Acoustical characterization of exploding hydrogen-oxygen balloons

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Abstract: Exploding hydrogen-oxygen balloons are popular chemistry demonstrations. Although initial research experimentally quantified potential hearing risk via analysis of peak levels [K. L. Gee *et al.,* J. Chem. Educ. **87,** 1039–1044 (2010)], further waveform and spectral analyses have been conducted to more fully characterize these impulsive noise sources. While hydrogen-only balloons produce inconsistent reactions and relatively low, variable levels, stoichiometrically mixed hydrogen-oxygen balloons produce consistent high-amplitude noise waveforms. Preliminary consideration is also given to the potential use of these exploding balloons in architectural acoustics applications.

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1. Introduction

Investigation of impulsive noise source characteristics and propagation has included diverse motivations and applications, from hearing risk to community annoyance. Impulsive noise sources examined previously include firecrackers,[1,2] starter pistols,[2] medium[3] and large[4] caliber weaponry, improvised explosive devices, and various firearms.[5–7] In architectural applications, impulsive noise sources can be useful in obtaining room responses. This has been one motivation for the examination of the acoustics of burst, air-filled balloons.[2,8] Deihl *et al.*[9] measured the N-pattern pressure waveform produced by the bursting of a round balloon, a topic treated analytically by Blackstock.[10] However, in practice, balloons are not usually perfectly round and rarely burst evenly. Jambrosic *et al.*[2] investigated various sizes of popped balloons as impulsive sources in comparison to firecrackers and an explosive acetylene mixture. They determined that the explosive impulsive noise sources produced relatively consistent N-like waveforms, whereas the balloon bursts were low-amplitude, irregular, and dependent on balloon size. Patynen *et al.*[8] further showed that the sound radiation from popped balloons is not omnidirectional, particularly at low frequencies.

This letter presents a characterization of exploding hydrogen-oxygen balloons as an impulsive noise source. Early experiments[11] to quantify peak levels from these popular introductory chemistry demonstrations were significantly updated in a recent paper by Gee *et al.*[12] The letter includes further analysis of the experimental data described in Ref. 12, providing a more thorough acoustical characterization of the hydrogen-oxygen balloons. Time waveform and spectral analyses are presented with attention given to details including peak levels, A-durations, and characteristic frequencies. In the same vein as Patynen *et al.,*[8] preliminary consideration is given to determining potential suitability[13] of these explosive hydrogen-oxygen balloons as an impulsive noise source in room acoustics.

2. Experimental setup

Measurements were taken in a large anechoic (80 Hz to 20 kHz) chamber at Brigham Young University. GRAS type-1, 6.35 mm pressure microphones were positioned for grazing incidence in 30° increments over a 150° span at a distance of 1.83 m. Data from additional microphones at 0.91 and 3.66 m were considered previously.[12] The microphones were mounted at source height at the ends of thin wooden dowels attached to tripods. Pressure waveform data were recorded with 24-bit National Instruments PXI-4462 cards at a sampling frequency of 192 kHz. Balloons were clamped to a ring stand and then ignited at the balloon base using a small butane torch attached to a meter stick. Figure 1 includes photographs from the test.

Data were recorded for 12 different types of balloons. Nearly round latex balloons with an approximate 23 liter capacity were filled with four different amounts of hydrogen and with three different ratios of hydrogen and oxygen. The gas ratios were dependent on the final chemical reaction, $2\ H_2\ (g) + O_2\ (g) \rightarrow 2\ H_2O\ (g)$. Balloon gas mixtures included pure hydrogen, half the stoichiometric ratio of hydrogen to oxygen (a 4:1 ratio), and the full stoichiometric ratio of hydrogen to oxygen (a 2:1 ratio). Balloon properties are summarized in Table 1 with a two letter code, the first letter indicating the amount of hydrogen in the balloon, and the second letter indicating the ratio of oxygen added.

3. Results

This section contains level-based, waveform, and spectral analyses of the balloon data. Although this letter focuses solely on the 1.83 m data, the 0.91 and 3.66 m data provide two noteworthy results. First, a comparison of levels produced at each distance demonstrates evidence of spherical spreading.[12] Results also indicate nonlinear waveform steepening in the pre-shock regime for the larger (e.g., CC and DC) balloons. Further details on nonlinear propagation of pressure waves from exploding balloons are described by Muhlestein *et al.*[14,15]

3.1 Level-based analyses

The level-based metrics discussed are peak sound pressure levels (L_{peak}) and, because L_{peak} does not fully characterize the level-based nature of the balloon explosions, the unweighted sound exposure levels (SEL) and the 8-h, A-weighted equivalent levels ($Leq_{A,8h}$). The SEL provides a measure of the overall sound energy, and the $Leq_{A,8h}$ has gained acceptance as an alternative impulse noise risk criterion.[1,16,17] Note also that the SELs and 8 h *Leq*'s are obtained from one another by adding/subtracting 44.6 dB to account for the difference in averaging time. C-weighted levels, which are not included, are similar to the unweighted levels.

