Firework Salute Sound Characteristics and Perception: Background and Theory

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Abstract: The aesthetics of the sound produced by exploding firework salutes is not well addressed in the scientific literature. This paper presents a brief summary of what is known about impulse sounds as it may apply to exploding firework salutes. Also included are three hypotheses relating to the aural and physical perception of such sounds by humans, in the hopes that someone will test and expand on them.

Introduction

In most instances, the sound accompanying an explosion is a nuisance, an undesirable consequence of using explosives to do work. However, in fireworks, the sound from an explosion is often the primary effect being sought; and it is sought for its entertainment value; one might even say, for its aesthetic value. Accordingly, the acoustic characteristics of the air-blast waves produced by fireworks and how they are perceived by the audience are important. Unfortunately, the aesthetic quality of blast waves is a subject that has not been well reported in the scientific literature. It is the authors' hope that this discussion of the human perception of the sound produced by exploding firework salutes may stimulate a scientific investigation of the subject.

Background information

The explosive sound produced by a salute is technically referred to as an impulse sound because it is an event of very short duration. Figure 1 is an illustration of an idealized blast-pressure wave from an explosion.

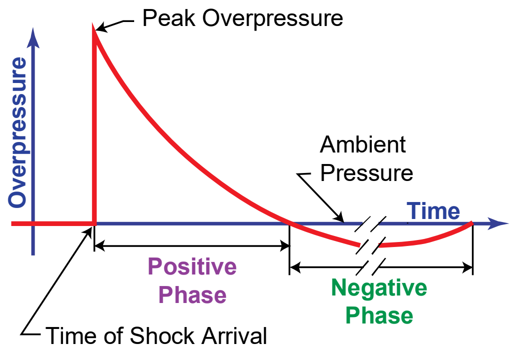

__Figure 1__. Illustration of an idealized air-blast wave from an explosion.

An air-blast wave is a shock wave; as such, it travels faster than the speed of sound in air. Prior to the arrival of the leading edge of the blast wave at the location of the observer, there is no deviation from ambient atmospheric pressure (i.e., there is no precursor to the sound of the explosion). Upon arrival of the blast wave, there is a near instantaneous jump in air pressure from ambient to the peak overpressure of the blast wave. Thereafter, the pressure returns relatively slowly, but still quickly, back to ambient air pressure. This first portion of the blast wave is referred to as its positive phase, and it lasts approximately 0.1 millisecond for a 1½ inch (38 mm) firecracker at close range (i.e., roughly a few feet or a meter), to approximately 3 milliseconds for a 3 inch (76 mm) aerial salute at typical spectator distances (i.e., roughly a few hundred feet or a hundred meters). Following the positive phase, there is a negative phase, which, at close range, is much less extreme in magnitude, but it lasts somewhat longer than the positive phase. For powerful explosions, there may be another much weaker positive phase following the negative phase. Figure 2 shows the blast wave recorded from an exploding 3 inch (75 mm) test firework salute at a distance of 4 feet (1.2 m), with the salute suspended and the air-blast detector mounted approximately 5 feet (1.5 m) above the

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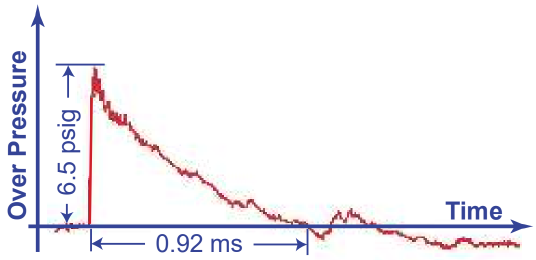

Figure 2. *Example of the air-blast wave from a 3 inch test salute recorded at a distance of 4 feet.*

ground. (The detector used in this and the other salute examples was a free-field piezoelectric blast gauge aimed directly at the exploding salute. The units of overpressure in this and the other salute examples is pounds per square inch gauge (psig), which is the pressure above ambient atmospheric pressure, where 1 psig corresponds to 6.89 kPa overpressure. The data were recorded using a digital oscilloscope.)

