Impulsive Sound

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Introduction

Impulsive sound is a basic type of sound event. It is relevant for the assessment of noise annoyance and hearing risks. Despite its very basic nature and high relevance, many definitions [1] on what impulsive sound actually is are rather vague, along the lines of it being characterized by short duration, abrupt onset, and typically high peak sound pressure.

The International Standards Organization [2] is currently looking into harmonizing definitions and criteria for impulsive sound in standards concerning acoustics. This paper aims to provide some suggestions on minimal properties of impulsive sound in this context.

Impulsive Sound Signal

A physicist's approach to understanding what impulsive sound looks like is taking a guess what the sound pressure signal might look like. With the minimal assumption that there is a jump up in sound pressure and some kind of quick but finite decay of this sound pressure, a simple guess for the shape of this signal would be a step function and exponential decay.

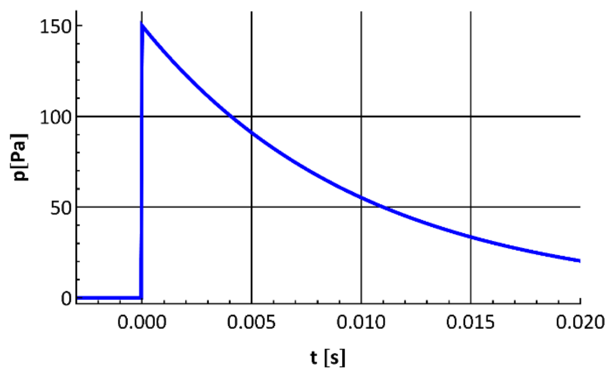

Figure 1: Sound pressure vs time signal for step function and exponential decay

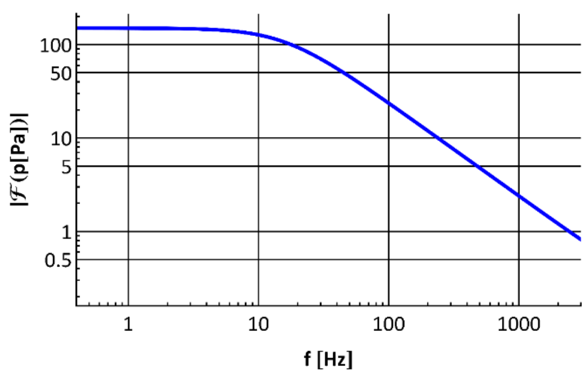

Figure 2: Spectrum for step function and exponential decay

The sound pressure signal is defined by just the peak pressure p_0 and the decay time τ:

$$p(t) = p_0 e^{-\frac{t}{\tau}} \theta(t) \qquad \text{[Pa]} \qquad (1)$$

The spectrum can be determined by Fourier-transformation from the time to the frequency domain. (Example in figures 1 and 2.)

Leading edge of the signal

When sound is propagated through air, higher frequencies are more strongly absorbed than low frequencies [3]. Assuming the signal has this finite jump at the source, and the spectrum shown in figure 2, higher frequencies will be increasingly damped with increasing distance. Fig. 3 shows examples for increasing distances from the source. All other effects such as geometric divergence, that just decreases the overall level without changing the shape of the signal, are ignored.

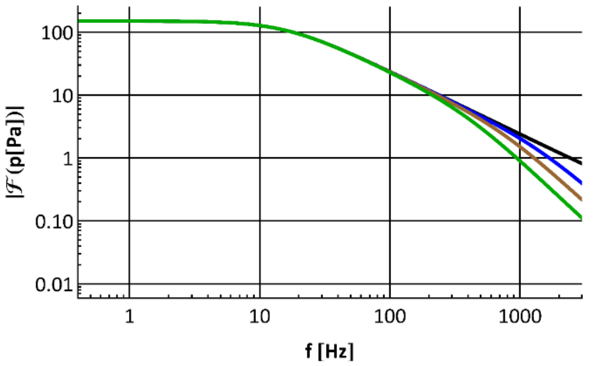

Figure 3: Spectra of the exponential decay function at the source, and for increasing distances

