1974). The chamber data is shown in Fig 1, where it is compared with the ISO standard threshold (ISO:226 2003). The Watanabe and Møller threshold at 4Hz is 107dB. Yeowart and Evans give higher binaural thresholds: 112dB at 4Hz and 121dB at 2Hz.

The mechanism of hearing down into low frequencies is through normal excitation of the auditory cortex, as shown by fMRI investigations (Dommes, Bauknecht et al. 2009). Dommes, Bauknecht et al used functional Magnetic Resonance Imaging (fMRI) to investigate responses of the brain when exposed to infrasound both above and below the hearing threshold. Audible infrasound excited the auditory cortex,

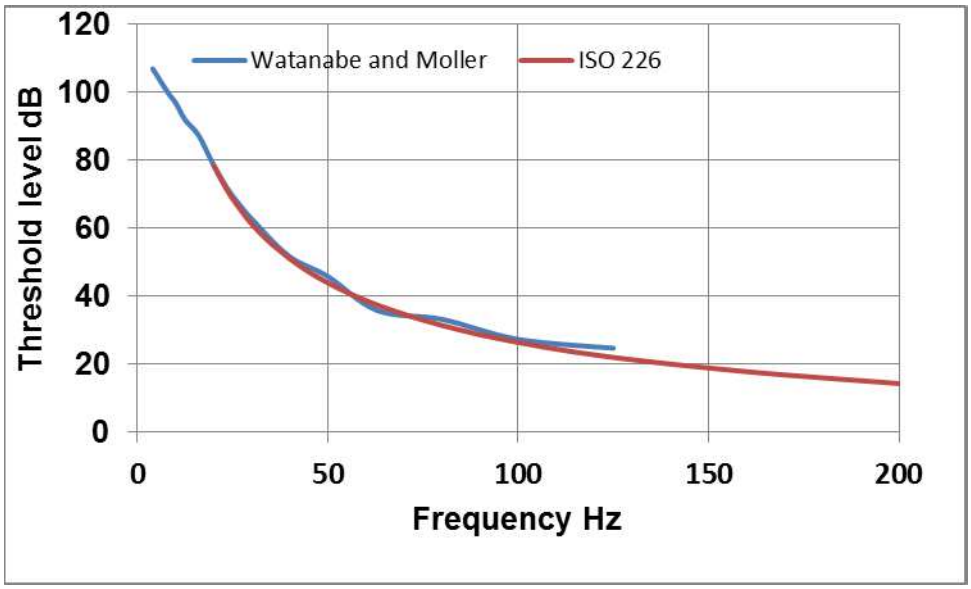

Fig 1 Low frequency hearing thresholds

which is where hearing perception occurs. Inaudible infrasound did not show an excitation. This is to be expected if infrasound enters into the hearing system, and is transmitted to the brain in a similar manner to higher frequency sounds. The following frequencies and levels were used by Dommes, Bauknecht et al.

Freq Hz	500	48	36	12	12	12
Level dB	105	100	70	120	110	90

They summarise the results of their work as:

> "In our study, no other cortical regions owed a comparably extensive response to the high-level stimuli as did the auditory cortex, indicating that LFT [low frequency tones] were mainly perceived via acoustic pathways instead of representing a somatosensory phenomenon."
>
> "In our study, cortical activation patterns appeared to be similar for all frequencies applied, suggesting that LFT are processed in a similar way as frequencies of our main hearing range (200 to 5000Hz)."
>
> "We presented the 12Hz stimuli at three different levels. Tone bursts of 120 and 110 dB resulted in cortical activation. The 90dB stimulus did not induce a significant response of the auditory cortex in group analysis which, in agreement with the findings of Møller and Pedersen (2004), indicates that this SPL is below the estimated perception threshold for 12 Hz." (Møller and Pedersen 2004)

This shows that low frequency tones and infrasound are perceived through the normal auditory pathways, the same pathways as for higher frequencies.

Furthermore, sounds, including infrasound, which are below the hearing threshold, do not produce a response in the auditory cortex, as is also the case for higher frequencies at levels below threshold. Whilst the lowest frequency used was 12Hz, the regular slope of the hearing threshold indicates that similar processes are likely to apply at lower frequencies.