Air-blast waves from all explosions have a similar shape. For detonations, the reaction rate of the explosive charge is sufficiently high to immediately produce a shock wave in air. For deflagrations and mechanical explosions, air shock waves are often produced as the result of the process sometimes described as 'shocking-up'. This process is illustrated in Figure 3.[1a]

Any sufficiently great pressure pulse in air, regardless of its initial shape (e.g., see 'Initial' in Figure 3), will naturally evolve into a shock wave, which is explained as follows. All parts of the pressure pulse move away from the source at the speed of sound. However, the high-pressure pulse compresses the air, with the higher pressure portions of the pulse compressing the air to a greater extent than the lower pressure portions of the pulse. The act of compressing the air results in its momentarily being heated to a higher temperature, where the extent of the heating is a function of the amount of compression. Because the speed of sound increases with temperature, this means that the higher pressure portions of the pulse travel at a greater speed than the lower pressure portions of the pulse. This has the effect of the higher pressure portions of the pulse starting to catch up to the leading lower pressure part of the pulse (see 'Later' in Figure 3). This process continues until the pressure pulse has transformed itself into a shock wave with the standard shape (see 'Still Later' in Figure 3).

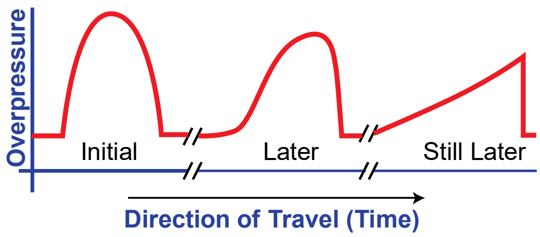

Figure 3*. Illustration of the 'shocking-up' process for a high-pressure pulse in air.*

As an acoustic wave propagates away from its source, it experiences attenuation, the total of which (A_t) can be considered to be the sum of the three sources of attenuation.[2]

$$A_t = A_s + A_a + A_e \qquad (1)$$

Here A_s, described as the geometric spreading attenuation, is simply due to the air-blast wave spreading out geometrically as it expands in the atmosphere. The second term, A_a, described as the atmospheric absorption attenuation, is a function of the thermodynamic properties of the atmosphere, which affects most strongly the higher frequency components of the blast waveform. For example, under the atmospheric conditions of 1 atm (14.7 psi) pressure, a temperature of 20 °C (68 °F) and 50% relative humidity, the atmospheric attenuation coefficients for sounds of 125, 500, 2000 and 8000 Hz are 0.445, 2.73, 9.86 and 104 dB/100 m, respectively.[2] The third term in Equation 1, A_e, is the attenuation from everything else, including ground effects.

While a blast (i.e., shock) wave is not strictly an acoustic (i.e., sound) wave, blast waves too experience similar attenuation as they travel away from their source (and blast waves do eventually degrade into acoustic waves). For example, blast waves also experience geometric spreading attenuation (A_s) and atmospheric absorption attenuation (A_a). There is, however, a significant difference in the atmospheric absorption attenuation of blast waves, for as long as they remain shock waves. The attenuation of the high frequency components (in a Fourier sense) can be

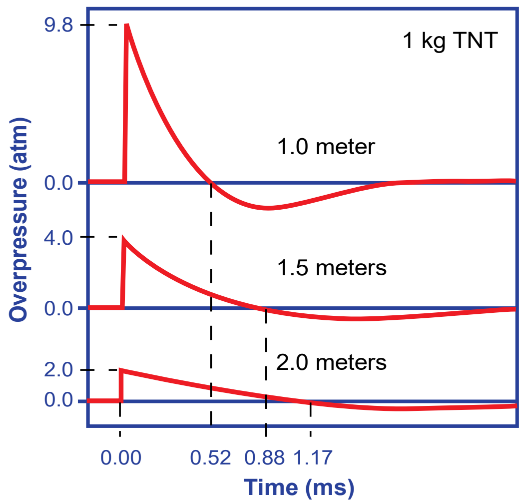

Figure 4. *Illustration of the attenuation of a powerful air-shock wave over a very short distance.*

significantly offset by the continuing 'shocking-up' process.

The net effect from these sources of attenuation is for the peak overpressure to rapidly decrease and the duration of its positive phase to increase. This is illustrated in Figure 4, even for very short distances from an exploding 1 kg charge of TNT.[1b] (In this figure, time zero was set to correspond to the arrival of the blast wave at the location of the recording blast gauge.)

