ACOUSTIC LIMITING IN HEADSET SYSTEMS

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1 INTRODUCTION

This paper begins with a brief review of European acoustic limiting legislation, and then goes on to discuss how the prescribed limits are implemented in current headset systems. The primary acoustic protection is provided by limiting devices that are integrated into the headset itself. The operation of these devices is described in detail. Other signal processing can enhance the headset user's comfort, and some of the available techniques are discussed. Finally, the time-weighted average workplace noise exposure of headset wearers is considered. This is affected by factors beyond the sphere of influence of currently available headset systems, so demands a wider ranging strategy for monitoring and control.

2 EUROPEAN LEGISLATION FOR ACOUSTIC LIMITING

2.1 Continuous and Peak Limits

In Europe the legislation governing continuous and peak noise exposure is the general product safety directive [1] (GPSD), and the low voltage directive [2] (LVD). These directives state that products shall not endanger safety when properly installed and maintained and used in applications for which they were made, but they do not give any specific acoustic limits. Guidance on applicable limits can be found in various product-specific standards and in the national legislation and guidelines that pre-date the introduction of the European directives. In the absence of specific legislation governing acoustic limiting for headsets, manufacturers may use these documents to justify their declarations of compliance with the product safety and low voltage directives.

One of the relevant standards is TBR8 [3]. Annex C specifies continuous and peak noise exposure limits for telephone terminals, and states that in the absence of any relevant safety standard, a supplier's self-declaration may be based on them. These limits, summarised below, are equally applicable to telephony headsets.

- For continuous signals, the sound pressure level in the artificial ear should not exceed 24 dBPa (rms unweighted).
- Peak signal level in the artificial ear should not exceed 36 dBPa.

The limits are for sound pressure levels measured in an ITU-T Recommendation P.57 [4], type 1 artificial ear, which measures sound levels referred to the Ear Reference Point (ERP). Measurements using an ITU-T recommendation P.58 [5] head and torso simulator (HATS) more closely simulate real-life usage for most lightweight headsets. HATS is a life-size manikin fitted with artificial ears that provides an acoustic model of a "typical" adult human. It uses P.57 type 3.3 artificial ears, which measure sound level referred to the Eardrum Reference Point (DRP). A standard DRP to ERP correction factor is applied to measurements made on HATS when comparing them to the TBR8 limits.

Other UK documents that provide useful guidance on headset acoustic limiting requirements and test procedures are DTI 85-013 [6] and BS6317 [7]. They also specify a continuous sound pressure level limit of 24 dBPa.

2.2 Time-Weighted Average Exposure Limits

The current European legislation on workplace noise exposure is the Noise at Work Directive [8]. However new legislation, the Physical Agents (Noise) Directive [9], will be incorporated into law in EU member states on or before 15 February 2006.

These directives specify certain action levels, each with a limit on both continuous and peak sound level. If a telephony headset complies with the GPSD and LVD, as described in section 2.1, it will automatically satisfy the peak limits specified in the Noise at Work and Physical Agents (Noise) Directives. In the GPSD and LVD, continuous sound pressure level is measured over short time periods only. However, in the context of workplace noise exposure legislation, continuous noise exposure is a time-weighted average (TWA) measurement, normalized to a standard 8-hour working day. The TWA calculation method is defined in the Noise at Work Directive. The two action levels defined in the Noise at Work Directive are shown in table 1.

Table 1: Maximum sound levels defined in the noise at work directive

	Continuous sound exposure maximum limit	Peak sound pressure level maximum limit
Lower action level	85 dB(A)	200 Pa
Higher action level	90 dB(A)	200 Pa

The physical agents (noise) directive defines two action levels, which are 5dB lower than the action levels in the noise at work directive. It also defines limit values that may not be exceeded under any circumstances. These are shown in table 2.