Table 2 displays trial and angle-averaged L_{peak}, SEL, and $Leq_{A,8h}$ from the 1.83 m data. Included in parentheses is the range in level over all microphones and

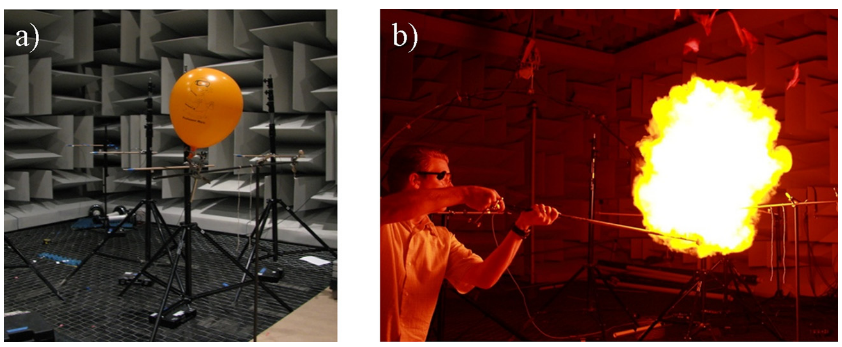

Fig. 1. (Color online) (a) Photograph of a portion of the anechoic chamber setup. (b) A small hydrogen balloon explosion.

Table 1. Identification codes and properties of balloons used, along with number of trials recorded per balloon type.

ID	Moles H_2	Moles O_2	Volume (l)	Diameter (cm)	Trials
AA	0.07	0.00	1.98	15.6	4
AB	0.07	0.018	2.48	16.8	4
AC	0.07	0.035	2.97	17.8	3
BA	0.22	0.00	6.23	22.8	3
BB	0.22	0.055	7.78	24.3	3
BC	0.22	0.11	9.34	26.1	3
CA	0.37	0.00	10.5	27.1	4
CB	0.37	0.93	13.1	29.2	4
CC	0.37	0.185	15.7	31.1	3
DA	0.52	0.00	14.7	30.4	4
DB	0.52	0.13	18.4	32.8	3
DC	0.52	0.26	22.1	34.8	3

trials. The mean L_{peak} were obtained by averaging peak pressures, whereas the mean SEL and $Leq_{A,8h}$ were calculated via energy-based averages. The L_{peak} column, shown graphically in Ref. 12 indicates high levels from these reasonably sized balloons; the DC balloon average level exceeds 161 dB re 20 μPa at 1.83 m. Despite the greater distance, this level surpasses L_{peak} from various small-caliber weapons at shooter position.[6] Table 2 also indicates the L_{peak} for hydrogen-only balloons is both less dependent on balloon size and is much more variable. On the other hand, the balloons mixed with oxygen generally produce more consistent levels that grow more quickly as a function of balloon size. For the three larger balloons, the full stoichiometric average peak levels are about 3 dB greater than those for the 50% mix.

The repeatability (or lack thereof) of the various balloon explosions extends to the other metrics as demonstrated by the range in levels. The variability of the hydrogen-only balloons is further described in that the mean level changes over the AA through DA balloons differ considerably for the three metrics: 7.3 dB, 13.3 dB, and 5.4 dBA for L_{peak}, SEL, and $Leq_{A,8h}$, respectively. On the other hand, the increases for the three metrics and the AC through DC balloons are more consistent: 18.0 dB, 19.0 dB, and 17.4 dBA, suggesting the overall noise event is dominated by the peak. The 50% mix changes represent an intermediate case.

Table 2. Trial and angle-averaged peak sound pressure levels (L_{peak}), sound exposure levels (SEL), and 8-hr A-weighted equivalent levels ($Leq_{A,8h}$) for each type of balloon at a distance of 1.83 m from the source. Also included are the maximum deviations, considering both trials and angles. See the text for further explanation.