Figure 5 illustrates the air-blast wave from an exploding 3 inch (75 mm) firework salute recorded at a distance of 370 feet (110 m). The salute was suspended, and the air-blast detector was mounted approximately 5 feet (1.5 m) above the surface of the ground. (Again in this figure, time zero was set to correspond to the arrival of the blast wave at the location of the recording blast gauge.)

Comparing Figures 2 and 5, note the great reduction in peak overpressure, 6.5 psig (45 kPa) versus 0.046 psig (0.32 kPa). Also there is an increase in the duration of positive phase, 0.9 ms versus 3 ms. In addition, the magnitude of the negative phase in Figure 5 is increased relative to its positive phase, giving this blast wave somewhat more nearly the appearance of a single cycle of a sine wave. It is thought that this is an indication that the initial air-blast wave has substantially degraded from a shock wave into a sound wave. Eventually, as air-blast waves propagate even farther from their source, they lose much of the sharpness of their leading edges.

Probably the most important characteristics of a salute, as heard by the audience at a firework display, are its loudness, its tonal quality (mellow boom versus a sharp crack sound), and the physical sensation as felt by spectators (what is sometimes described as a 'chest thump'). Each of these characteristics is a subjective response to the air-blast wave as perceived personally by spectators.

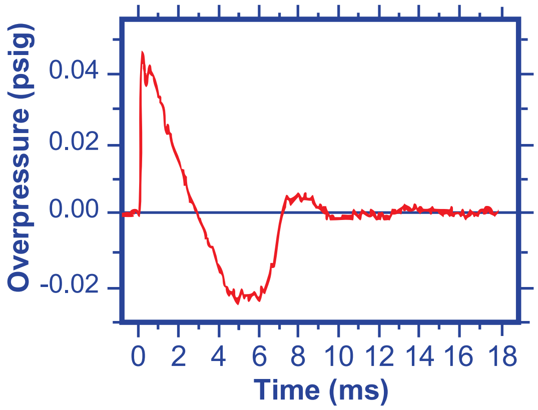

***Figure 5**. Example of air-blast wave recorded at a distance of 370 feet from a 3 inch firework salute exploded near ground level.*

As subjective responses, they are not amenable to direct physical measurement using scientific instruments. For that reason, in the research of the perception of salute sounds, it is necessary to include human observers, during testing, to provide their personal ratings of the characteristics of salute sounds. Additionally, during testing, measurements using scientific instruments are needed to define the physical parameters of the sounds to which the panel of human observers are exposed. In that way, it should be possible to correlate the perceived responses of the test subjects to a range of air-blast waves of differing physical parameters. In the text that follows, the three characteristics of salute explosions will be considered in somewhat more detail.

Loudness

Sound pressure level (SPL) is measured in decibels (dB) and is related to the pressure (P) of a sound wave, in comparison with a reference sound pressure (P_0), as indicated in Equation 2.[3]

$$\text{SPL} = 20 \log_{10} (P/P_0) \qquad (2)$$

In Equation 2, for the purpose of this discussion, P_0 is the standard reference pressure of 0.0002 microbar (root mean square). This reference pressure is generally accepted as the minimum audible sound for humans at 1000 Hz.[3] When converting to pressures measured in pounds per square inch, P_0 becomes 2.9×10^{-9} psi, and Equation 2 can be rewritten as,

$$\text{SPL} = 170.8 + 20 \log_{10} P \qquad (3)$$

At the reference frequency of 1000 Hz, over the range of intensity from the threshold of hearing to the threshold of feeling, sound pressure levels in decibels are arbitrarily set equal to 'loudness levels' (L_N) with the units of phons[3], i.e.,

$$L_N \text{ (in phons)} = \text{SPL (in decibels)} \qquad (4)$$

Over the range of loudness level from 40 to 100 phons, 'loudness' (N), with units of sones, as perceived by human subjects under ideal conditions, is related to loudness level as shown in Equation 5.[3]

