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Review

Review of Acoustic Sources Alternatives to a Dodecahedron Speaker

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Abstract: An omnidirectional source is required in many acoustic measurements. Commonly a dodecahedron speaker is used but due to various factors (e.g., high cost, transportation difficulties) other acoustic sources are sometimes preferred. In this review, fifteen acoustic source alternatives to a dodecahedron speaker are presented while emphasis is placed on features such as omnidirectionality, repeatability, adequate sound pressure levels, even frequency response, accuracy in measurement of acoustic parameters and fulfillment of ISO 3382-1 source requirements. Some of the alternative acoustic sources have the appropriate features to provide usable results for acoustic measurements, some have acoustic characteristics better than a dodecahedron speaker (e.g., omnidirectionality in the high-frequency range), while some can potentially fulfill the ISO 3382-1 source requirements. Collected data from this review can be used in many areas (e.g., ISO measurements, head-related transfer functions measurements) for the appropriate selection of an acoustic source according to the expected use. Finally, suggestions for uses and future work are given aimed at achieving further advances in this field.

Keywords: acoustic measurements; impulse response measurements; omnidirectional source; dodecahedron; acoustic parameters; sound source; reverberation time; ISO 3382; auralization

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1. Introduction

From the point of view of acoustics, a source is a region of space, in contact with the fluid medium where new acoustic energy is being generated, to be radiated outward as sound waves [1]. Source mechanisms, according to Fahy [2], may be broadly placed in one of the following three general categories on a phenomenological basis: fluctuating volume/mass displacement or injection, accelerating/fluctuating force on fluid and fluctuating fluid shear stress. Enlightening examples and description of the generation of sound from each category can be found in [3]. The most common category is the first one (fluctuating volume/mass displacement or injection) with sources such as loudspeakers, handclaps and vibration surfaces. The fluctuating volume/mass displacement or injection is the rate of change of the rate of fluid volume displacement (i.e., the volume acceleration) which determines the strength of the sound generated. It has to be noted that vibrating surfaces could also exert fluctuating forces on a contiguous fluid as byproducts of the fluid displacement activity [2]. Categorization of sources according to the generation of sound is also presented by Kurze [4].

Insights into the behavior of many practical acoustic sources can be obtained by considering elementary, idealized sources. A source that is concentrated at a point and produces an omnidirectional sound field is called a simple source or a monopole source [5]. The conceptually simplest sound source with finite extension is the spherical source, often referred to as 'pulsating' or 'breathing sphere' [6], which falls into the category of fluctuating volume/mass displacement or injection. A sphere, pulsating harmonically at any frequency at which its circumference is very much less than an acoustic wavelength, generates a sound field close to that of an ideal point monopole, except in the near field [7].

1.1. Acoustic Measurements with Omnidirectional Sources

A practical implementation of a pulsating sphere producing an omnidirectional field is useful in many fields of acoustics. An omnidirectional sound source is required in many acoustic measurements set by the International Organization for Standardization (ISO) as well as many standards set by national organizations, such as the American National Standards Institute (ANSI), the German Institute for Standardization (DIN-Deutsches Institut für Normung) and the British Standards Institution (BSI).

Due to the large number of standards, we will only mention standards for acoustic measurements by the ISO where a source with omnidirectional characteristics is required, such as ISO 3382-1 [8], ISO 3382-2 [9], ISO 3382-3 [10], ISO 354 [11], ISO 17497-1 [12], ISO 17497-2 [13], ISO 16283-1 [14], ISO 16283-3 [15] and ISO 10140-2 [16].

ISO 3382-1 describes the appropriate measurement of the impulse response and acoustic parameters of performance spaces, ISO 3382-2 of ordinary rooms and ISO 3382-3 of open-plan offices. An impulse response is the temporal evolution of the sound pressure observed at a point in a room as a result of the emission of a Dirac impulse at another point in the room. Acoustic parameters can be obtained directly from the impulse response and used to assess the acoustic quality of a space and provide guidance for possible improvements. ISO 354 describes the measurement of the sound absorption coefficient of materials performed in a reverberation chamber. ISO 17497-1 describes the measurement of the random-incidence scattering coefficient in a reverberation room (part two in a free field). ISO 16283-1 describes the measurement of the airborne sound insulation in buildings (part three for façade sound insulation) and ISO 10140-2 describes the laboratory measurement of sound insulation of building elements.

An acoustic source is also necessary for the measurement of head-related transfer functions (HRTFs) which are important for auralization purposes in many fields, such as virtual and augmented reality. HRTFs are defined as the free-field transfer functions, from a point sound source to each of the two ears on a fixed head. In practice HRTFs, describe the overall filtering effect imposed by anatomical structures. As stated by Xie [17], "in far-field HRTF measurements, the point sound source needed can be approximated by a common, small, loudspeaker system, where measurement errors caused by the size and directivity of the loudspeaker, as well as the multiple scattering between subject and loudspeaker, are negligible". However, in near-field measurements, the size of the source and scattering between subject and source is a key element for accurate measurements [18]. Under such conditions, a commonly used loudspeaker can no longer be regarded as a point source. Therefore the appropriate sound source is necessary for the measurement of the HRTFs. In relevant research [19], a dodecahedral sound source with a small radius (0.035 m) is proposed.