Table 2: Maximum sound levels defined in the physical agents (noise) directive

	Continuous sound exposure maximum limit	Peak sound pressure level maximum limit
Lower action level	80 dB(A)	112 Pa (135 dB(C))
Higher action level	85 dB(A)	140 Pa (137 dB(C))

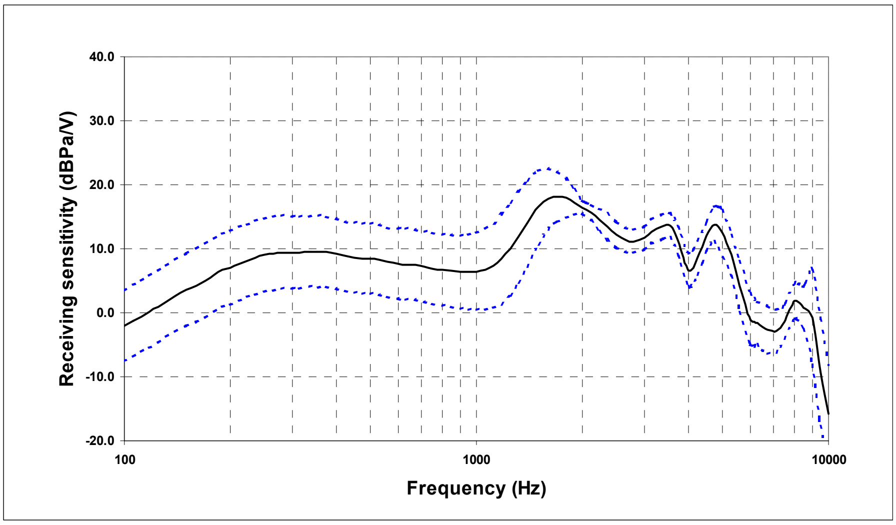
Limit values	87 dB(A)	200 Pa (140 dB(C))

The measures that must be taken when the lower action limit is exceeded include making ear defenders available to workers. Clearly this is impractical for headset users, so headset noise exposure levels must be kept below the lower action level.

3 HEADSET RECEIVING CHARACTERISTICS

Figure 1 is the receiving frequency response of a typical headset. The solid line is the average frequency response for this headset model. The dotted lines are the bounds of the 99% confidence interval, which describes the range of manufacturing tolerance. The transmission bandwidth for normal narrowband telephony is 300 Hz to 3.4 kHz, so this is the region of greatest interest. Details of the frequency response and their implications for acoustic limiting are discussed further in section 5.

Figure 1: Typical receiving frequency response of a telephony headset. (Mean response and 99% confidence limits)



4 HEADSET SYSTEM ACOUSTIC LIMITING STRATEGIES

Wireline telephones, whether analogue, digital or VOIP, are affected by high intensity voltage transients that occur on the telephone or data network. These can cause audible noise spikes. Fax and DTMF tones, acoustic feedback or network faults can generate loud sounds of longer duration. Malicious callers may also make loud noises deliberately. Therefore acoustic limiting devices are required to ensure that the statutory requirements for acoustic protection are satisfied. Although acoustic limiting devices could be fitted either in the telephone, the headset, or a headset adapter unit, they are usually incorporated into the headset itself. This ensures consistent limiting performance when the headset is used with a range of different telephones and accessories. Indeed, for this very reason, DTI 85/013 [6] requires headsets to contain intrinsic acoustic shock protection, and not depend solely on protection circuitry within the associated telephone or PBX operator console. Most reputable manufacturers of headsets for office and call-centre applications use in-headset acoustic limiting devices as the primary protection against excessive sound levels. Section 5 explains the range of devices used and their principles of operation.

Mobile and cordless telephone handsets are not subject to the high amplitude line-transients that can occur on wireline-connected telephones. Therefore they can adopt a simpler acoustic limiting strategy, relying on the limited voltage drive capability of the codec and power amplifier that drive the transducer. For example consider a telephone receiver with the same frequency response as the headset shown in figure 1. The maximum sensitivity (upper 99% confidence interval) is 23 dBPa/V. Therefore the receiver cannot generate sound levels in excess of 24 dBPa if the drive voltage is limited to 1 dBV rms or less. This limiting strategy is acceptable for a telephone's built-in receiver, since the manufacturer can select a transducer with appropriate sensitivity to match the power amplifier circuitry. However most headset manufacturers also use this limiting strategy for mobile and cordless telephone headsets. Its advantage is low cost, but the disadvantage is that, unlike the telephone's built-in receiver, a headset may be used with many different telephone models. This results in inconsistent acoustic limiting, and in some cases the statutory requirements for acoustic shock protection may not be met.