2. The ear is a two way street

The ear is a mechanical system which operates in both forward and reverse directions. In normal, forward operation, sound waves excite the tympanic membrane (ear drum), which drives the ossicles to impart vibrations to the cochlear fluid (perilymph) via the oval window. (Fig 2) These vibrations propagate up and down the cochlea to the pressure release of the round window, causing waves along the basilar membrane, which excite the hair cells. These then send signals via the

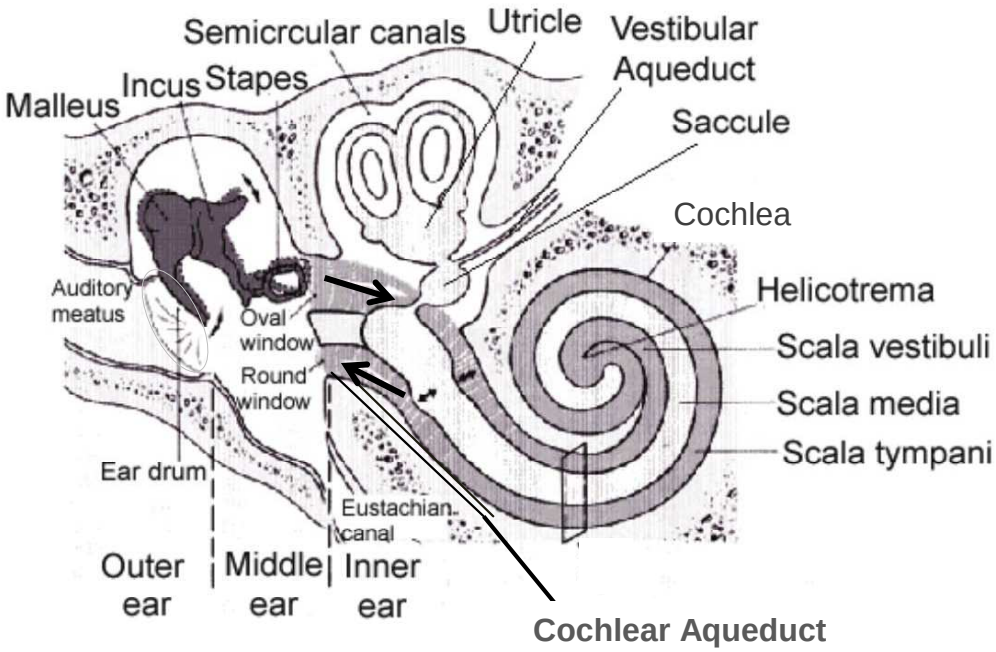

Fig 2 Action of the ear. Adapted From (Maroonroge, Emanuel et al. 2009)

auditory nerve to the auditory cortex, where they are interpreted as sound The system is mechanical up to the oval window and hydrodynamic within the cochlea.

Reverse action of the ear was demonstrated through otoacoustic emissions (OAE) in which “ringing” of the cochlear amplifier, which is based in the outer hair cells, sends vibrations back through the oval window and ossicles to excite the tympanic membrane (TM). Vibrations of the TM can be detected by a microphone in the ear canal (Kemp 2002).

Another example of reverse action of the ear is recent development of a hearing aid which by-passes the ossicles, and is useful for patients with conductive hearing loss. A small vibrator is attached to the round window and is energised from sounds detected externally. The vibrator sends signals in reverse direction through the cochlea, via the round window and, in this way, excites the basilar membrane and produces the correct perception of sounds. (Skarzynski, Olszewski et al. 2013).

In a simple device, for example a lever or a transformer, forward and reverse operation are reciprocal. This assumption will be made, initially, for forward and reverse ear operation of the tympanic membrane-ossicle-oval window system, but modified later.

3. Function of the cochlear aqueduct.

The cerebrospinal fluid originates mainly from the choroid plexus in the ventricles of the brain and bathes the brain and the spinal cord in the subarachnoid space, providing protection, lubrication and an egress for metabolic wastes. The fluid can be sampled by lumbar punctures. The cochlear aqueduct is a small duct which connects the subarachnoid space to the perilymphatic space of the inner ear, permitting bidirectional flow of cerebrospinal fluid and allowing pressure equalisation