$$\text{Log}_{10}\, N = 0.03\, (L_N) - 1.2 \qquad (5)$$

By substitution from Equation 4,

$$\text{Log}_{10}\, N = 0.03\, (\text{SPL}) - 1.2 \qquad (6)$$

Then solving for 'loudness' (N, in sones),

$$N = 10^{(0.03)(\text{SPL}) - 1.2} \qquad (7)$$

Loudness is expressed in a linear scale, such that at the reference frequency of 1000 Hz, a sound with a loudness (N), which is twice that of another sound, is heard (i.e., perceived) to be twice as loud by a typical observer under ideal conditions. In terms of decibels (at the reference frequency of 1000 Hz and in the range from 40 to 100 dB), each increase of 10 dB corresponds to a doubling of the loudness of the sound. Accordingly, from Equation 7, sounds of 40, 50 and 60 dB will be perceived as having loudness (N) of 1, 2 and 4 sones, respectively.

At typical spectator distances (roughly 400 feet, 110 m), the sounds from firework salutes are substantially greater than 100 dB and are not even remotely close to pure 1000 Hz tones. Thus, test subjects are likely to respond differently than the above theory suggests. Nonetheless, as a hypothesis for testing, one might start by assuming that the perception of even these very loud impulse sounds follows the same general relationships described above. Indeed, if that were the case, it would be relatively easy to characterize the perceived loudness of the sounds of salutes (as a function of distance from the source), using data recorded with standard sound measuring instruments.

Tonal quality

For non-impulse sounds of sufficient duration, the frequency of the wave form fundamentally determines the tone or pitch of the sound, with high frequencies being heard as high-pitched sounds and low frequencies heard as low pitched sounds. The reciprocal of frequency is the 'period' of the wave, which is the time duration of one complete air-pressure cycle of the sound wave. Thus, for non-impulse sounds of sufficient duration, short period (i.e., high frequency) sounds are heard as being high pitched, whereas long period sounds are heard as being low pitched.

Even for pure tones, the sound must persist for some interval of time before its pitch will be perceived by a human observer. If the sound persists for only a very short time, it will be heard simply as a 'click', devoid of any sensation of pitch.[4a] If the tone persists a little longer, it will still be heard primarily as a click, but now with at least some minimal tonal quality (i.e., perceived as a somewhat high or low pitched click). The length of time that the tone must persist for it to begin to be perceived as having some tonal quality is called the 'click-pitch threshold', and that length of time depends on the frequency of the tone. Table 1 presents information on the approximate click-pitch threshold times for pure tones of various frequencies (the table values are derived from data in reference 4a). Note that, while the number of cycles the tone must persist for it to have some perceived tonal quality decreases for lower frequency tones, the corresponding required time duration that the tone must persist increases.

Table 1. *Approximate 'click-pitch threshold' for various frequency tones*[4a]

Frequency (Hz)	Period (ms)	Click-pitch threshold (ms)	Number of cycles
2000	0.5	3.5	7.0
1000	1.0	3.5	3.5
500	2.0	6	3.0
250	4.0	11	2.7
125	8.0	18	2.2

Based on the air-blast wave form shown in Figure 5, the period of the wave (i.e., the time duration of its positive plus negative phases) is approximately 7 milliseconds, corresponding to a frequency of approximately 140 Hz (i.e., 140 cycles per second). Using the information in Table 1, the click-pitch threshold for such a sound requires a duration of approximately 16 milliseconds (or roughly 2.3 cycles) for there to be a perceived tonal quality to the sound. Accordingly, essentially no tonal quality would be expected for the blast wave from the explosion recorded in Figure 5. However, to the contrary, as a matter of common experience, there is at least some minimal perceived tonal quality associated with such explosions. For example, consider the sound produced by two explosions occurring near ground level. The first is the explosion of a standard 1.5 inch (38 mm) firecracker at a distance of several feet (roughly 2 m), and the second is the explosion of a 3 inch (75 mm) salute at a distance of a few hundred feet (roughly 100 m). Both explosions will produce an air-blast wave of roughly 0.05 psi (0.34 kPa) peak overpressure. However, the period (the duration of positive plus negative phases) of the salute's blast wave will be approximately 35 times longer than that of the firecracker (roughly 7 ms versus 0.2 ms). Certainly there is a perceived tonal difference between the sounds of the two explosions, with the salute explosion sounding much more mellow than the firecracker. Almost certainly the difference in tonal quality of these two explosions is the result of the great difference in the periods of their air-blast waves, even though both are less than the click-pitch threshold.

