Sound Pressure Levels and Alarm Tone Waking Effectiveness

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Abstract

Effective notification of occupants from fire alarms is critical to evacuation and protection of life. Requirements for smoke alarm signals and sound pressure levels have generally remained consistent for over 50 years. A major change occurred in 2010 when the harmonic tone with low frequency, 520 Hz principle tone tested in research by Dorothy Bruck at the Victoria University was adopted into NFPA 72 for hard-of-hearing and fire alarm system devices in sleeping areas. Research showed that this tone was more effective at waking among at-risk populations of children, the elderly, the hard-of-hearing, and even the intoxicated. However, increased power requirements and limited battery power have precluded the requirements for residential alarms. This study evaluated 50 years of requirements and research to assess if a reduction in the 85 dBA at 10 ft (3.05 m) requirements could be justified to bring the low frequency tone into battery operated smoke alarms. The assessment determined that for at-risk groups, a reduction of 10-20 dBA could provide equivalent waking performance. For the broader population, a slight reduction of 0-6 dBA could also be justified with equivalent performance.

This recommendation only accounts for equivalent waking with equal installation. Accounting for other factors such as the increased transmission of the low frequency and increased perceived loudness of the harmonic tone, further reduction could potentially be justified. As a result of the composite analysis and research, the required sound pressure levels for low frequency alarms was reduced to 79 dBA at 10 ft (3.05 m) for UL Standard 217 for single- and multiple-station alarms.

Keywords: Sound pressure level; waking effectiveness; alarm; notification; signaling; audible awakening threshold; low frequency alarm; harmonic alarm

Introduction

Early notification of a fire event is perhaps the most crucial factor in reducing the threat to life. Early notification provides occupants time to safely escape before life threatening conditions develop. Sensor performance of smoke alarms and detectors plays a crucial role in providing early notification but the signaling audibility and effectiveness are just as critical for affecting life-saving outcomes. The notification performance becomes especially critical when occupants are sleeping.

Requirements for smoke alarm signaling have existed since the first edition of *NFPA 74, Standard for the Installation, Maintenance, and Use of a Household Fire Warning System,* in 1967 [1]. This standard provides the first device-based performance requirement that alarms “shall be audible in all bedrooms with intervening doors closed” in Section 2130 [2]. This was changed to require 85 dBA at 10 ft in 1974 [3]. Over the subsequent decades, installation-based requirements have been clarified to requiring 75 dBA at the pillow as a definition of audibility in the bedrooms, requiring alarm locations on each floor, outside sleeping areas, and eventually in the bedrooms and with interconnections between alarms. Additional adoptions require the use of a standardized temporal pattern for the alarm sounding and the need for low-frequency 520 Hz harmonic tones for sleeping areas and for the hard of hearing.

Low power consumption and low cost with high sound output drove the commercial market toward the use of piezoelectric sounders during the early proliferation of residential smoke alarms. The piezoelectric sounders could produce the required 85 dBA sound pressure level (SPL) at 10 ft using a minimal amount of current from the batteries. Piezoelectric sounders produced tones with high frequency pitches over 2000-5000 Hz. Research conducted in the 1960s and 1970s on the various stages and depths of sleep, audible awakening thresholds (AAT) for various populations, and general notification (e.g., telephone rings, emergency sounders) attempted to quantify the minimal SPL required to awaken the general population, but also questioned and challenged the use of such a tone. Despite some concerns from various researchers, industry agreement was reached in the late 1970s that the 85 dBA piezoelectric sounders could provide 75 dBA of SPL in bedrooms when installed just outside the sleeping areas. General agreement was also reached that this 75 dBA level would be sufficient to awaken most occupants. Recommendations were made for pitch varying and whooping sounds, low frequency sounds, complex harmonic sounds, and even spoken voice messages, but little was done to modify the standard requirements based on these recommendations.

Over three decades numerous researchers evaluated the real-world effectiveness of smoke alarm notification signals. Studies often confound numerous potential factors that impact the effectiveness of waking people. Factors include the stage of sleep at the time of waking [4] or if it was measured, the length of sleep prior to waking, the age and gender of the subjects, the hearing capability of the subjects, the use of drugs, alcohol, or hypnotic sleeping aids, prior training or exposure to the alarm signals in the tests (naivety) of the subjects, the conduct of tests in laboratories or in homes, the criteria used to determine if the subject became "awake", and the exposure frequencies (e.g. alarms per night, total number of nights, etc.) during the experimental period. These issues don't even account for one of the most critical issues, the delivery, presentation, control, and definition of the test tone. Tested tones include single tones of various pitch, harmonic tones, white noise, or even voices, explosions, crackling, or footsteps. Tones have been presented at fixed SPL, or through stepped SPL increments with different length of tone presentation and intermittent quiet periods. Sounds have been presented by using real smoke alarms, recorded sounds played over speakers, or through earpieces. Most individual studies were able to draw comparative conclusions between their own data, but identification of definitive conclusions between studies has proven difficult.