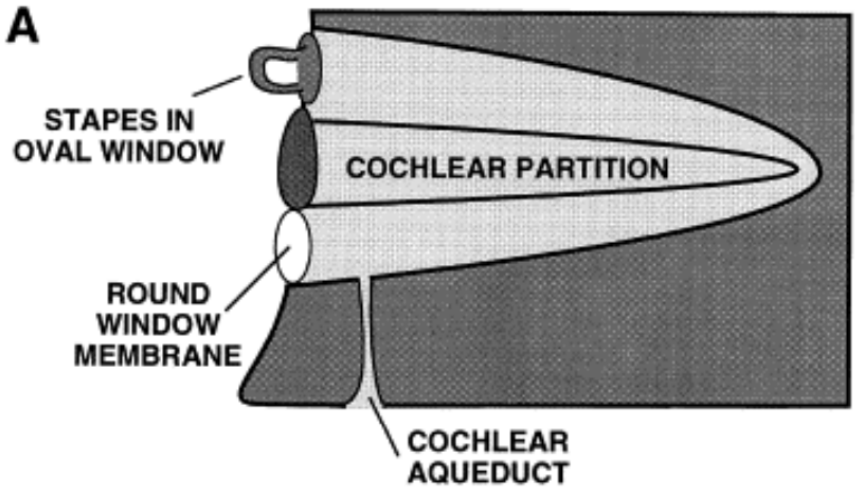

Fig 3 Illustrating the cochlear aqueduct (Gopen, Rosowski et al 1997)
The cochlear partition contains the basilar membrane

of the cochlea, Fig 3. The cochlear aqueduct offers a high resistance to high frequencies and there has been some discussion about its function, but it appears to pass low frequency fluctuations, originating in the cerebrospinal fluid, into the fluid of the inner ear (Traboulsi and Avon 2007). This effect is strong enough to drive the ear in reverse so that the infrasound generated by heartbeat and breathing, which enters the inner ear via the cochlear aqueduct, can be detected with a microphone in the ear canal.

Some properties of the cochlear aqueduct have been given by Gopen, Rosowski et al. (Gopen, Rosowski et al. 1997).There are normal biological variations in dimensions, but the following were used as an average for modelling.

Length = 10mm

Radius = 0.1mm

At low frequencies, the acoustical impedance of the cochlear aqueduct (Z_{CA}) is resistive with $R_{CA} \approx 2.5 \times 10^{11}$ acoustic ohms ($Pa.s.m^{-3}$).

Additionally:

Cochlear impedance: $Z_C \approx 70 \times 10^9$ acoustic ohms

Stapes impedance: $Z_S \approx -j(3.3 \times 10^{14}/\omega)$ i.e. stiffness controlled

Round window impedance: $Z_{RW} \approx Z_S/10$

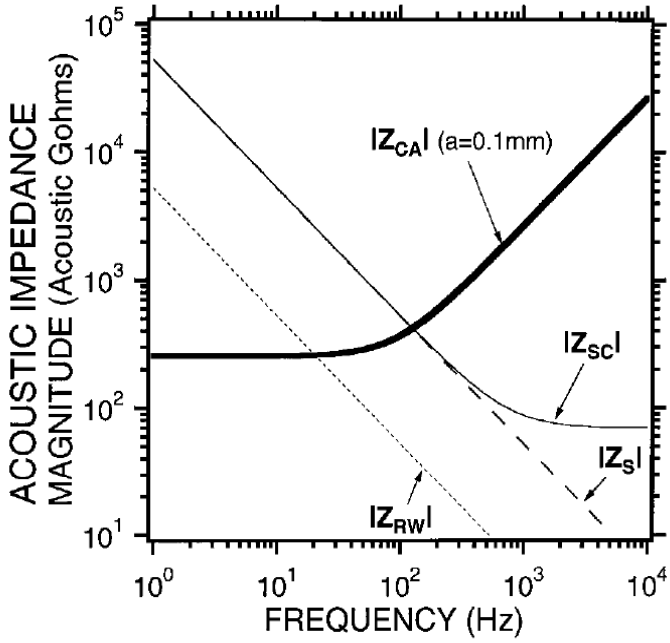

Fig 4 . Impedance magnitudes of cochlear aqueduct $|Z_{CA}|$, round window $|Z_{RW}|$, stapes and cochlear partition $|Z_{SC}|$, stapes alone, $|Z_S|$ from Gopen, Rosowski et al 1997

Fig 4 shows the magnitudes of these ear impedances. The cochlear aqueduct is resistive up to nearly 100Hz, after which the mass component of its contained fluid becomes increasingly significant. The stapes-cochlear partition and the round window are both stiffness controlled, with $|Z_{SC}|$ about 10 times the magnitude of $|Z_{RW}|$. Vibrations at low frequencies, passing through the cochlear aqueduct, see the impedances of the round window and the stapes-cochlear partition in parallel and, since $|Z_{SC}| >> |Z_{RW}|$, most of the flow goes to the round window. However, the remaining energy, which travels through the cochlea to the oval window, is sufficient to vibrate the ossicles and tympanic membrane.