1.2. Requirements for Omnidirectional Sources

Requirements for an omnidirectional sound source aimed for acoustic measurements are provided in ISO 3382-1 [8], ISO 16283-1 [14], ISO 10140-5 [20] and ISO 140-3 [21]. However, the most referred ones are the requirements on ISO 3382-1. Those are:

"The sound source shall be as close to omnidirectional as possible. A maximum deviation of directivity of source in decibels for excitation with octave bands of pink noise and measured in free field is expected (Table 1)".

"The sound source shall produce a sound pressure level sufficient to provide decay curves with the required minimum dynamic range, without contamination by background noise. In the case of measurements of impulse responses using pseudo-random sequences (e.g., maximum-length sequence (MLS) [22]), the required sound pressure level might be quite low because a strong improvement of the signal-to-noise ratio by means of synchronous averaging is possible. In the case of measurements which do not use a synchronous averaging (or other) technique to augment the decay range, a source level will be required that gives at least 45 dB above the background level in the corresponding frequency band".

Table 1. The maximum deviation of directivity of source in decibels for excitation with octave bands of pink noise and measured in free field (ISO 3382-1).

Frequency (Hz)	125	250	500	1000	2000	4000
Maximum deviation (dB)	±1	±1	±1	±3	±5	±6

Less stringent requirements for a maximum deviation of directivity are described in ISO 16283-1 [14] and ISO 10140-5 [20] (Table 2). Specifications are also described in ISO 140-3 [21] which is now withdrawn. ISO 10140-5 states that: "Uniform omnidirectional radiation can be assumed if the directivity index (DI) values are within the limits of ±2 dB in the frequency range of 100 Hz to 630 Hz. In the range of 630 Hz to 1000 Hz, the limits increase linearly from ±2 dB to ±8 dB. They are 8 dB for frequencies of 1000 Hz to 5 000 Hz". It should be noted that the specifications are exactly the same for ISO 16283-1 beside a small difference. The ISO 16283-1 requires ±5 dB for 800 Hz a difference which is indistinguishable between the standards.

Table 2. The maximum deviation of directivity of source in decibels for excitation with octave bands of pink noise and measured in free field (ISO 16283-1, ISO 10140-5 and ISO 140-3 (withdrawn)).

Frequency (Hz)	100	630	1000	5000
Maximum deviation (dB)	±2	±2	±8	±8

Figure 1 presents the limits for the maximum deviation of directivity for all the standards. ISO 140-3 is also presented since it is still sometimes referred in some dodecahedron speaker specifications. Directions for the measurement of directivity can be found in some standards such as ISO 3382-1, ISO 10140-5, ISO 16283-1 and ISO 16283-2. The maximum acceptable deviations from omnidirectionality are measured when averaged over 'gliding' 30° arcs in a free sound field. In case a turntable cannot be used, measurements per 5° should be performed, followed by 'gliding' averages, each covering six neighboring points. The reference value shall be determined from a 360° energetic average in the measurement plane. The minimum distance between source and microphone shall be 1.5 m during these measurements. However some concerns have been expressed about measuring the directivity according to those standards [23–25]. Also, a new descriptor for measuring the directivity of dodecahedron speakers and omnidirectional sound sources has been proposed [26].

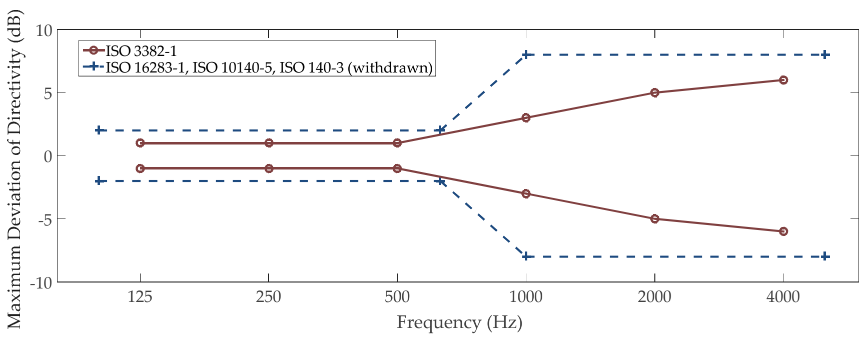

Figure 1. The maximum deviation of directivity of source in decibels for excitation with octave bands of pink noise and measured in free field for ISO 3382-1, ISO 16283-1, ISO 10140-5 and ISO 140-3 (withdrawn).