ID	L_{peak} (min/max)	SEL (min/max)	$Leq_{A,8h}$ (min/max)
AA	126.1 (−3.6/2.8)	96.0 (−3.0/4.5)	45.1 (−4.5/3.5)
AB	144.9 (−3.9/3.6)	114.3 (−1.6/3.1)	60.6 (−3.4/3.1)
AC	143.5 (−0.9/0.8)	113.8 (−1.0/2.4)	59.1 (−1.8/2.1)
BA	133.1 (−2.2/2.3)	104.8 (−1.6/2.3)	50.3 (−2.3/2.0)
BB	149.6 (−1.2/1.2)	121.7 (−1.4/2.4)	64.5 (−2.6/2.2)
BC	152.4 (−0.9/1.0)	125.3 (−2.4/0.7)	69.3 (−2.7/0.7)
CA	131.0 (−5.4/1.1)	105.0 (−3.6/3.1)	50.9 (−13.0/3.5)
CB	155.2 (−3.7/4.6)	127.6 (−1.9/2.3)	71.2 (−3.9/3.0)
CC	158.1 (−1.1/1.5)	130.2 (−0.9/0.8)	74.0 (−2.1/1.7)
DA	133.4 (−9.7/5.2)	109.3 (−3.1/4.8)	50.5 (−7.0/3.5)
DB	158.4 (−2.1/1.5)	131.0 (−1.0/1.0)	73.8 (−2.0/1.5)
DC	161.5 (−2.3/1.7)	132.8 (−1.4,1.5)	76.5 (−2.5/2.5)

The $Leq_{A,8h}$, and by addition of 44.6 dBA, the A-weighted SEL, show that there is less A-weighted noise exposure from these balloon explosions than might be expected given the peak levels achieved. As shown further in the waveform and spectral analyses, this is caused by the relatively low-frequency nature of the signal. For example, the A-weighted SEL is approximately 10–11 dB less than the unweighted SEL for all four stoichiometrically mixed balloons. It also stresses potential differences between assessing auditory risk based on peak levels versus cumulative, A-weighted exposure. Although even one exposure to a DC balloon explosion may be considered hazardous using NIOSH's peak level-based criterion,[6] a person located at 1.83 m without hearing protection could observe seven DC balloon explosions in an 8 h period without exceeding the currently recommended[17] 85 dBA cumulative exposure criterion. Given the very high peak level, however, we strongly discourage even one such exposure!

3.2 Waveform and spectral analysis

It is convenient to discuss the waveform and spectral analysis jointly. First examined are waveforms for balloons with the same amount of hydrogen but different mixtures. This comparison provides insight into how chemical reaction characteristics are related to the details found in the pressure waveforms. Figure 2(a) shows waveforms for three separate trials of a pure hydrogen "C" size (0.37 moles hydrogen) balloon (CA). While the time waveforms follow a similar trend, there are marked inconsistencies in level, duration, and details of the reaction. This is caused by the fact that oxygen must be drawn from the outside volume of air for the reaction to take place. The result is a highly variable explosion as pockets of hydrogen gas mix with the air and combust. Because of the random, relatively slow reaction, the hydrogen balloons produce low-amplitude peak sound pressure levels, averaging around 130 dB re 20 μPa. Furthermore, high-speed video analysis[14] has shown that the reaction proceeds slowly enough to allow the balloon to completely unwrap before the explosion begins. This initial unwrapping, i.e., bursting of the balloon, is observable in all three waveforms. Considering only the initial peaks in Fig. 2(a), seen at times of 2-4 ms, the approximate rise times (1.8 ms) and levels (120 dB re 20 μPa) are consistent with the results presented by Patynen *et al.*[8] for popped balloons.

Hydrogen-oxygen balloons combust far more predictably than the pure hydrogen balloons. Figure 2(b) provides time waveforms (aligned at the zero-crossing) recorded at the same microphone from three separate trials of CC hydrogen-oxygen balloons. [This is the same amount of hydrogen as in Fig. 2(a), but with the proper ratio of oxygen to hydrogen.] The waveforms are remarkably similar in terms of peak level, duration, and overall shape. This consistency is even greater as a function of angle for each trial.