4 Mechanism The cochlear aqueduct transmits pressure pulsations, which occur in the cerebrospinal fluid due to heartbeat and breathing, from this fluid to the inner ear fluid. Salt and Hullar suggested that the nearby round window acts as a pressure release to the pulsations into the inner ear from the adjacent aqueduct, so negating any effect of vibrations from the cerebrospinal fluid.(Salt and Hullar 2010). However, from above, Some of the incident energy travels backwards through the cochlea and stapes, exciting the tympanic membrane. Following on from Gopen,

Rosowski et al, Traboulsi and Avon considered the cochlear aqueduct to act as a low pass filter, with a corner frequency of about 20Hz, and detected pressure peaks in the inner ear (cochlea) at 0.2Hz from breathing and at 1Hz from heartbeat.(Traboulsi and Avon 2007). Recent work has measured the transfer function between pulsations occurring in the carotid artery in the neck and the consequent pressure detected in the ear canal, when it was occluded by a microphone (Furihata and Yamashiti 2013). The mechanism here is that the low frequency pulsations from heartbeat and breathing transfer to the cerebrospinal fluid, which transmits them to the inner ear via the cochlear aqueduct. The consequent pulsations in the inner ear drive the ossicles in reverse, as in otoacoustic emissions. Furihata and Yamashiti deduce the displacement of the tympanic membrane from the pressure measured in the 700mm^3 volume of the occluded ear canal.

The infrasonic pulsations which enter the inner ear via the cochlear aqueduct spread throughout the cochlea and activate the hair cells along the basilar membrane, in a similar manner to the operation of the vibratory hearing aid on the round window.

Spontaneous otoacoustic emissions (SOAE), which appear to be at single frequencies, actually show modulation sidebands under detailed analysis, the modulation being closely correlated with heart beat (Long and Talmage 1997). For example, a SOAE of 1658Hz had associated components at about 1657Hz and 1659Hz, both 15dB down on the central component. Long and Talmage suggested that the components may be due to changes in blood flow altering the mass of the basilar membrane, although other causes were also considered. This work illustrates the interaction between the inner ear and the beating heart.

5. Further Development. Consider the ossicles and associated membranes (tympanic membrane, oval window) as a bidirectional mechanical system. In normal hearing, the displacement of the tympanic membrane is transmitted through the ossicles to the oval window and into the cochlea. In the reverse process, the oval window is driven by internally generated pulsations of the cochlear fluid, leading to displacements of the ossicular chain and of the tympanic membrane. Initially, assume a simple transformer model in which the forward and reverse processes are balanced. That is, a forward gain of about 25dB and a reverse loss of the same magnitude occur. Then, if the tympanic membrane displacement which results from internally generated vibration of the oval window is known, an external sound, which produces the same displacement of the tympanic membrane, will lead to similar displacement of the oval window.

In order to make an estimate, it is necessary to know:

- The displacement of the tympanic membrane when driven by an internal source.
- The external airborne sound which also produces this displacement.

6. Magnitudes – Internal source Furihata and Yamashiti, measured the pressure due to tympanic membrane deflection in the known volume of the occluded ear canal. Levels were 95-98dB, leading to an estimate of tympanic membrane displacement of approximately 0.1µm. Analysis of the waveform, as detected in the ear canal, is shown in Fig **5** over a period of 600 seconds for frequencies below 5Hz.

There is a prominent 1Hz, from heartbeat, with 2Hz and 3Hz harmonics. Below 1Hz there are the frequencies from breathing and other internal sources. This energy has travelled back through the cochlea and ossicles to vibrate the tympanic membrane.

