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THE SAFETY ISSUES OF INTENSE AIRBORNE ULTRASOUND: PARAMETRIC ARRAY LOUDSPEAKER

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Abstract

It is usually convened that industrial noise involves human-audible sounds from machineries especially those that are generated at high decibels. However, nowadays, new ultrasonic applications have seen much widespread prevalence in some electrical appliances; ultrasonic toothbrushes, ultrasonic contact lens cleansers, car parking sensors and medical sonar-devices. Although the present diminutive occupational and domestic ultrasonic devices do not overly emit intense airborne ultrasounds, they could signify a starting trend of newer and more powerful ultrasonic radiating devices to come. Particularly, one example is the growing application of an innovative speaker; parametric array loudspeaker (PAL). The PAL is a unique loudspeaker in the sense that it emits finite-amplitude ultrasounds (~60kHz, ~130dB) so as to exploit their nonlinear interaction in the atmospheric air, hence producing a highly directional insonified column of audible sound. The characteristics of the PAL in unbounded medium are discussed since its operation is closely related to the propagation of ultrasound in air. Presently, most applications concerning PAL thus far utilize its far-field region for directional audio listening purposes. Hence, safety issues regarding intense airborne ultrasonic waves impinging human become imperative. Although human exposure of intense ultrasound can be a subjective matter, many past research in this non-ionising radiation have hinted indicative evidences to suggest potentially real undesirable effects, both auditory and bodily. These can be ascertained by some primary dosimetrics, namely sound pressure level of the ultrasound, frequency of the ultrasound and the lesser-elaborated ultrasound exposure duration. It is intended to provide an account of existing global guidelines and standards on the airborne ultrasound exposure limits in order to indicate their safety relevance governing the PAL. Finally, a brief review on the status of airborne ultrasound on human beings in Japan is discussed.

INTRODUCTION

Airborne ultrasound is defined as the mechanical vibrations propagated at frequencies above human audibility, usually >20kHz. However, the upper limit of human hearing can occasionally be ambiguous as higher hearing annex of up to 24kHz [1] was also reported. Adding to the quandary, some literature even refers high human-audible frequencies as ultrasounds [2]. There is a distinction between airborne ultrasound, conduction ultrasound and ultrasound that propagates through other interfacing media other than air. In this paper, the term ultrasound applies to continuous wave mode, intense airborne ultrasound only.

The following section will discuss the variety of ultrasonic equipment found in domestic, medical and industrial equipment. Particularly, a unique loudspeaker, which utilises intense ultrasounds, will be focused. A concise outlook on the dosimetrics of ultrasonic exposure regulating standards will be briefly discussed followed by some recent developments of ultrasound in Japan. Lastly, the bioeffects of ultrasonic on humans are presented.

A PLETHORA OF AIRBORNE ULTRASONIC DEVICES

Since the 1960s, the advent of relatively powerful ultrasonic devices has increased the dosage of ultrasound exposure on humans living in the urban area [3]. Some of these devices emit intense ultrasounds without the knowledge of the members of general population since they cannot be heard at all. Occupational ultrasound exposures also pose a greater risk than never before due to more powerful equipment. It is astonishing to find that, to date, there is a lack of reports on noise pollution arising from pure intense ultrasonic source in general.

Generally, ultrasonic devices can be categorised as domestic, medical and industrial. Occupational ultrasonic equipment exposes its users on a prolonged basis at higher intensities, whereas domestic devices are more intermittent/infrequent and weaker in power. Most commercial ultrasonic devices have frequencies ranged between 20kHz-300kHz at 125 dB, 1m from source [4], whereas occupational ultrasonic equipment are usually higher powered ranging from 20kHz-1MHz of varied large intensities [5]. Some recent domestic and occupational devices accounted include the superaudio CD (SACD) and DVD-audio [6], video displays [7] and in the urban area, electrical arcing of high-frequency inverters switching action found in transformers indirectly emit ultrasounds [4],[8]. Some of the devices' primary designs are not to radiate airborne ultrasounds but indirectly emit stray intense ultrasounds during operation. Examples are siren and jet engines [8], aerodynamic noise [9], and ultrasonic tissue-cutting knives. It should be noted that most of these noises do not solely consist of pure ultrasonic tones but broadband noises.