The statutory acoustic limiting threshold of 24 dBPa is significantly louder than typical telephone listening levels. Therefore limiting at a lower threshold, or implementing advanced signal processing, can enhance comfort. Some of these signal processing techniques are described in section 6. Adapters that include such processing are available for connection between a telephone and headset.

5 IN-HEADSET ACOUSTIC LIMITING

Several types of acoustic limiting device can be built into headsets, although they all use the same basic principle. They limit the electrical signal that drives the headset transducer, which in turn limits the sound level generated. In general there is no power source available in a headset other than the transducer drive signal, so in-headset acoustic limiters are either passive devices or very low power active circuits.

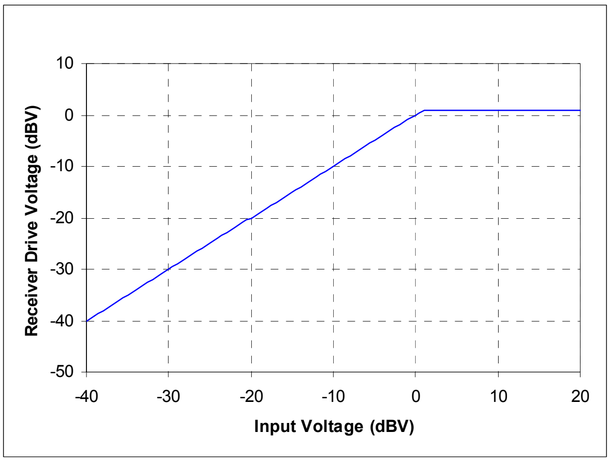
The electrical limits and the resulting acoustic limits are related by the headset's receiving sensitivity. Figure 1 shows the receiving sensitivity versus frequency for a particular headset model. The two most important features are that the average receiving sensitivity varies by more than 10dB over the frequency range 300 Hz to 3.4 kHz, and that the manufacturing tolerance of receiving sensitivity is up to ±6 dB at many frequencies. Therefore fixed voltage limiting results in acoustic limits that vary by more than 10 dB, depending on the signal frequency. Also the acoustic limiting levels vary ±6 dB between different headsets of the same model, due to manufacturing tolerances. These are the main factors that determine the achievable accuracy of headset acoustic limiting.

Figure 1 is derived from measurements on HATS, which is a good but not perfect model of real headset usage. Human headset wearers are likely to experience greater variations in sensitivity than those shown on figure 1. This is because leakage at the headset-to-ear seal influences the receiving sensitivity. The leakage depends on the wearer's ear shape, the headset wearing style and size adjustment, and on the type (foam, leatherette, etc) and state of repair of the ear pad. Leakage predominantly causes a reduction of receiving sensitivity at low frequencies. Headsets with high acoustic impedance are affected more than low acoustic impedance headsets.

The required limiting voltage is defined by the receiver characteristics. For the headset of figure 1, the maximum sensitivity (99% confidence interval) is 23 dBPa/V. Therefore the voltage applied to the receiver must be limited to 1 dBV rms or less to limit the sound level to a maximum of 24 dBPa.

Figure 2 is the transfer function of the ideal limiting device. Output voltage rises linearly with increasing input voltage until the output reaches 1 dBV. The output voltage then remains at this level as the input continues to increase.