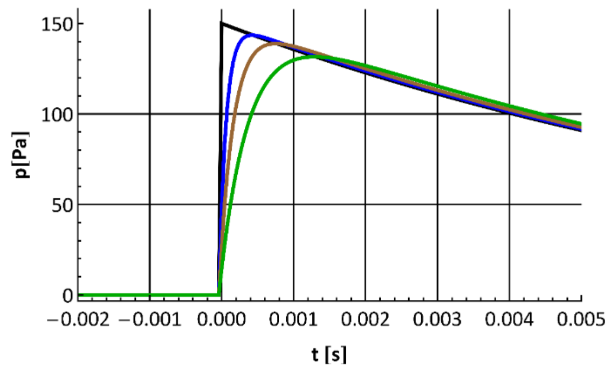

Figure 4: Sound pressure vs time signal for exponential decay example with air absorption

By Fourier-transform, the signal can be taken back from the frequency domain to the time domain. Figure 4 shows the corresponding examples as sound pressure vs time signals. The high frequency attenuation due to air absorption results in the leading edge of the signal being further reduced in sharpness with distance. The peak pressure is decreased, and the signal rise time slowed down. The apparent rise time is exaggerated by the horizontal time scale used in figure 4. The signal rise times shown in table 1 are all below 1ms, so even at fairly large distances the leading edge can be expected to be very steep.

Table 1: Max-pressure p_{max} and signal rise time t_{rise} for example in figure 4

d [m]	p_{max} [Pa]	t_{rise} [ms]
0	150.0	0.00
500	143.5	0.20
1000	139.9	0.36
2000	131.6	0.68

Sound signal generation

The key property of the signal above is the finite step up in sound pressure. To generate such a signal, air needs to be pushed instantaneously, resulting in a discontinuous jump in sound velocity.

There are two general ways to achieve this:

- mechanical impact (e.g. hammer hitting a plate)
- a shock wave (from e.g. an explosive)

To understand what signals generated in this way look like, consider the simple case of a spherical source without any directivity. For this case, the solutions for harmonic signal are known. Figure 5 shows sound velocity and sound pressure renormalized to fit in one plot. The signal is driven by air being pushed, which corresponds to sound velocity driving the signal, with the sound pressure following. Both signals are harmonic and decaying with distance.

Figure 6 shows the same, but for a lower frequency. At the source radius, sound velocity pumps the same, but it becomes apparent that sound pressure – while following sound velocity – is smaller.

As frequency decreases this effect becomes more pronounced. The ratio between is sound pressure and sound velocity can be plotted vs frequency, as shown in figure 7. The effect that the ability of sound velocity to drive sound pressure decreases with dropping frequency is called radiation resistance.

The spectrum for exponential decay as shown in figure 2 is finite for small frequencies. To get such a sound pressure signal, due to radiation resistance, sound velocity would need to go to infinity for small frequencies, making an exponential decay function an unlikely sound pressure signal.

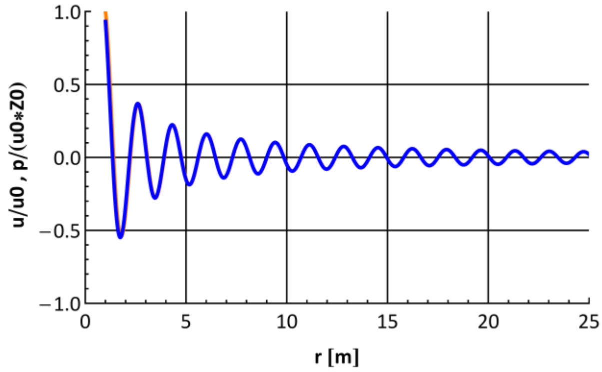

Figure 5: Sound velocity (orange) and sound pressure (blue) for a spherical source with radius 1m and frequency 200Hz.

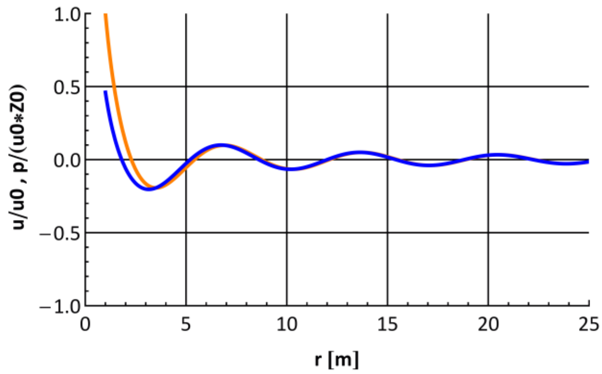

Figure 6: Sound velocity (orange) and sound pressure (blue) for a spherical source with radius 1m and frequency 50Hz.