1.3. Dodecahedron Speakers

The most common practical implementation of a pulsating sphere producing an omnidirectional field is a dodecahedron speaker. As Kuttruff states [27]: "its radiation characteristics (pulsating sphere) can be approximated within certain limits by a regular dodecahedron or icosahedron composed of 12 or 20 regular polygons, respectively, each of them fitted out with a loudspeaker in its center". However, commercial implementations exist mainly for the dodecahedron speakers and less for the icosahedron speakers.

Dodecahedron speakers are omnidirectional sources widely used for room acoustics measurements. Commercially available dodecahedron speakers are manufactured and tested in order to meet the ISO 3382-1 sound source requirements. The omnidirectional directivity is approached by placing 12 electrodynamic loudspeakers (direct radiator type) in a regular 12-face polyhedron. The dodecahedron speaker, in essence, is a "dodecahedron arrangement of drivers to approximate the omnidirectional sound radiation characteristics of a monopole" [28]. However, other polyhedron loudspeakers can also be used which in some cases can be viewed as equally omnidirectional [29].

In practice, since dodecahedron speakers cannot emit sufficient acoustic power if an impulsive signal is applied directly, alternative excitation signals are used. The most common ones are maximum-length sequence (MLS) [22] and exponential sine sweep (ESS) [30] which are described in Annex A and B of ISO 18233 [31], respectively. Application of these methods ensures that the loudspeaker can emit a large amount of energy with longer duration without challenging its limited peak power capability, while impulse responses with a high time resolution can still be obtained afterward through post-processing. These deterministic excitation signals can be accurately reproduced and thereby enhance the repeatability of the measurements. Since the dodecahedron speaker utilizes MLS or ESS signals, enhancement of the signal-to-noise ratio by 20 dB to 30 dB or more compared to the classical method may be obtainable, as ISO 18233 [31] states. However, as ISO 18233 also states, the use of loudspeakers typically introduces non-linear distortion in the system which increases with the excitation level and violates the requirement for linearity, hence appropriate signal levels should be chosen. Optimum signal-to-noise ratios can be found in Stan et al. [32], while comparison of the two methods can be found in [33]. The appropriate choice of excitation signal for acoustic measurements can be depended on the background noise [34].

Drawbacks of Dodecahedron Speakers

Despite the widespread use of dodecahedron speakers, there are certain drawbacks associated with them. Namely, we can say deviation from omnidirectionality, low-frequency performance and practical reasons such as high cost.

The dodecahedron speaker fails to be an exact approximation of a monopole source since there is a deviation from omnidirectionality. The directivity of a dodecahedral loudspeaker can be considered uniform in the low-frequency range, while at higher frequencies (namely above 1 kHz), sound radiation shows greater deviation [26]. Because of the finite difference in distance between the loudspeaker diaphragms as well as the fact that these usually have a conical shape and are not a continuous part of the spherical surface, the radiation pattern is not ideally spherical at frequencies where the distance between loudspeakers or the depth of the cones are larger than a small fraction of the wavelength. Typically, the deviations start to become large when $ka > 3$, where a is the radius of the sphere and k is the wavenumber [35]. These deviations seem to increase, the smaller the measuring distance from the sound source inside the critical distance [36]. It has also been shown that constructive interference of the pressure field across the spherical baffle surface and not individual loudspeaker pistonic radiation characteristics is the most significant factor with respect to deviations from omnidirectional radiation [37]. Another reason for the deviation from omnidirectionality is that the impulse response of a dodecahedron speaker will feature contributions due to edge diffraction. Correspondingly, the frequency response of the loudspeaker will feature frequency response irregularities [35]. It has to be noted that these deviations from omnidirectionality have an effect on the measurement of the impulse response and acoustic parameters of a space [24,25].

However, stepwise rotation of a dodecahedron sound source can be employed to improve the accuracy of room acoustic measurements [38]. Also, three-way measuring loudspeakers with omnidirectional characteristics have been proposed as a possible solution [39]. There are also commercial implementations in which the twelve drivers of the dodecahedron speaker are placed in a sphere in order to avoid edge diffraction.

Another drawback, especially for dodecahedron speakers of smaller size, is their output in the low-frequency range. Since dodecahedron speakers utilize electrodynamic loudspeakers (direct radiator type) their performance at low frequencies depends on the size of the drivers [40,41]. This means that smaller-size dodecahedron speakers usually have lower output at low frequencies. However, subwoofers can be used in combination with a dodecahedron speaker in order to increase the sound pressure levels at low frequencies [39,42].

There are also other drawbacks of dodecahedron speakers, mainly due to practical reasons. Their high cost makes them probably the most expensive equipment in an acoustic measurement setup. Also, their heavy weight combined with their large volume makes transportation difficult e.g., transfers to airports. There are also cases where their use is required in places where there is no electricity supply. An external generator or an appropriate dodecahedron speaker with an internal generator can be used, which further increases the cost.

1.4. Aim of This Review

The authors would like to express the two main reasons which motivated the writing of this paper. Firstly, in order to provide the acoustic community with an organized overview of the alternative acoustic sources to a dodecahedron speaker and to present them in a way that emphasizes their important elements. There is a considerable amount of literature on the subject. However, there are no surveys presenting and examining all of these sources. Collective reference for audio sources can be found in the introduction of some publications [26,43].