It should be noted that when salutes explode high in the air and the observer's ear is several feet (roughly 2 m) above the ground, there will be a significant delay between the arrival time of the air-blast wave coming directly from the salute and the arrival time of the same blast wave after its having been reflected off the ground. This produces an overall effect of the blast wave going through what appears to be two cycles rather than only one. Figure 6 is the recorded blast wave from a test salute exploding approximately 400 feet (120 m) in the air with the sound detecting instrument positioned approximately 5 feet (1.5 m) above the

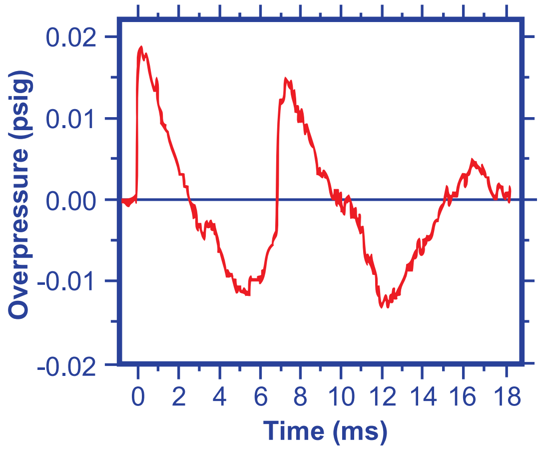

Figure 6. Example of an air-blast wave recorded a few feet above the ground, from a salute exploding high in the air.

ground. In this case, the total duration of the blast wave is approximately 16 milliseconds, thus approximately equalling the click-pitch threshold for an approximately 140 Hz sound.

There is another potential complicating factor with respect to the perception of salute sounds. For non-impulse sounds, there is an interrelationship between the perceived loudness and the perceived pitch of those sounds. Specifically, loud tones less than roughly 1500 Hz are perceived to have slightly lower pitches, while loud tones greater than roughly 1500 Hz are perceived to have slightly higher pitches.[4b] Thus, in salute testing, there may be some degree of interplay between a spectator's perception of loudness and the tonal quality of exploding salutes.

It can be assumed that the combined duration of positive and negative phases of an air-blast wave is analogous to the period of a repeating wave form. Despite the duration of the impulse sounds from salutes often being less than the click-pitch threshold, as a test hypothesis, and with all else being equal, impulse sounds with long phases can be anticipated to be heard as somewhat more 'mellow booms', as compared with short phase sounds, which are expected to be heard more nearly as 'sharp crack' sounds.

Physical sensation

The physical response of an object to air-blast pressure waves depends on peak overpressure, the duration of positive phase, and the 'critical time' of the object (which can be estimated to be one quarter of the reciprocal of resonant frequency of the object[1c]). When the duration of positive phase is much longer than the critical time of an object, the physical response of that object is approximately proportional to the air-blast wave's peak overpressure, whereas, when the duration of positive phase is shorter than the critical time of an object, the response is approximately proportional to the blast wave's pressure impulse (i.e., the area under the pressure *versus* time blast wave curve). In the case of the human body, it would seem that the duration of the positive phase of a salute sound is likely to be shorter than the critical time of most of one's more massive body parts. Thus, as another test hypothesis in a study of the perception of salute blast waves, it can be presumed that the physical sensation felt by the observers will correlate with the pressure impulse of the blast wave. That is to say, for two equally loud sounds, the one with the longer positive phase will be felt by observers to produce a greater pressure sensation (i.e., chest thump).

Conclusions

In summary, three possible hypotheses for a study of salute sound perception by humans are:

1. The perceived loudness of a salute sound will approximately follow Equation 7, above.
2. For salute sounds of approximately equal loudness, those with a longer phase duration will be heard as being more mellow in tonal quality.
3. For two salute sounds with the same peak overpressure, the one with the longer positive phase will be felt by observers to produce a greater blast-pressure sensation (i.e., chest thump).

Acknowledgements

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