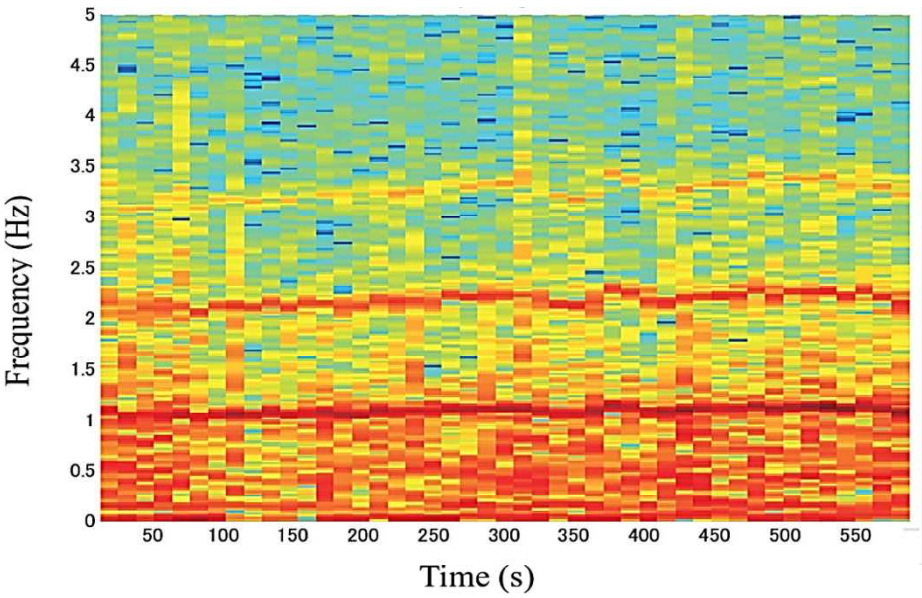

Fig 5 Spectrum of infrasonic pressure in the occluded ear canal

7. Magnitudes – External source. The displacement of the tympanic membrane by external sound sources has been measured by a number of authors, normally using optical methods of varying complexity.

- The displacement at low frequencies from an excitation of 60dB was about 1nm (Dalhoff, Turcanu et al. 2007).
- The displacement at low frequencies from an excitation of 80dB was 10-15nm (Huber, Schwab et al. 2001).
- Comparison of several measurements showed that the maximum displacement at low frequencies was from ≈ 2x 10^{-2} to 0.1µm per Pascal, as in Fig 6. (Rosowski, Cheng et al. 2011)

Fig 6, which shows deflections normalised to 1Pa, has an average deflection at low frequencies of approximately 5 x 10^{-2} µm /Pa, or 0.1µm at 2Pa (100dB).

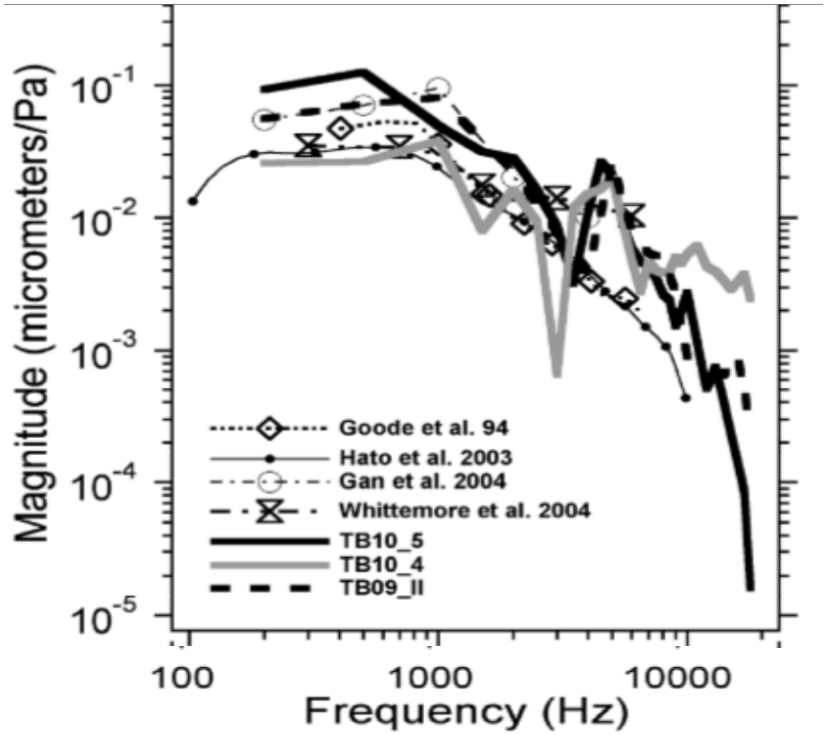

Fig 6 Tympanic membrane displacements. From Rosowski and Cheng

The different measurements described above are consistent, as 1nm = 0.001µm, 10nm = 0.01µm and a 20dB change in pressure level produces a ten times change in displacement. Therefore, 0.1µm displacement of the tympanic membrane can be associated with an external level of about 100dB.