Secondly, there seems to be a need for alternative sound sources to a dodecahedron speaker for acoustic measurements. Numerous examples can be found in the literature where alternative sound sources were used. Some examples and the sources that were used are: The measurement of impulse responses in open-air theatres (firecracker) [44,45], in churches (pistol shots and balloons) [46], in Buddhist temples (balloons) [47], measuring the acoustics of catacombs (balloons and firecrackers) [48,49], measurements in Stonehenge (balloons) [50], measurements in the Notre-Dame cathedral (balloons) [51], measurements in the Hagia Sofia (balloons) [52], measurements in urban environments (pistol shots) [53], green roofs absorption (pistol shots) [54], measurements in subway stations (firecrackers) [55], the acoustic of caves (balloons) [56,57], room acoustics (handclap) [58], barrier attenuation (shotshell primer) [59] and classroom acoustics [60] (wooden clapper). The reason that prompted the use of these alternative sources will be presented in the following related chapters.

It is worth noting that this review refers to sound-source alternatives to a dodecahedron speaker. This review does not include sources for the determination of sound power levels as stated by ISO 6926 [61] and used in various measurements such as ISO 3741 [62], ISO 3743-1 [63] and by the survey methods described in ISO 3747 [64]. Also this review does not include sources described in IEC 60268-16 [65] which specifies objective methods for rating the transmission quality of speech with respect to intelligibility (the standard requires a mouth simulator having similar directivity characteristics to those of the human head/mouth).

This paper has been organized in the following way: Section 2 presents the acoustic sources along with the relevant studies. The third section presents a discussion of the aforementioned studies and a critique of the significant findings and identifies areas for further research. Finally, the conclusion section gives a brief summary and contextualizes the research.

2. Acoustic Source Alternatives to a Dodecahedron Speaker

This chapter will present fifteen acoustic sources alternatives to a dodecahedron speaker (Table 3). The list includes only sources for which relevant publications were found in the literature. The most common alternative acoustic sources with the most references and practical applications are the balloon, gunshot, firecracker, handclap and inverse horn design. These sources are going to be presented first. The next sources in the list (wooden clapper, shotshell primer, rotation of directional speaker, ultrasound piezoelectric transducer, ring radiator, explosive mixture of acetylene gas with air and compressor nozzle hiss) have a smaller number of references in the literature. Directional speakers which are next in the list are not alternative sources to a dodecahedron speaker since they are not omnidirectional. However, they are used as such and therefore have been included in the list. There is a considerable amount of literature concerning the application of lasers in acoustics. However, a laser-induced breakdown is a relevant new acoustic source with potential for practical applications. Finally, electric spark sources have been mainly used for the simulation of acoustic phenomena using scale models. However, there are some publications where they are used as an alternative source for acoustic measurements and they are therefore included in this review.

Table 3. List of acoustic source alternatives to a dodecahedron speaker.

1. Balloon	7
2. Gunshot	9
3. Firecracker	10
4. Handclap	11
5. Inverse horn design	13
6. Wooden clapper	14
7. Shotshell primer	15
8. Rotation of a directional speaker	15
9. Ultrasound piezoelectric transducer (spherical distribution)	16
10. Ring radiator	17
11. Explosive mixture of acetylene gas with air	18
12. Compressor nozzle hiss	18
13. Directional speaker	19
14. Laser-induced air breakdown	20
15. Electric spark source	21

Emphasis will be placed on features such as omnidirectionality, repeatability, frequency response, adequate sound power, accuracy in measurement of acoustic parameters and fulfillment of ISO 3382-1 sound source requirements. The reason why these features were chosen to be presented in is because they are the most commonly studied features to be found in the literature and they also define the acoustic behavior of acoustic sources.

Source omnidirectionality is one of the two sound source characteristics required from the ISO 3382-1 standard. Omnidirectionality ensures uniform space excitation necessary for correct impulse response measurement. The directivity of the source influence the measurement of impulse responses and acoustic parameters of spaces [24,25]. For each source, we have collected various research that have investigated the directivity of the source in accordance with ISO 3382-1 or with more general criteria.

Source repeatability ensures that the same sound filed is produced from the sound source for each measurement and hence similar impulse response and acoustic parameters are measured. Source repeatability is considered to be given for acoustics sources that utilize electrodynamic speakers (e.g., dodecahedron speaker). However, for sources of the impulsive type (e.g., handclaps and balloons) repeatability is not certain and may involve large variations. For each source we have collected relevant data from the literature.

Adequate sound pressure levels (according to ISO 3382-1) ensure that there will be no contamination in the acoustic measurements by background noise. Sound pressure levels should be studied in conjunction with a frequency response of the sound source since ISO 3382-1 requires source level at least 45 dB above the background level in the corresponding frequency band (if synchronous averaging is not available). For each source, total sound pressure levels have been collected from the literature and for each frequency band if available.