From this plethora of ultrasonic devices, an imminent commercial audio sound device, known as the parametric array loudspeaker (PAL) which emits intense ultrasounds, will be discussed further in the next section.

THE PARAMETRIC ARRAY LOUDSPEAKER

The complete historical origin and theory of the parametric array can be referred to the well-documented literature [10]. In the simple sense, PAL exploits the nonlinearity interaction of two closely-spaced ultrasounds in air, so as to produce a highly directional insonified column of audible sound. Following the derivations appeared in earlier work [11], consider in 3-dimensional axes where only the axis of propagation x is of interest and the remaining two has negligible contribution to its propagation. Using the equation of continuity, the conservation of momentum and the adiabatic equation of state, it can be shown that sound waves propagation is basically described to be theoretically nonlinear. However, for a well-collimated intense ultrasound, the mathematical model for the parametric array has to account for additional dissipation and diffraction effects that are all significantly manifested during propagation. Therefore, this leads to a more generalized and widely accepted Khokhlov-Zabolotskaya-Kuznetsov (KZK) equation given as [12]

$$\frac{\partial^2 p}{\partial x \partial \tau} - \frac{\beta_2}{2\rho c^3}\frac{\partial^2 p^2}{\partial \tau^2} - \frac{\delta}{2c^3}\frac{\partial^3 p}{\partial \tau^3} = \frac{c}{2}\Delta_\perp^2 p \qquad (1)$$

where p, ρ, β_2, $\tau = t - x/c$, c, δ are the fluid pressure, particle density, coefficient of 2nd-order acoustic nonlinearity, time delay, speed of sound and sound diffusivity respectively.

Now, ultrasound decays rapidly away from the source as air absorbs 99.9% of the energy [2]. The absorption coefficient α is susceptible to atmospheric compositions, temperature and propagating frequency f, which is given by [13]

$$\alpha = \frac{f^2}{p_0}\left[1.84\times10^{-11}\mathrm{T}^{\frac{1}{2}} + \mathrm{T}^{-\frac{5}{2}}\left(0.01275\frac{e^{-2239.1/T_{air}}}{F_{r,O} + f^2/p_0^2 F_{r,O}} + 0.1068\frac{e^{-3352/T_{air}}}{F_{r,N} + f^2/p_0^2 F_{r,N}}\right)\right] \qquad (2)$$

where $F_{r,O} = \left(24 + 4.04\times10^4 h\frac{0.02+h}{0.391+h}\right)$, $F_{r,N} = \left(\mathrm{T}^{-1/2}\right)\left(9 + 280he^{4.17\left(\mathrm{T}^{-1/3}-1\right)}\right)$ and $\mathrm{T}=T_{air}/T_0$, are the relaxation frequencies for oxygen and nitrogen and ratio of air temperature to reference temperature (293.15K) respectively. The absolute humidity $h=h_r(p_{sat}/p_0)$, where h_r and p_{sat} are the relative humidity and saturation vapour pressure respectively. Ultrasonic pressure level (UPL) is described as strong only near to the source. Commercially available PAL comes with a delimiting UPL as a safety measure.

Another impediment to airborne ultrasound intensity is the acoustic saturation, $p_{acoustic\_sat}$. The SPL in the far-field based on the weak shock theory is limited by [11]

$$p_{acoustic\_sat} = \frac{\rho_0 c_0^3}{2\beta f x} \qquad (3)$$

where β=1/2(γ+1), ρ_0, c_0, f, x, are the coefficient of nonlinearity, ambient density (kg/m^3), small-signal sound speed (m/s), frequency (Hz), and axial distance from the ultrasonic source respectively. Increasing the ultrasonic frequency will render a lower $p_{acoustic\_sat}$ value and any further increase of input power will be loss as spurious heat.

DOSIMETRICS OF AIRBORNE ULTRASOUND

The 1960s literature had led to some preliminary recommendations based upon a few limited experimental assessments. These were subsequently and openly adopted by national and international organisations with sufficient recitations over time to gain an authoritative footing, although somewhat imprudently since there is a dearth of meticulous and concrete reference materials. Table 1 tabulates the ceiling values as recommended by national, international, organisational research groups and individuals. It can be seen that at 20kHz, the ambiguous upper hearing limit has quite different criteria.