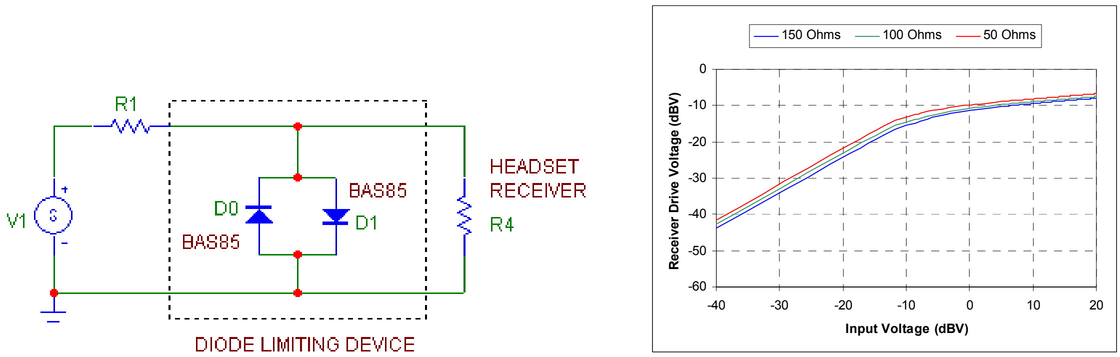
Figure 2: Output vs. input transfer function of an ideal limiting circuit.



Telephones and headset adapters typically drive the headset from a source impedance in the range 50 to 600Ω, although a few have higher or lower impedances. The acoustic limiting device is connected in parallel with the headset receiver. It has a non-linear current vs. voltage characteristic, such that its impedance changes from high to low when the limiting threshold voltage is exceeded. The limiting device works in conjunction with the telephone's source impedance to limit the drive voltage applied across the receiver's terminals.

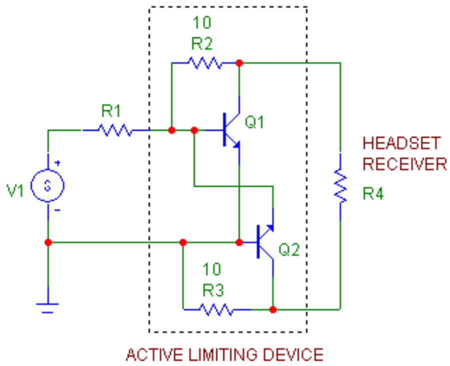
Figure 3 shows the circuit configuration for three different types of limiting device: diodes (a), an active limiting circuit (b) and varistor (c). SPICE simulations of these circuits' transfer functions (Vout vs. Vin) are also shown, for source impedances of 50, 100 and 150 Ω. Practical implementations use extra components to "fine-tune" the limiting levels and the shape of the transfer functions to suit particular receiver transducers. However the simplified circuits of figure 3 illustrate the main features of each type of limiter.

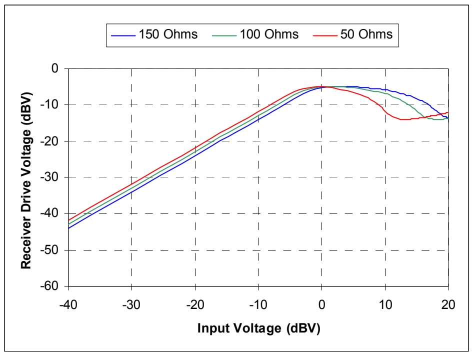
Figure 3(a): Diode limiting circuit, and its voltage transfer function



The diode limiter of figure 3(a) approximates to the ideal limiter characteristics, and can be implemented at low cost. Schottky, silicon, and zener diodes are available with different forward "knee" voltages, so can be used as limiting devices for receivers with different sensitivities. However the diode limiter has two disadvantages. The transition from non-limiting to limiting regions is slow, which causes audible harmonic distortion of signals below the limiting threshold. Also the clamping that occurs in the limiting region is imperfect, so the output continues to rise slowly with further increases in input voltage. Limiting also depends on the source impedance.