Even frequency response (or relatively even frequency response) ensures correct impulse response measurement which is important for auralization purposes through the process of convolution [66]. Although there are no specific restrictions in ISO 3382-1 about the source even frequency response, beside the following: "the source and associated equipment should be adequate to radiate a sufficient signal level in all of the octave bands for 125 Hz to 4000 Hz", however, restrictions can be found in ISO 16283-3: "The sound field generated by the loudspeaker shall be steady and have a continuous spectrum in the frequency range considered. The differences between the sound power levels in the one-third octave bands that define the octave bands shall not be greater than 6 dB in the 125 Hz octave band, 5 dB in the 250 Hz octave band and 4 dB in octave bands with higher center frequencies". Relevant information considering the frequency response has been collected from the literature for each source.

Accuracy in measurements of acoustics parameters depends on omnidirectionality, frequency response and sound pressure levels of the acoustic source. Research from the literature is presented in acoustic parameters that were measured with the use of alternative acoustic sources. Emphasis is given where comparisons have been made with dodecahedron speakers.

Finally, ISO 3382-1 source requirements as stated in the introduction involve omnidirectionality and adequate sound pressure levels. Concluding remarks if the acoustic source fulfills ISO 3382-1 source requirements or potentially fulfills the requirements are going to be presented.

2.1. Balloon

The balloon is an affordable solution commonly used as an alternative source for acoustic measurements. The impulsive nature of the popping explosion is the fundamental property of interest [67]. However, the impulse response of a balloon burst is not ideal. Measurements can be found in many kinds of research and for different balloon sizes [67,68]. "When a balloon is burst perfectly, the resulting acoustic disturbance should have the shape of the letter N" [69]. In reality, there are deviations in the expected N shape of the acoustic disturbance which results in an N wave spectrum containing nulls [70]. As Horvat et al. [68] states, "balloons require more time to release the acoustic energy (compared to other sources) due to the certain amount of time required for cracking the balloon wall".

According to the research presented in the introduction, the justifications that prompted its use were mainly the lack of electric supply [47,56,57], affordability and ease of use [52]. Referring to the research that utilized the balloon as a sound source: "The difficulty of operating in a cumbersome environment prevented the use of a sound source like a dodecahedron loudspeaker with a power amplifier" (Acoustic of caves [57]), "However, the site is in condition of repairs; hence, it is not possible to use such measurement techniques (dodecahedron speaker)" (Buddhist temple [47]), "Balloons are inexpensive and easy use" (Hagia Sophia [52]), "Due to the impossibility to connect to the electricity grid, the use of the whole equipment was not possible as recommended by ISO 3382" (Acoustic of caves [56]).

Considering omnidirectionality, the balloon as a sound source does not fulfill the ISO 3382-1 standard, especially for lower frequency bands. A study from Pätynen et al. [67] showed that for different balloon types, the magnitude of deviations for directivity below the 500 Hz octave band is on the order of 6–9 dB, well above the standard limits. However, directivity at higher frequencies fulfilled the omnidirectional source conditions. The degree of omnidirectionality improved with balloon size for midrange frequencies and larger balloons were close to the standard in the 1 kHz band. The balloon was found to radiate mostly toward the direction of needle impact. Also in the same study there seemed to be evidence that there are variations in actual directivity as a function of inflation levels. Similar results about the omnidirectionality have been reported by Griesinger [71] and Cheenne et al. [72]. Schlieren imaging of a balloon burst [73] reveals that the shock front is not quite spherical. However, Vernon et al. [74] showed that hydrogen-oxygen balloons seem to show better omnidirectionality with much less directional deviation. The maximum deviations fit within the ISO 3382-1 limits at the high frequencies and nearly fit within the limits at the low frequencies.

Concerning the question of repeatability, the balloon does not satisfy this requirement, but only under certain conditions. Studies by Griesinger [71] and Horvat et al. [68] have shown that the balloon has poor repeatability. Also, Topa et al. [75], in order to evaluate the repeatability of measurements and the effect this has on the acoustic parameters, performed measurements with balloons for the same source and microphone positions. Results for Clarity (C_{80}) revealed differences for the whole frequency range. However, Pätynen et al. [67] have reported that balloon directivity patterns are stable over repetitions if certain criteria are met. Spectra and radiated sound from a balloon were quite constant for a given balloon type with consistent inflation and performing the same popping method. Consistent inflations levels were evaluated by measuring the maximum width diameter with a 1 cm margin of error. Also a study by Cheenne et al. [72], where anechoic recordings of balloon bursts were systematically acquired for various conditions of balloon diameters, puncture location and inflation pressure, reports that the results are quite consistent when averaged over one-third octave bands. However it seems both the results found in the studies of Griesinger [71] and Cheenne et al. [72] are difficult to replicate in real-life measurements in order to achieve similar results.

Relating to sound pressure levels, Horvat et al. [68] measured differed sized balloons and found levels ranging from 133 to 138 dB. Results from Pätynen et al. [67] ranged from 121 to 137.5 dB. Highest sound pressure levels were found, as expected, for the largest balloons.