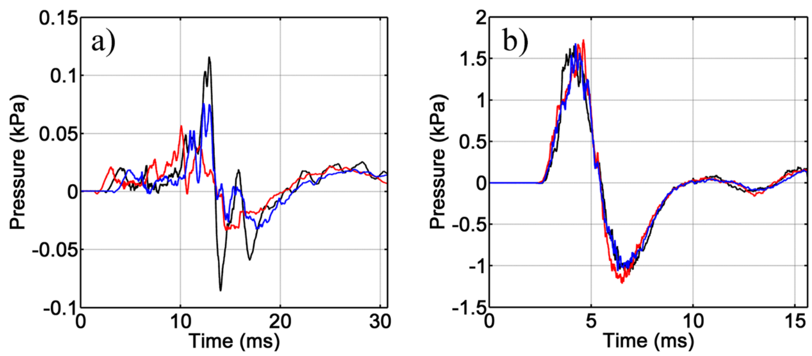

Fig. 2. (Color online) Time waveforms from three different trials of "C" size balloons (0.37 moles of hydrogen). (a) CA (pure hydrogen) balloon waveforms. (b) CC (stoichiometric hydrogen-oxygen) balloon waveforms.

The "C"-sized balloons are used as a baseline for further comparisons. Figure 3(a) shows a direct waveform comparison for varying ratios of hydrogen to oxygen and the "C" sized (0.37 moles hydrogen) balloon. The differences in duration, characteristic shape, and level between the CA and CC balloons are more readily seen in addition to the intermediate case, the CB balloon. Although the CB balloon contains only half the oxygen required to initiate the full reaction, its behavior is much more like that of the CC than the CA balloon. The durations are similar with the CB balloon having a slightly slower rise and lower peak pressure. In examining waveforms from various trials, the CB balloon generally reaches a peak level and then declines more rapidly, whereas the CC balloon waveform hovers around the peak pressure longer.

Figure 3(b) displays the angle and trial-averaged one-third octave band SEL for each balloon type. The CA balloon spectrum is significantly lower in level and has a different characteristic shape. The spectra for CB and CC balloons follow a similar trend; this is consistent with the time waveforms in Fig. 3(a). However, the high-frequency levels for the CC balloon are appreciably greater, and appear to stem from the multiple high-level, high-frequency peaks present in the CC waveforms in Figs. 2(b) and 3(a).

Figure 3(c) depicts pressure waveforms for the different sizes of stoichiometric balloons. Referring to Table 1, the volume of the AC balloon is 2.97 l whereas the volume of the DC balloon is 22.1 l. However, the average A-duration of all four balloons is consistent within 0.7 ms; the angle and trial-averaged A-duration for AC through DC balloons is 3.6, 3.5, 2.9, and 3.0 ms, respectively. Despite the different fuel volumes, the reaction appears to occur over the same time frame for the stoichiometric balloons. However, although the reaction takes approximately the same time for each balloon size, the peak pressure and particle displacement, and therefore the time required for the air to return to equilibrium post-reaction, is volume-dependent.

Figure 3(d) provides the average one-third octave band SEL of each size of stoichiometrically mixed balloon. Exploding hydrogen-oxygen balloons produce primarily low-frequency content, with characteristic frequencies on the order of 100–200 Hz. This differs considerably from firearms,[6] with peak frequencies in the 1 kHz range, and explains why the high peak levels produce only moderate A-weighted equivalent levels in Table 2. While the characteristic frequency shifts slightly upward with decreasing balloon size [consistent with the overall impulse lengths in Fig. 2(c)], the change is relatively minor. This result differs from that found by Patynen *et al.*,[8] who describe a more significant correlation between *popped* balloon volume and characteristic frequency. The difference here is due to the fact that the chemical reaction takes place on a similar time scale and the balloon burst itself is not important to the overall sound generation.

3.3 Possible room acoustics applications

Similar to the recent paper by Patynen *et al.*[8] for popped air-filled balloons, we have also considered omnidirectionality of the exploding hydrogen-oxygen balloon as an impulsive source for room acoustics. ISO 3382 (Ref. 13) provides a table of maximum allowable deviation in directivity as a function of frequency for electroacoustic sources. The standard requires that measurements be either averaged over 30° spans using gliding arcs or discrete measurements taken at 5° intervals. Although the tests performed did not meet the resolution required, as only six point measurements were taken at 30° intervals, the results for the data available are still noteworthy. Figure 4 shows the trial-averaged directional deviation in decibels for each octave band, along with the ISO 3382 allowable deviation. To produce the trial-averaged curves, each explosion was considered individually to find the average level and maximum positive and negative deviations before performing an energy-based average.