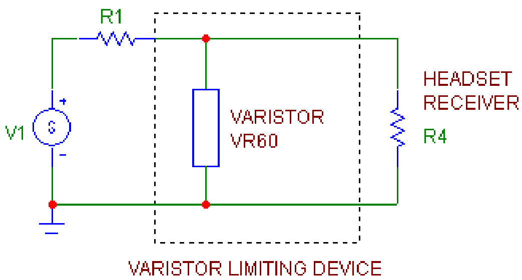
Figure 3(b): Active limiting circuit, and its voltage transfer function

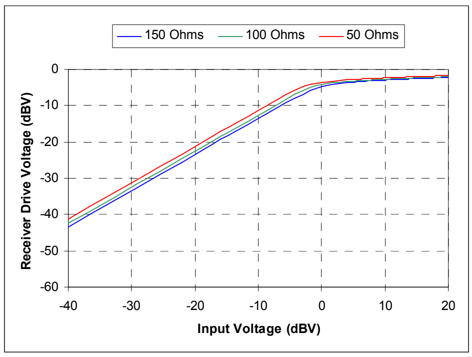




The active clamping circuit of figure 3(b) may either be implemented as a discrete transistor circuit or as an integrated circuit. It has a faster transition from non-limiting to limiting than the diode circuit, so causes less distortion for signals below the limiting threshold. When the input voltage exceeds the threshold, the output voltage “folds-back” to a lower voltage. The highest output voltage is at the point where the transition from non-limiting to limiting occurs. At that point there is very little variation of output voltage with source impedance, although it varies significantly at higher input voltages.

Figure 3(c): Varistor limiting circuit, and its voltage transfer function





The varistor limiter shown in figure 3(c) is similar to the diode circuit, but has a faster transition from non-limiting to limiting region and exhibits harder clamping in the limiting region. Varistors are available with a range of clamping voltages to suit different receiver sensitivities.

Receiving sensitivity varies slightly with amplitude as well as with frequency, and the onset of limiting generates a series of harmonics at multiples of the input frequency. It is therefore essential to verify the performance of limiting devices by directly measuring sound pressure level with a wide range of input conditions, and not just rely on performance predictions from frequency response measurements like figure 1. Frequency should be varied in 1/3-octave or closer steps. Input voltage should also be varied because, as Figure 3(b) illustrates, the maximum output voltage does not always occur at the maximum input voltage. BS6317 [7] specifies a test voltage of 24 dBV rms from a source impedance of 600 Ω, applied at the telephone line interface, for acoustic shock tests on analogue telephone terminals. It is appropriate to test headsets with a lower maximum voltage (15dBV) and lower source impedance (150 Ω) to more closely represent the electrical signal at a typical telephone headset or handset port.

6 ADVANCED ACOUSTIC LIMITING TECHNIQUES

The acoustic limiting devices described in section 5 simply clip the headset drive signal when it exceeds a certain voltage. They limit almost instantaneously, but at an uncomfortably high sound level. They also cause severe distortion when they start limiting. They should be regarded in the same way as electrical fuses – a reassuring last line of defence, but ideally one that will never be used. It is better to prevent the sound level ever reaching the 24 dBPa limiting threshold. However simply restricting the maximum volume setting is not the answer - received speech must be loud enough to hear above normal call-centre and office background noise. Sections 6.1 to 6.3 examine some of the signal processing techniques that make this possible. Such processing cannot be integrated into a headset that has no power source available. It is usually implemented in headset adapters that connect between the telephone and headset.

6.1 Compression

Compression, or automatic gain control (AGC), seeks to maintain a constant output sound level for widely varying input level. It works by measuring the headset signal level over a relatively long time period (tens to hundreds of milliseconds) and adjusting the gain of the headset amplifier to maintain a constant output. Too short a compression time-constant interferes with speech dynamics and reduces intelligibility, and too long a time constant reduces the effectiveness of the compression.