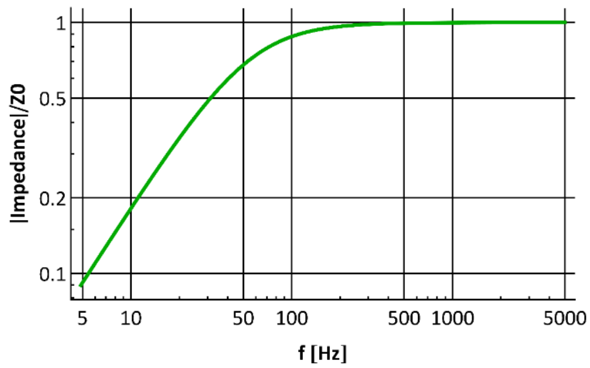

Figure 7: dynamic ratio between sound pressure and sound velocity, or radiation resistance

Possible source signals

Radiation resistance necessitates a signal shape that is more physically plausible than the simple exponential decay. Looking again for a minimalistic solution, a system that jumps to a finite value and then decays can be looked at as a damped harmonic oscillator. A damped harmonic oscillator exhibits three regimes:

- High damping – system returns to equilibrium without oscillation (overdamped)
- Low damping – system oscillates while decaying (underdamped)
- Critical damping – transition between the two, returning as quickly as possible without oscillation

The overdamped case corresponds to a simple exponential decay, as discussed above. Decay with harmonic oscillations adds some extra complexity.

The spectrum for the case of critical damping is shown in figure 8. The shape of this spectrum just happens to look like that of the exponential decay function for high frequencies and matches radiation resistance for low frequencies.

In the time domain, this signal is called the Friedlander [5] wave. It is the basic sound pressure time signal expected for blast waves whenever more detailed source information is not available. It has the shape of exponential decay with an overshoot:

$$p(t) = p_0 \left(1 - \frac{t}{t_s}\right) e^{-\frac{t}{t_s}} \theta(t) \quad \text{[Pa]} \qquad (2)$$

The decay time t_s and the corresponding location of the maximum in the spectrum is determined by the radius of the source. There are only two independent parameters for the signal: The radius of the source and the peak sound pressure. Figure 10 shows how the peak in the spectrum is shifted to lower frequencies as the radius of the source increases.

Special case of a blast source

If the source of the signal is an explosive blast, further assumptions can be made. The explosion creates a small volume with high temperature and high pressure. This volume initially expands with a speed that is greater than the speed of sound. The front of such a volume expanding at a speed faster than the speed of sound is also called a shock wave. As the volume expands, the rate of expansion decreases, until at some point it drops below the speed of sound. At this point, acoustic waves can escape, the acoustic bang is generated. The radius at which this happens is the radius of the signal source, and it depends on the energy of the explosive charge, as does the peak sound pressure. In this special case, the shape of signal is determined by just one parameter. In this idealized model, the radius of the source, the decay time of the signal, the peak sound pressure, are all determined by the energy of the explosive.
This model is known as the Weber-model [6].

More general signals

The impact of a hammer to a plate can generate a similar signal, but the parameters are not directly coupled. The signal decay time is determined by the radius of the plate, while the peak pressure is determined by how hard the plate is struck.

The given examples are oversimplified on purpose. Obviously not every object impacted just happens to be critically damped or have a nice spherical shape. But instantaneous moment transfer will result in a discontinuity in sound velocity, giving the resulting signal a leading edge with a jump in sound pressure.

For the case of hitting an object with a hammer, a simple case of ringing is shown in figures 11 and 12. The decay of the sound pressure signal is modulated by a harmonic oscillation, the spectrum shows a corresponding peak.