Table 1: Selected ultrasound exposure standards at 1/3 octave-bands.

Countries/Organisations/ Individuals	Frequency at 1/3 octave bands (kHz)							
	20	25	31.5	40	50	63	80	100
Grigor'eva (1966)	120	120	120	120	120			
Parrack (1966)	105	110	115	115	115			
*USSR (1975)	110	110	110	110	110	110	110	110
Acton (1975)	75	110	110	110				
*Canada (1980)	80	110	110	110	110	110		
*IRPA (1984)	75	110	110	110	110	110	110	110
Health Canada (1991)	75	110	110	110	110			
Sweden (1992) [14]	105	115	115	115	115	115	115	115
Poland (2001) [15]	110	125	130	130				
*ACGIH (2004) [16]	105	140	145	145	145	145	145	145
Japan (2005) [17]	110	110	110	110	110			

* Recommended standard for a notional working day exposure (4-8 hours/day for 5 days each week).

Due to space constraint, only references that cannot be found in [18] are hence referenced. It is noteworthy to find that ACGIH suggested an unusually excessive 30dB as compared to their previous recommendation. The motivation behind ACGIH's recommendation has been explicated as to "represent conditions under which it is believed that nearly all workers may be repeatedly exposed without adverse effect on their ability to hear and understand normal speech." [15]. Lenhardt reasoned that "this was not based on risks associated with the ultrasound itself (which they deemed to be harmless), but on the risks associated with subharmonics usually present when using industrial ultrasonic equipment" [19]. However, Lawton believes that the change is linked to Parrack's report [8] where "ultrasonic tones at slightly higher levels were shown to produce TTS which recovered within a relatively short time post-exposure." [20]. Although the present regulations on airborne ultrasound are different in each country, it appears that in recent years, ultrasonic exposure criteria have increased steadily, probably because of a better acquired understanding towards ultrasound exposure.

Another common dosimeter used to quantify ultrasound is the exposure duration. For exposure time <4hrs, various standards allow the UPL to be corrected as in Table 2.

Table 2: Recommended ultrasound intensity correction at different time exposure.

	Ultrasonic SPL (dB) correction for <4 hours exposure						
Countries	0min	1min	5min	15min	1 hr	2 hr	4 hr
USSR (1975)		+24	+18	+12	+6		
Sweden (1978)	+9				+3		
IRPA (1981)	+9				+6	+3	
Poland (2001)	+27	+20	+15	+9	+6	+3	

It is, however, observed that exposure time regulation follows a somewhat -3dB abatement rule similar to audible sound criteria even though there are no evidence to suggest that <140dB ultrasound produces temporary threshold shift (TTS) as compared to its audible compatriots. Notwithstanding, it is suggested that perhaps exposure correction should be amendable based on other readily observable bioeffects such as heating or even cavitation.

Airborne Ultrasound In Japan

In the 1970s, the Japan Society of Obstetrics and Gynaecology formed a Committee on Biomedical Engineering exploring the bioeffects of ultrasound. The Japan Industrial Standard (JIS) and Japan Society of Ultrasound in Medicine (JSUM) subsequently adopted their recommendations. However, most of the pioneering work are geared toward ultrasonic diagnostic equipment [21]. Standards on airborne ultrasound impinging on humans have not received much attention due to the sporadic prevalence of ultrasonic devices and lack of reports on significant ultrasonic noise pollution or health damages in Japan for the past few decades. Recently, ultrasonic devices have seen much prevalence and the National Institute of Advanced Industrial Science and Technology (AIST) is recognising its importance [22]. Initial work is largely based on providing acoustics standards on ultrasound measurements and cooperation with the medical and industrial fields will be established so as to study airborne ultrasound.

In the 1980s, a Japanese research team did some ground work on PAL [23]. Their concern on the safety aspect of the PAL on human auditory was not referred to any standing national/international standards at that time. However, they did suggested that increasing the ultrasonic frequency will result in higher absorption coefficient which lowers the UPL and hence safer to humans [23]. From Equation 1, the actual energy loss will be greater because of nonlinearity, dissipation and diffraction in the PAL propagation.