Regarding frequency response, the balloon does not offer adequate excitation at the low frequencies [68]. The spectral content of balloon bursts clearly indicates the direct relation between balloon size and the overall spectrum. Specifically, the largest balloons were found to provide the highest amount of excitation, especially at low $^{1}/_{3}$-octave (or octave) bands, where proper excitation always represents a problem. For smaller balloon size, the excitation at low bands decreased. This is expected to cause variations in acoustic measurements especially where the background noise is high. Results also indicate that frequency responses have two emphasized frequencies which depend on balloon size and inflation level [67]. However, exploding hydrogen-oxygen balloons produce primarily low-frequency content, with characteristic frequencies on the order of 100–200 Hz [74].

In regard to the measurement of acoustic parameters, there are several studies where this matter is addressed [68,75–78]. A study by Jambrosic et al. [76] showed that for measurements of reverberation time (RT) with the use of a balloon, results will deviate in the low-frequency range in rooms, compared with studies using standard techniques (dodecahedron speaker). However, if the measured room is large and reverberant, smaller deviations are to be expected. A study by Topa et al. [75], revealed similar deviation in the low-frequency range for measurements of RT and early decay time (EDT). Also measurements of clarity (C_{80}) and center time (T_s) suffered from great deviations in the whole frequency spectrum. Griesinger [71] also stated that directionality of the source (balloon) is important for measurements of speech intelligibility. However, a technique by Abel et al. [70] can improve the measured results by converting recorded balloon pops into full audio bandwidth impulse responses. The technique is synthesizing the impulse response of the balloon pop according to the echo density and frequency band energies estimated in running windows.

In conclusion, the balloon does not meet the ISO 3382-1 sound source requirements since it cannot be considered an omnidirectional source and it also has a low sound level in the low-frequency range.

2.2. Gunshot

A gunshot is produced by a firearm which can be characterized as a "heat engine that converts stored chemical energy into kinetic energy" [79]. The sound from a firearm discharge consists of multiple acoustic events: the ballistic shockwave, internal gas leaks or ejections, the muzzle blast and reflections. The primary sound is the muzzle blast which is an explosive shockwave in air produced by propellant gasses under extremely high pressure that expands rapidly once the bullet exits the muzzle. The impulse response and the waveforms from each acoustic events which it is composed are presented in a study by Beck [80]. Impulse responses from different firearms can be found in the literature [81].

Traditionally, acousticians have used a firearm with blank cartridges as a sound source for acoustic measurements since it is an impulsive source that is lightweight and small enough to be easily transported. A gunshot is explicitly specified in the standard ISO 354 [11] as a possible alternative sound source. As the ISO states: "It is impossible in practice to create and radiate true Dirac delta functions, but short transient sounds (e.g., from shots) may offer close enough approximations for practical measurements". It is important to notice that a lot of the research for firearms has been conducted for forensic analysis or gunshot detection systems [81–84].

According to research presented in the introduction, the justifications that prompted its use as a sound source were emission of high sound levels [54] and ease of use [53]. Referring to the research: "Use of a starter pistol as an excitation source is a potentially useful impulse response recording method, especially in situations where use of the equipment required for sine sweep measurement is impractical or inappropriate" (Measurements in urban environments [53]), "A main advantage of such a device is the emission of high sound levels which makes a shot easily identifiable even at locations with high background noise levels" (Green roofs absorption measurements [54]).

Considering omnidirectionality, the gunshot appears to have directional characteristics. As presented in ISO 17201 [85], the muzzle blast is directional with sound levels on-axis ahead of the muzzle higher than levels directly behind the muzzle by up to 20 dB. Freytag et al. [79] state that "one explanation for the directivity of muzzle blasts is that the sound source is rapidly accelerating at muzzle discharge". Griesinger [71] states that the pistol appears to be directional at low frequencies, where there is a rise in energy from the side. Similar results about the directional characteristics of the handgun and for large-caliber weapons can be found in [86,87]. Recordings of different handguns as a function of azimuth can be found in [81]. In a study by Settles et al. [88] utilizing shadowgraphy, shockwaves of gunshots are depicted and variation in directionality is evident among different guns. However, a study of different handguns by Lamothe and Brandley [89] indicated that a 0.38 caliber gun has the best omnidirectional characteristics.

Concerning the question of repeatability, Dezelak et al. [90] state that differences in the noise characteristics between individual cartridges for the same gun are usually small, so the impulsive source can be replicated to a high degree. However, a study by Maher and Routh [81] comparing the on-axis peak pressure levels for ten shots for different handguns revealed that variability was observed among different guns. Griesinger [71] states that handguns have poor repeatability.