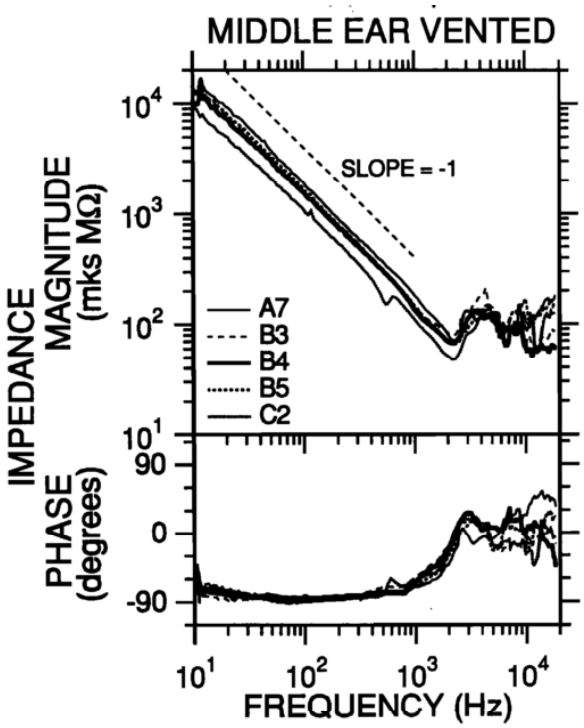

Fig 7 Gerbil middle ear input impedance

Although the tympanic membrane exhibits complex vibration patterns at high frequencies, it moves uniformly at low frequencies(Cheng, Hamade et al. 2013). Fig 6 indicates approximately constant displacement at low frequencies, which is expected from a resonant membrane below its natural frequency.

Human tympanic membrane studies have generally been limited to a low frequency of around 100Hz, but work on animals has used lower frequencies. For example, the gerbil tympanic membrane deflection has been investigated down to 10Hz. (Ravicz, Rosowski et al. 1992). Fig 7 shows frequency dependence of the live gerbil middle ear input impedance.

The impedance is inversely proportional to velocity, which leads to constant displacement for constant force.

Considering the similarities between all mammalian ears, the work on gerbils is a good indication that human ears will continue at constant displacement down to lower frequencies than shown in the measurements of Fig 6.

Therefore it is assumed that external infrasound at a level of 100dB will cause a tympanic membrane displacement of 0.1µm down to very low frequencies. This is similar to the value found for internal infrasound by Furihata and Yamashiti in Section 6 above.

8 Discussion The pressure fluctuations in the occluded ear canal, measured by Furihata and Yamashiti, were used to determine the changes of the small volume enclosed between the microphone and tympanic membrane, and hence the average displacement of the tympanic membrane. Factors which might affect the result include:

- Flexible walls of the ear canal
- Heat loss to the walls of the ear canal
- Pressure increase of the enclosed volume opposing the movement of the tympanic membrane
  .

These effects tend to reduce the pressure in the ear canal volume, so underestimating the tympanic membrane displacement from internal infrasonic sources.

Is the assumption of reciprocal forward and reverse action of the ear valid? It is known that the forward gain of the ear is about 25dB. The reverse gain is not as well known. The forward middle ear pressure gain is defined as

$\overrightarrow{M_1} = \frac{P_v}{P_{ec}}$ and the reverse gain as $\overleftarrow{M_2} = \frac{P_{ec}}{P_v}$

Where P_{ec} is the ear canal pressure and P_v is the vestibule pressure of the cochlear fluid. (Puria 2003)

Puria measured down to 100Hz on cadaver ears and showed that the gain varied with frequency. Forward gain peaked at 1kHz at about 20dB, but dropped and levelled off at low frequencies (100Hz). Reverse gain at 1kHz was about -30dB, showing an additional 10dB reverse loss. This means that the middle ear is not a reciprocal mechanical system, but has additional losses in the reverse direction, and the simplifying assumption made earlier must be corrected. At the lowest frequency given by Puria(100Hz), forward gain was -5dB and reverse gain -45dB, leading to a 40dB loss.