The Japanese regulations on airborne ultrasound were recently pronounced by the Japan Industrial Safety and Health Association (JISHA), although concrete exposure limits can be found in JIS C1010-1 [17]. Under the Japanese Enforcement Regulation of the Labour Standards Law (Article 35), worker's accident compensation covers the necroses of human tissue caused by ultrasonic means. The Industrial Safety and Health Law (Article 22, No.2) enforces employer to take necessary measures to prevent health impairments due to ultrasound. Hence, the question of legal compensation from inimical intense ultrasound exposure cannot be underestimated.

BIOEFFECTS OF INTENSE ULTRASOUND ON HUMAN

The physiological effects of intense ultrasound have been well documented including TTS, excessive fatigue, nausea, loss of equilibrium and tinnitus. These symptoms are somewhat constitutional due to different degrees of exposure, susceptibility and recovery threshold of humans. Acton attributed those subjective effects to be likely caused by cavitation or spurious high-frequency audible noise [24], since it is known that many ultrasonic devices generate spurious subharmonics [25].

Perhaps the most deliberating literature dealing with intense ultrasound of the PAL can be found in an ad hoc report commissioned to investigate PAL's bioeffects [19]. Experiments were conducted on 20 subjects exposed to 58kHz of 121dB ultrasounds, demodulated at 2kHz at 80dB for 5mins at 1m. They concluded no statistically significant TTS or permanent threshold shift (PTS). Pompei notably reported that subjective effects and even substantial auditory pain was experienced at a lower ultrasonic frequency (30-40kHz) as in all early versions of PAL. He believes that the listening risk of PAL operating at 50-70kHz is as harmless as conventional loudspeakers. He further suggested that any thermal heating of PAL would probably diminish at higher ultrasonic carrier frequencies. This appears to oppose another researcher's emphasis that the intensity scale is more important than the ultrasonic frequency scale when considering the hazards of ultrasound [9]. The physiological effects of ultrasound are depicted in Figure 1.

It has to be stressed that any physiological effects are unlikely with most of the modern ultrasonic equipment as they are rarely >140dB [26]. Moreover, reports on mild skin warming [24] did not consider efficient blood circulation (perfusion) which will repress localized heating [27], and convective heat dissipation as well. Besides, the ultrasonic beam intensity is distributed nonuniformly over the insonified area and exposed tissue properties vary across the surface. Also, human skin reflects ultrasounds well and the absorption coefficient decreases rapidly as the ultrasonic frequency increases [8].

Considering most international standards, which effectively were based on past reports on ultrasonic bioeffects, it is not clear why adjunct intensity limits near 140dB was not adopted since many literature evidently pointed no TTS for <140dB. Based on the extensive documentation produced thus far, it is hence suggested that the unique nature of sound production by PAL should not produce any significant physiological effects if operated between 50-70kHz at ≤137dB (with a safety factor of 3dB to limit the threshold of skin clefts heating [24]). This recommendation is also aligned closely to proposals made by Lenhardt [19] and Health Canada [28].

UPL (dB)	
180	Death (projected) (20kHz, 40mins)
	Loss of equilibrium (20kHz, 160-165dB)
160	Dizziness (20kHz, 160-165dB)
	Mild skin warming (159dB, 20-30kHz)
	Mild fever body warming (155dB)
	TTS (20-37kHz, 148-154dB, 5mins)
	Mild heating (skin clefts) (140-150dB)
140	No TTS
120	No physiological effects (20kHz, 110-115dB, 1hr)
100	Most occupational exposure, <120dB
	No hearing loss

References to the above assertions can be found in [28].

Figure 1 – Physiological effects of airborne ultrasound on humans

CONCLUSIONS

This paper effectively raises the awareness of using PAL as a practical audio device while maintaining its dosimetrics under the level of any known physiological disorders. It is endeavoured to dispel injudicious attributions of unconfirmed, uncontrolled or inadequately established publications on the bioeffects of intense ultrasound so that they do not built upon unnecessary apprehensions which will arrest the development of useful technologies in the future. For the unique sound production of PAL, it is recommended that a strict observance of 50-70kHz at ≤137dB in the insonified field should be abided. In addition, critical assessments interpreting the grounds of human disorders has to consider less subjective constitutional elements such as any pathological history, age of individuals, and even race and gender.

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