Regarding frequency response, several studies have shown that energy falls rapidly in the low-frequency range for handguns [71,79,89–91]. The frequency spectrum of a gun typically has a peak energy output in the 1 kHz to 2 kHz region [71]. Below this frequency the energy falls off rapidly (~14 dB/octave on a 1/3 octave analyzer). However the 0.38 caliber gun exhibits a significantly flatter frequency response [89]. For that reason, Bradley [92] used a 0.38 caliber pistol firing black powder in his research for auditorium acoustic. On the contrary, high caliber weapons have higher energy in the lower frequency range [87].

Relating to sound pressure levels, measurements from Beck et al. [80] ranged from 151 to 161 dB and measurements from Jambrosic et al. [91] measured variations from 148 to 168 dB. As expected, the handgun emits one of the highest sound pressure levels among sound sources.

In regard to the measurement of acoustic parameters, research by Fausti and Farina [77] revealed differences between RT measurements with a gun and techniques utilizing a dodecahedron speaker especially in the low-frequency range (more than 0.3 s difference in the 125 Hz octave band). A study by Jambrosic et al. [76] revealed differences in the measurement of RT between pistol shots of different calibers. In a study by Bradley [92], comparisons between measured values and calculated values (RT, C_{80}, C_{50} and C_{35}) based on ideal exponential decays showed that such predictions are not particularly accurate but give an indication of the mean trends. In a study by Dezelac et al. [90], a gunshot was used for sound insulation measurements. Similar results were found in a comparison between the apparent sound reduction index of a common partition obtained by the gunshot and conventional methods (utilizing a dodecahedron speaker). An advantage that a gunshot has as an impulsive sound source is that it offers the possibility of removing the flanking transmission, since a gun is much more decoupled with a floor, than a heavy loudspeaker [90].

In conclusion, the gunshot does not meet the ISO 3382-1 sound source requirements since it cannot be considered an omnidirectional source. However, it produces high sound pressure levels and therefore it is used in practice as a source in various measurements.

2.3. Firecracker

Firecrackers are small explosive devices primarily designed to produce a large amount of noise. They are wrapped in a cardboard or plastic, and usually in cylindrical cartridges casing to contain the explosive compound. The propellant inside is a kind of powder which can be a mixture of substances such as flash powder, cordite, smokeless powder, black powder, sulfur, charcoal, potassium nitrate, etc. Firecrackers, similar to other impulsive acoustic sources, have a typical N-pattern sound wave. As Horvat et al. states [68] "The explosion of a firecracker filled with explosive charge will provide a typical N-pattern sound wave, due to the fact that the burning speed of the explosive charge is high enough to enable almost instantaneous combustion of the whole quantity of explosive, thereby releasing a high amount of energy in a very short period of time". Impulse responses of firecrackers can be found in [26,93] while comparisons of different firecracker impulse responses can be found in [94].

According to research presented in the introduction, the main justification that prompted its use was to maximize signal to (background) noise ratio (SNR) for outdoor measurements [44,95]. Referring to the research: "Firecrackers were used in S1 and S2 (source positions), in order to overcome the problem of the low signal-to-noise ratio" (Open-air theatre [44]), "they (firecrackers) could maximize the signal-to-background noise ratio (SNR), ...dodecahedral source could have a limited sound power for open-air conditions" (Open-air theatre [95]). It is important to notice that in both these cases the source was used for open theater measurements. Firecrackers were also used in the research due to the lack of electricity [45,49].

Considering omnidirectionality, firecrackers seem to be among the few acoustic sources that do not exhibit directional characteristics. Arana et al. [93] performed directivity measurements with 16 microphones in a sphere of a 1.65 m diameter. For the measurements, different combinations were used, and microphones were placed at the vertical and horizontal planes and also on different meridians and parallels. Results presented in a polar shape (microphones were put on the equatorial circumference every 22.5°) showed that the directivity index of the sound levels obtained from a 20-explosion sample is less than 1 dB for all third-octave bands from 125 Hz to 8 kHz. The omnidirectional directivity of a firecracker can also be seen in a study by Settles et al. [88], exhibiting a shadowgram sequence of an explosion of 1 g of triacetone triperoxide in a cardboard cylinder.

Concerning repeatability, Arana et al. [93] presented temporary forms of acoustic signals from firecrackers revealing small but noticeable differences. In the same study, dispersion is evident in spectral power measurements and directivity diagrams. In a study by San Martin et al. [26] the standard deviation (STD) of the effective decay range (EDR) between measurements with a dodecahedron and a firecracker was assessed. The EDR (in dB) is a parameter which describes the available decay curve range to obtain the RT. It was found that due to the different sound power from each explosion, firecrackers have greater dispersion, especially in the high and medium frequencies compared to measurement with a dodecahedron speaker. The study concludes that, concerning repeatability, the firecrackers do not guarantee the extraordinary repeatability of techniques based on deterministic signals (MLS and ESS). In order to check the repeatability of measurements with firecrackers and the effect this has on the acoustic parameters, Topa et al. [75] performed measurements for the same source and microphone positions. Results for C_{80} revealed differences for the lower frequency band.