Compression differs in two important ways from the acoustic limiters described in section 5. Limiters simply clip signals that exceed a certain threshold, causing severe distortion, whereas compression does not distort the input signal. Compression stabilises the headset listening level to a comfortable volume chosen by the user (say, somewhere in the range –25 to 0 dBPa). The headset user does not have to adjust the volume control to cope with quiet or loud callers, since the compression mechanism adjusts all calls to the same level. Any abnormally loud signals are also limited to the same comfortable level. The disadvantage of compression is that its relatively slow time constant allows short bursts (tens to hundreds of milliseconds) of high level sound through before the AGC reacts and reduces the volume. It is therefore best used as an adjunct to in-headset limiting devices rather than as an alternative. More sophisticated compression schemes, using knowledge of speech signal statistics, can provide faster compression attack time in the presence of sudden loud noises.

6.2 Frequency dependant limiting

Figure 1 showed that a headset's receiving sensitivity varies with frequency. Different headset models have different frequency responses. Therefore any limiting or compression scheme that regulates the voltage driving the headset receiver results in acoustic limiting that varies with frequency. Digital signal processing (DSP) makes it feasible to compensate for the frequency responses of individual headset models and provide acoustic limiting at a chosen sound level, independent of frequency.

DSP also allows frequency-dependant limiting to be implemented, complying with any chosen frequency response mask. For example Telstra has specified a headset noise limiter [10, 11], which implements both frequency and duration-dependant limiting, which it believes will reduce the incidence of acoustic shock. The scientific basis for the chosen limits is disputed, and there is little supporting evidence published in the open literature. However it is a good example of the type of advanced signal processing that DSP makes possible.

6.3 "Intelligent" limiting

DSP also enables other "intelligent" limiting techniques such as enhanced compression, selective attenuation or removal of certain types of sound and non-causal processing (i.e. where the output depends on both past and future system inputs, which can be carried out by introducing delays). The possibilities are virtually unlimited, but the key to success is to identify techniques that produce proven benefits for headset users, and to make them simple to use.

7 WORKPLACE NOISE EXPOSURE LIMITING

Adequate control of workplace noise exposure in call-centres and offices demands a holistic approach, considering not just the headsets and telephone infrastructure, but also such issues as acoustic design of the buildings, layout of agents' workstations, shift-patterns worked and equipment maintenance.

Employers are responsible for assessing and when necessary measuring noise exposure levels in the workplace. Compliance with acoustic shock legislation [1,2] is largely guaranteed by selecting headsets incorporating acoustic limiting devices and using them with a compatible telephone system. However compliance with noise exposure legislation [8, 9] cannot be guaranteed simply by choice of equipment. It depends upon how that equipment is used: volume setting, length of working day, frequency and duration of telephone calls, etc.

Noise exposure of headset wearers can be measured in their normal working environment. The equipment required for such noise assessments is costly, and accurate results demand both knowledge of acoustic measurement techniques and a good understanding of headset systems. Several commercial and academic organizations, including Plantronics, provide headset noise assessment services.

Professional-grade headsets are robustly constructed to withstand the rigors of regular use in a call-centre. However periodic maintenance is recommended to optimise performance. Call-centre managers may also wish to audit the performance of their headsets' acoustic limiting devices at regular intervals. To enable this, Plantronics' manufacture the "✔-box" (tick-box) headset confidence checker, which quickly and simply tests whether the acoustic limiting devices are fitted and functioning correctly. The maintenance and acoustic limiting audit records provide evidence of due diligence in meeting health and safety legislation to both the company's employees and external health and safety inspectors.

8 CONCLUSIONS

The primary protection against excessive sound levels is the acoustic limiting devices that are integrated into the headset itself. These ensure compliance with the continuous and peak sound level limits required by European legislation. All telephony headsets designed by reputable manufacturers for call-centre and office applications contain such limiting devices, although many mobile-phone headsets do not have acoustic protection devices fitted.

Other signal processing can enhance the headset user's comfort. Simple compression amplifiers have been available for some time, but the advent of DSP considerably extends the possibilities for headset signal processing.

The time-weighted average workplace noise exposure of headset wearers is affected by factors beyond the sphere of influence of currently available headset systems, such as the length of shifts worked and the number and duration of calls. It is therefore not possible to meet European workplace noise exposure legislation simply by specifying and using particular telephone and headset equipment. Administrative procedures for sound level monitoring and control are required.

9 REFERENCES

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