Cheng et al measured forward transmission in cadaver ears using a loudspeaker source and measured reverse transmission by direct mechanical stimulation of the

ossicular chain. (Cheng , Harrington et al. 2011). Results showed that "The ear canal pressure….. produced by TM motions evoked by reverse stimulation is usually 40 dB lower than the forward sound stimulus needed to produce similar stapes motion across most of measurement frequency range". Thus, in the expressions for M_1 and M_2 above, for equivalent values of $\boldsymbol{Pv}$ (pressure in the vestibule), the forward ear canal pressure $\boldsymbol{Pec_{(forward)}}$ is greater than the ear canal pressure received by reverse transmission $\boldsymbol{Pec_{(reverse)}}$.

Both Puria and Cheng worked with fresh cadaver ears. Live gerbils at higher frequencies showed a 20-25dB forward gain and a 35dB loss for reverse transmission. (Dong and Olson 2006)

Forward transmission ends at the compliant round window and the volume velocities of the oval window and round window are almost the same. In contrast, reverse transmission sees the relatively high impedance of the ossicles. The pressure difference across the scala in the cochlea is lower for reverse transmission than for forward transmission. (Steiger, Rosowski et al. 2013)

The work on forward and reverse transmission indicates that a direct comparison of the tympanic membrane displacements, as suggested in the simple reciprocal model, underestimates the level in the inner ear from internally generated infrasound. The underestimate is not well known, but could be 10- 20dB, or perhaps up to 40dB at low frequencies. Consequently, to allow for the reverse losses, the forward pressure in the ear canal, from external sources, should be increased by, say, 20dB. This requires a forward tympanic membrane displacement of 1.0 µm, which results from the ten times higher pressure, to give similar effect in the vestibule to that which gives a reverse tympanic membrane displacement of 0.1 µm. The forward tympanic membrane displacement will now correspond with an external sound of 120dB.

This is a greater level than the levels from wind farms in the same frequency region as that of the infrasound which is produced internally in the body. For example, the Shirley wind farm gave maximum of about 75dB at 0.3Hz. (Walker, Hessler et al. 2012). A number of other measurements indicate that, at typical nearby residential distances, the one- third octave level at 10Hz is 60~70dB, rising at ~ 5dB/octave into lower frequencies. (O'Neal, Hellweg et al. 2011) (Evans, Cooper et al. 2013) (Hayes 2006). More detailed analysis than one-third octave is required to show the components of the blade passage pulse.

Wind turbine infrasound levels are well below the hearing threshold of Fig1 and, following the work of Dommes, Bauknecht et al described earlier, will not excite the auditory cortex. There is also a large headroom for fluctuations.

The conclusion is that the continuous inner ear infrasound levels due to internal sources, which are in the same frequency range as wind turbine rotational frequencies, are higher than the levels produced in the inner ear by wind turbines, making it unlikely that the wind turbine noise will affect the vestibular systems, contrary to suggestions made following the measurements at Shirley. The masking effect is similar to that in the abdomen (Leventhall 2009). The body, and vestibular systems, appear to be built to avoid disturbance from the high levels of infrasound which are produced internally from the heartbeat and other processes. In fact, the

hearing mechanisms and the balance mechanisms, although in close proximity, have developed to minimise interaction. (Carey and Amin 2006)

Appendix

Professor Peter Seligman, an expert in cochlear implants, stated in his submission to the 2011 Australian Federal Senate inquiry into the 'Social and economic impact of rural wind farms':

> *"Aside from the issue of an adverse response to something which cannot be measured, it is worth noting that apart from external sources, the hearing and vestibular systems are subjected to very high levels of body generated noise. These include, walking, breathing, heartbeat, chewing and head movement. Body noises generated in this way were a problem in the Cochlear Ltd project to develop a fully implantable cochlear implant. In this case the microphone was implanted subcutaneously behind the ear. The level of infrasound picked up from the body by this microphone was a major problem and far exceeded all infrasound from external sources. In fact it was some ten times greater".* (Seligman 2011)

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