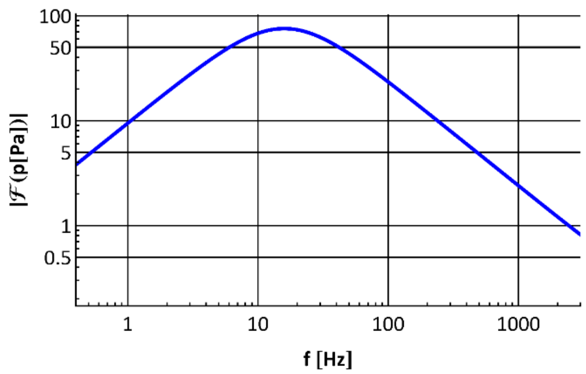

Figure 8: spectrum of a critically damped harmonic oscillator

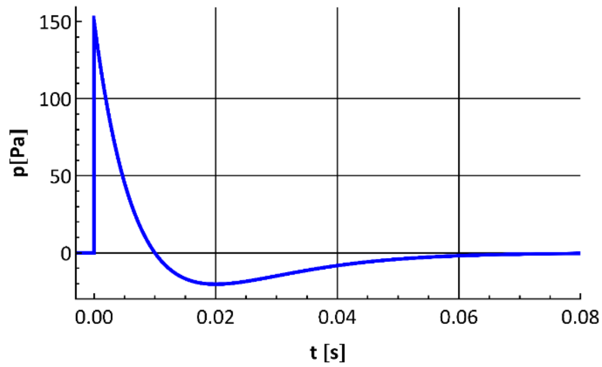

Figure 9: sound pressure vs time signal: Friedlander wave

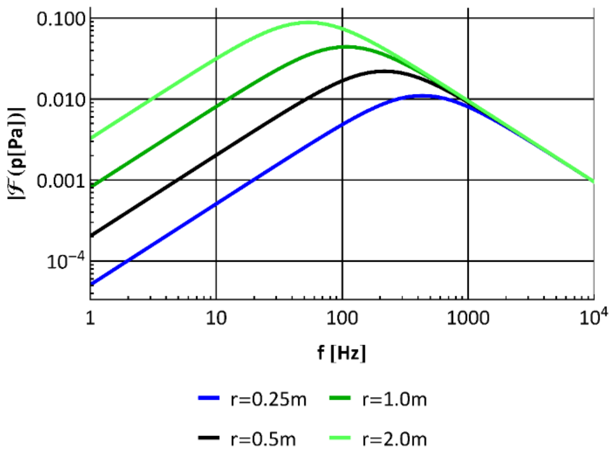

Figure 10: spectra of Friedlander waves, with the peak shifted to lower frequencies as the radius of the source is increased.

Realistic signal at receiver locations

While the discussed source signals are simplified and idealized, the leading edge of the signal is a discontinuous jump to a finite pressure at the source. Due to air absorption, this leading edge will be slightly softened. Understanding the effect of air absorption allows bounding the expected rise time at the receiver.

The shape of the trailing signal can depend on lots of details, but the decay time is largely determined by the size of the source. If an impulsive sound signal at a receiver is the result of sound propagation on one path or very similar paths, limits on signal decay time are known.

Often, impulsive sound signals at a receiver are the sum of many reflected signals coming to the receiver on different paths. This superposition of impulsive sound signals can result in prolonged signal decay times. The leading edge of the first signal to arrive at the receiver will still show the fast signal rise time of a single impulsive sound signal.