Perhaps the most impactful research toward affecting modern requirements for smoke alarm signaling was conducted by Dr. Dorothy Bruck and colleagues at the Victoria University from 1995 through 2010. This work evaluated the performance of real smoke alarm sounds and other signals to wake various segments of the population in controlled and repeated experiments. Multiple studies evaluated the populations at highest statistical risk for death in residential fires, including children, the elderly, and people affected by drugs, alcohol, or sleeping aids. Experiments identified serious shortcomings in the effectiveness of the existing high frequency piezoelectric sounders to affect positive waking outcomes for these segments of the population, even at higher audible thresholds than reasonably possible.

Not limited to identifying a gap, Bruck and her team also identified a solution. A square-wave harmonic tone with principle frequency at 520 Hz was repeatedly more effective at waking at-risk and challenging populations as well as the general population of adults with normal hearing. In this case, effectiveness can be defined either by the number of subjects awoken at a given SPL or by waking the same number of subjects at a reduced SPL. These studies provided the basis for requirements that were adopted into *NPFA 72, National Fire Alarm and Signaling Code*, in 2010 for sleeping areas and the hard of hearing [5].

Despite more effective waking performance, the implementation of 520 Hz sounders into battery operated smoke alarms for the consumer market has proven difficult. Low frequency alarms require up to 4 times the amount of power as high frequency sounders to meet the device specific requirements of Underwriter's Laboratories (UL) Standard 217 and UL 268 (85 dBA at 10 ft). The extra current draw is a severe limitation to the design of battery operated, single- and multiple-station smoke alarms. For this reason, the 520 Hz sounder requirements have not been applied to single- and multiple-station alarms in sleeping areas in Chapter 29 of NFPA 72, but only for notification appliances in Chapter 18, Section 18.4.6, Sleeping Area Requirements. Chapter 29 does require the 520 Hz tones only for mild to severe hearing loss. Chapter 24 also requires the incorporation of the 520 Hz tone into voice notification and mass notification systems in sleeping areas. In the Appendix of NFPA 72, Section A.18.4.6.3 clearly indicates that the 520 Hz tone in sleeping areas is only applicable to notification appliances connected to fire alarm systems and does not address smoke alarms for dwelling units [6].

It is desirable to provide sleeping areas in residential applications alarms with the more effective tones. With numerous states and local jurisdictions requiring residential smoke alarms with 10-year sealed batteries this has proven a potentially insurmountable technological hurdle to product design. The smoke alarm community has questioned whether a reduction in SPL could be justified for low frequency sounders. Justification would require clear demonstration from test data that increased waking effectiveness is maintained compared to traditional high frequency sounders operating at the 85 dBA at 10 ft requirement.

Overall Review

A detailed review of the historical research data that advised the creation of the existing device performance requirements was conducted in 2019 [7]. This included an historical timeline for development of the existing codes and standards and detailed summaries of literature reviews and experimental studies on waking effectiveness that guided the development of the codes and standards. Review included research used to justify the origins of the 85 dBA device and 75 dBA installation requirements as well as the research that identified the increased waking performance of the 520 Hz signal.

Discussion of Findings

The goal was to determine if sufficient data existed to justify a reduction in SPL for low frequency sounders and to identify remaining knowledge gaps.

Based on the reviewed test data, several quantified effects became evident. In every test scenario conducted, the low frequency harmonic tones were able to awaken an equivalent number of test subjects across every population (children, hard of hearing, the elderly, the intoxicated, etc.) at reduced SPL between 10-20 dBA lower than high frequency pure tone alarms. A low frequency alarm with reduced SPL (dBA) installed in the same location as a high frequency alarm with 85 dBA at 10 ft SPL harmonic can achieve equivalent waking performance for most people and most scenarios. It should be noted that equivalent in this case may mean waking between 50-90 % of test subjects, and this level of performance may not be considered adequate for emergency waking response. An equivalent performance to existing alarms for normal hearing adults, for whom existing tones are generally considered adequate, with an improvement for the at-risk groups would constitute a drastic improvement in fire safety performance.

A synthesized analysis of 50 years of waking performance data was conducted. This included average assessments of the 50 % waking thresholds (as a comparison metric, not a performance target) among multiple data sets, populations, and alarm tones. The comparison of this data clearly indicated the improved performance of the low frequency harmonic tone over traditional high frequency alarms. This effect was most apparent for at-risk populations, including children, older adults, people with hearing loss, the intoxicated, and subjects who took sleeping medication. Among this population, an average reduction in SPL up to 20 dBA was estimated to provide equivalent waking performance between low frequency harmonic alarms and high frequency alarms. Among the normal population, the effect was far less drastic. Depending on the way data was grouped, the improvement of low frequency alarms over high frequency alarms ranged from 6 dBA improvement to 2 dBA reduction in performance. It should be considered that the 6 dBA improvement was for test data compared when both alarm types were included in the same methodology. The 2 dBA reduction in average performance was estimated using a very limited set of low frequency data (n=17) and a very large set of high frequency data (n = 866) conducted with many different methodologies, alarm presentations, lab conditions, etc. that could easily bias this comparison. The high rate of variance even within single AAT experiments (>15 dBA) and potential historical bias (desensitized modern population) lead one to uncertain quantification for the normal population.