Figure 4 indicates that, unlike popped balloons,[8] hydrogen-oxygen balloon explosions are close to omnidirectional, with much less directional deviation. The maximum deviations fit within the ISO 3382 limits at the high frequencies and nearly fit

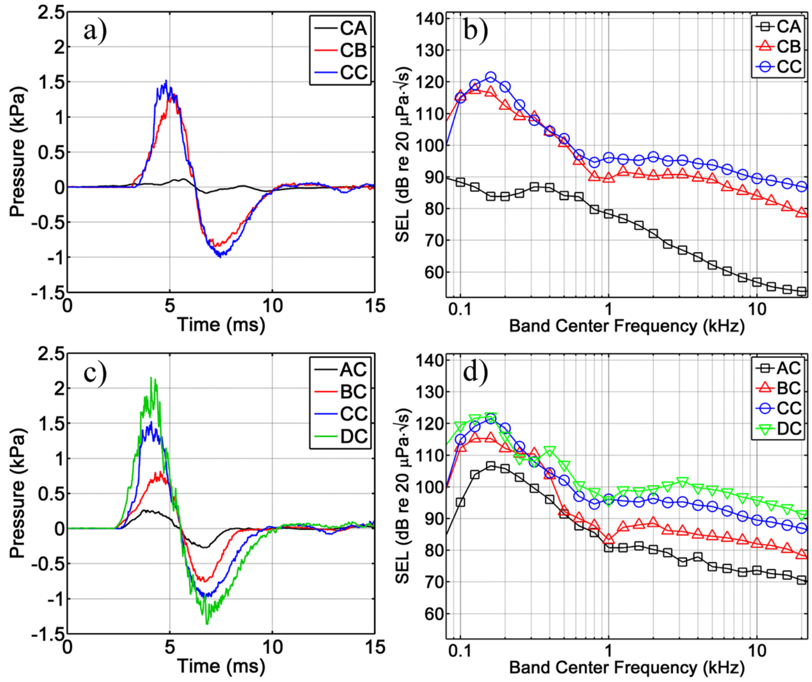

Fig. 3. (Color online) (a) Representative time waveforms of three "C" size balloons (0.37 moles of hydrogen and varying amounts of oxygen). (b) Average one-third octave SEL spectra from the balloon types shown in (a). (c) Representative waveforms for stoichiometrically mixed balloons of all four sizes. (d) Average SEL spectra from the balloon types shown in (c).

within the limits at the low frequencies. In fact, the smallest of the stoichiometric balloons (AC) essentially meets the standard. Finer resolution measurements with angular averaging, as described in ISO 3382 would almost certainly yield less deviation, as results averaged over 30° intervals should have less variability than point measurements with 30° resolution. These additional measurements, however, are required to more accurately determine the balloons' suitability as an impulsive noise source. As a final note, repeating the analysis in Fig. 4 for the balloons with half the stoichiometric ratio (AB - DB) yields very similar results. We can therefore reasonably conclude that if hydrogen-oxygen balloons are found to be sufficiently omnidirectional for architectural acoustics applications, then the precise filling of the balloons to the exact stoichiometric ratio is not required.

4. Conclusion

This letter has presented acoustical characteristics of hydrogen-oxygen balloon explosions. Although pure hydrogen exploding balloons produce low-amplitude, variable levels, moderately sized hydrogen-oxygen balloons represent a consistent, high-level noise source with relatively low characteristic frequency. This latter feature distinguishes these sources from firearms and other sources that produce the more familiar shock-like blast waveform. The balloon-produced impulses are more sinusoidal in nature but with small-scale features that contribute to the high-frequency content in the spectrum. Still because variations in time waveforms over angles and trial are minimal, the possibility that these hydrogen-oxygen balloons may meet the omnidirectionality requirements of ISO 3382 is intriguing. A relatively low-frequency, but high-bandwidth, high-amplitude impulsive source could be useful in architectural acoustics applications. However, further measurements with greater angular resolution are required to determine suitability.

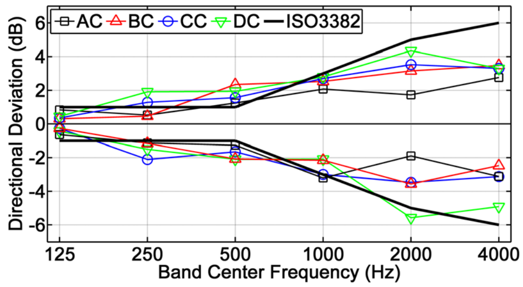

Fig. 4. (Color online) Trial-averaged directional deviation along with the ISO 3382 allowable limits.

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