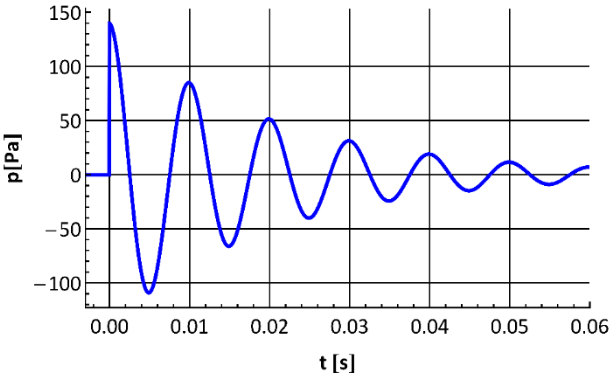

Figure 11: sound pressure vs time signal plate with ringing

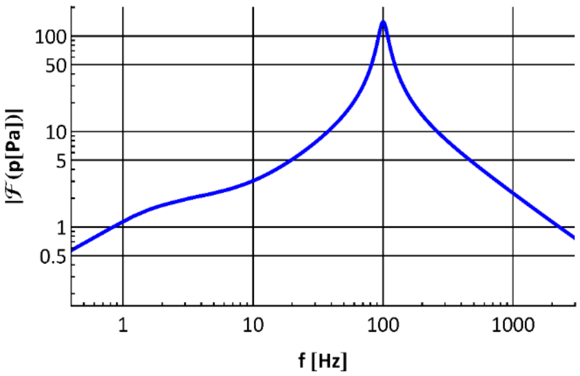

Figure 12: spectrum ringing plate

Assessment

While this paper focuses on physical properties of impulsive sound, the ultimate purpose of distinguishing impulsive sound from other types of sound is its special role in hearing risks and annoyance.

At a very basic level, C-weighting is a reasonable basis for assessing hearing risk, while A-weighting is commonly used for evaluating annoyance. Figure 13 shows the effect those frequency weightings have on the shape of an example impulsive sound signal. The frequency weighted peak pressures are reduced, and the overall shape of the signals noticeably changed.

Studies on hearing risk from impulsive sound typically focus on events that align with the understanding of impulsive sound developed in this paper—specifically, signals with a steep rise and short duration. Exposure limits based on C-weighted peak levels derived from such studies may underestimate the risks associated with other types of sound events, particularly those with longer durations.

Assessment of annoyance is usually based on a frequency weighting A, and often in combination with a time weighting F. Figure 14 illustrates how much the signal shape is changed, and especially how much the peak sound pressure is reduced due to the application of F-weighting.

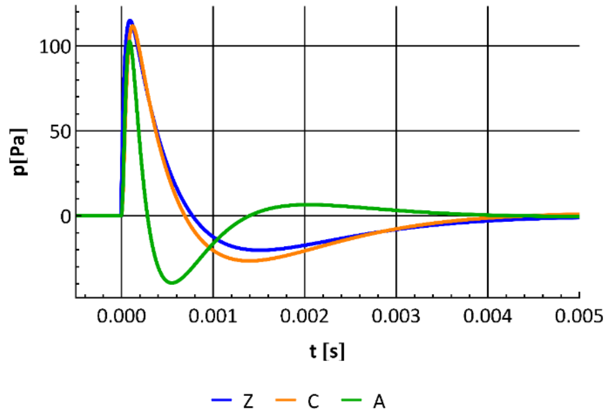

Figure 13: Sound pressure vs time signal with Z-weighting (linear, or no weighting), C-weighting and A-weighting

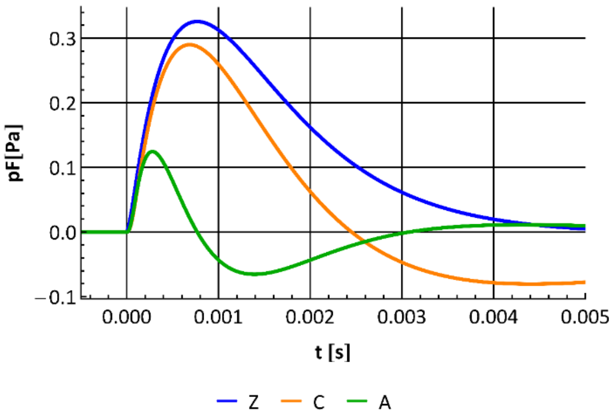

Figure 14: F-weighted sound pressure vs time signal for Z- weighting, C- weighting and A-weighting

Conclusion

Impulsive sound remains loosely defined in many standards. By examining simple, physically motivated signal models, this paper highlights key features that help characterize such sounds—particularly the sharp onset and decay behaviour. These insights may support more robust classification and assessment in future guidelines.

Literature

[1] e.g. ISO 1996 parts 1,2 and 3

[2] ISO/TC 43 Acoustics

[3] ISO 9613-1:1993, “Calculation of the absorption of sound by the atmosphere”

[4] ISO 10843:1997, “Methods for the description and physical measurement of single impulses or series of impulses”

[5] Friedlander, F. G. “The diffraction of sound pulses”, Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 186(1006), 322–344. 1946

[6] W. Weber: „Das Schallspektrum von Knallfunken und Knallpistolen…“; Akustische Zeitschrift 4 (1939), 377-391