In addition to waking performance, the sound transmission characteristics of the low frequency harmonics also result in higher SPL in bedrooms when installed outside the bedrooms. In multiple tested conditions, distances, door positions, and number of rooms, the low frequency harmonic tones consistently resulted in SPL 4-8 dBA higher than high frequency tones due to reduced signal attenuation. When installed inside bedrooms, the complex harmonic tone is less likely to produce destructive interference patterns and null zones or be masked by various ambient noises than pure tone alarms. In addition, complex harmonic tones give the impression of fullness with louder apparent sound that is not quantified by A-weighting measurement techniques.

Although test data is numerically strong indicating improved performance of low frequency alarms, the reasons for this improvement are less certain. The effectiveness of the low frequency tone may result from an increased total sound power level compared to high frequency tones. Due to the basis of the A-weighting scale on human hearing perception at low intensity (40 phon), the 520 Hz tone is measured with a 4.2 dBA reduction compared to 3100 Hz tones. This means that for the same dBA, the 520 Hz tone carries approximately 3 times the total wave power.

It has been proposed, although with limited data, that humans do not perceive sound in deep sleep based on the A-weighting scale, and thus the low frequency tone has been artificially and unnecessarily penalized by 4.2 dBA compared to high frequency alarms. In sleep, it may be possible that sounds are not heard and interpreted the same as when during waking, and rather the sounds are felt more by the raw power than by traditional transformations of sound by the ear and brain. The primary data set indicating this effect was collected by Levere et. al in 1972 testing only 8 college aged males and measuring the magnitude of EEG responses and so should be considered as a theory that may explain the improved waking performance only [8]. There is also no data clearly refuting or disproving this effect either.

Alternatively, the louder impression of the sound may have nothing to do with sleep but may be inherently related to the increased perceived loudness due to complexity and richness of tone. Several methods for quantifying perceived loudness have been proposed that indicate inadequacies in the A-weighted scale, including the method of Zwicker [9] and the Moore-Glasberg methods [10] recognized by ISO 532-2. These methods attempt to account for the cumulative effects of multiple harmonic frequencies and the increased perception of loud tones that the A-weighting scale does not. Regardless of why the low frequency tone is better, there is clear quantified numerical evidence that the tone provides equivalent performance at lower dBA values that traditional high frequency alarms.

Recommendations

While a primary goal of this research was to identify gaps toward reducing the SPL requirements of low frequency alarms few gaps remain for research and study. There is compelling evidence of the potential of low frequency harmonic tones with reduced SPL for alarms located in the bedrooms and outside the bedrooms to maintain more effective waking performance for both normal and at-risk populations. Although demonstrated in controlled testing, it is not entirely clear how compounding effects (e.g., hard of hearing and taking sleeping medication, etc.) could influence real world performance. The reasons why people respond to the alarm are not fully proven, but the improved performance is apparent in the conducted testing. A reduction in required SPL for low frequency alarms could be justified given the existing data. The recommended reduction should be minimized to meet the engineering design requirements due to power consumption and battery life to provide battery operated low frequency alarms in residential applications.

The remaining gaps include determining an acceptable magnitude for reduction. This decision would be based on weighing the increased performance for at-risk populations against the reduced or non-existent improvement for the normal population. A cursory comparison of the breadth of test data was conducted which indicates equivalent performance for at-risk populations at reduced SPL up to 20 dBA and for normal populations up to 6 dBA reduction. To fully reconcile these values statistically, access to the complete data sets for each considered experiment would be needed and a statistical analysis complete with uncertainty would be required.

In addition to considering measured waking performance, reduction in SPL could likely be justified if it is assumed that all alarms will be installed per code in every bedroom and interconnected. Even assuming alarms are only installed in hallways outside bedrooms in violation of requirements, there is also justification for a reduction in SPL of low frequency alarms due to the improved transmission of the tone through walls and doors. The next steps remain for the impacted parties, including manufacturers and life safety experts and authorities having jurisdiction, to review the data summarized in this report and determine if / how much of a reduction could be justified, and whether allowing reduced SPL low frequency alarms to exist is sufficient or if they should be required in all single- and multiple-station alarm installations.

Existing research does not indicate a definitive, quantified number for allowable SPL reduction or a distinct code change. No reasonable amount of further testing or study would provide such a clear and simple answer. The codes and standards governing the performance and installation of smoke alarms are based on consensus of committee and panels of experts and industry representatives. This report should provide sufficient data for members of those groups to review and understand and vet any potential proposal regarding this issue.

Resulting Outcomes

After publication of the review report, a recommendation for change was submitted to the Standards Technical Panel (STP) for UL 217 to reduce the required SPL of low frequency alarms to 79 dBA at 10 ft (3.0 m) distance. This reduction was justified by the analysis performed by the authors and was accepted without dissent. This reduction of 6 dBA reduces the total sound power by 4 times and makes the introduction of low frequency alarms to battery operated, residential sleeping areas technologically possible.

Acknowledgements

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