Regarding sound pressure levels, Horvat et al. [68] measured differed sized firecrackers and found levels ranging from 156 to 166 dB according to the size of the firecracker. Furthermore, the sound-to-noise ratio (SNR) between 1 and 8 kHz was found in a study [26] to be higher compared with measurements with dodecahedron speaker utilizing MLS and ESS signals. In an extensive work by Sharma et al. [96], sound pressure levels were measured for many different categories of firecrackers (ground shots, aerial shots and garland type) in an anechoic chamber and in a test site. There are also many kinds of research that have been conducted regarding sound pressure levels of firecrackers [94,96–98], related to the effect these levels have on hearing. It should be noted that because firecrackers cause high-pressure levels, care must be taken for the selection of a suitable microphone in acoustic measurements as well as appropriate precautions for the risk of hearing loss.

Relating to frequency response, results presented in various research [68,93,94] indicate that most energy emitted is concentrated in the frequency range from 500 Hz to 2 kHz with a roll-off below 1 kHz. San Martin et al. [26] stated that the biggest drawback of firecrackers is the low sound-to-noise ratio obtained for low frequencies. The same was denoted by Arana et al. [93], that the spectral power of a pseudo impulsive source (firecracker) is not sufficient in the low-frequency range. However, studies by Flamme et al. [94] and Horvat et al. [68] presented frequency spectra for different firecrackers showed that the maximum of energy is shifted towards lower frequencies with the increase of amount of explosive. The largest firecracker measured by Horvat et al. [68] exceeds 100 dB in the low-frequency range. This observation leads to the conclusion that in order to satisfy the ISO 3382-1 sound pressure level requirements (45 dB SNR) at low frequencies, the selection of the appropriate firecracker is necessary. Hence the utilization of firecrackers as an acoustic source in the low-frequency range should be exercised with caution and in conjunction with knowledge of the background noise levels for the optimal firecracker selection.

In regard to the measurement of acoustic parameters, San Martin et al. [26] present the most comprehensive research. Impulse response measurements across different halls performed with firecrackers (ten explosions) and two commercial dodecahedron speakers. The authors state that if both techniques are applied correctly, similar values are obtained for the acoustic parameters. In the same research, the STD for T_{30}, C_{80}, and G was also compared for the two sources (firecracker, dodecahedron speaker). The STD was found to be greater for the firecracker in the low-frequency range for T_{30} measurements across different enclosures. However the STD is remarkably higher for the dodecahedron speaker for C_{80} and source strength (G) in the high-frequency range across different enclosures. In a study by Arana et al. [93] acoustic measurements were performed with a firecracker. In the study it is stated that "average values for EDT were practically identical to those obtained with two other recent techniques" (however the techniques were not identified in the study). Also in a study by Topa et al. [75] measurements of acoustic parameters were performed with firecrackers, but they were only compared with measurements performed with balloons.

In conclusion, the firecracker as a sound source can potentially meet the ISO 3382-1 requirements concerning omnidirectionality. Research needs to be carried out according the ISO 3382-1 measurement procedure to certify that the firecracker can cover this requirement. Concerning the sound pressure levels requirements of ISO 3382-1, as stated in the introduction, they need to be at least 45 dB above the background level in the corresponding frequency band. Whether this condition is met depends on the firecracker used and the sound level that it creates in the low-frequency range, as well as the background noise in this frequency range.

2.4. Handclap

Handclap, the production of sound by striking the hands together, is an attractive source for acoustic measurements. It is common for acousticians to excite a room with a handclap in order to assess the quality of the space. It can also be used to detect unwanted acoustic phenomena such as echoes and flutter-echoes [26].

Sound generation by a handclap was the focus of some studies [99,100]. Research by Fletcher et al. [99] examined the underlying physics in order to explain the sound variations from a dull thud through a low-frequency pulse to a sharp high-frequency snap. Possible simplified geometries of a flat impact and a domed impact were examined. It was shown that a shock wave is generated for configurations of the hands that produce a loud sharp sound. The addition of a Helmholtz-type resonance is involved in the case of domed impacts. An impulse response of a handclap is presented in the same research. Schlieren imaging was used in a study [73] in order to depict shock waves from a handclap. In a study by Repp [100], the different sounds of a handclap were categorized in eight clapping modes according to hand configuration. A description and a figure for each configuration can be found in the research. The author states that additional variations may derive from such factors as hand curvature, stiffness, fleshiness of the palms, tightness of the fingers, precision and striking force. Relevant research by Peltola et al. [101] presents an analysis for synthesizing hand clapping sounds.

Some research utilized the handclap for acoustic measurements through the use of a smartphone as a sound recorder [102–104]. Measurements with a handclap were used mainly as a survey method for these studies to monitor room acoustics.

Considering omnidirectionality, a study by Griesinger [71] showed that a handclap has directional characteristics. Measurements in different directions revealed differences of more than 15 dB in certain frequency ranges. Therefore the handclap does not fulfill ISO 3382-1 requirements for omnidirectionality as expected.

Concerning repeatability, the handclap may have one of the lowest among acoustic sources. The reason being that the slightest variation of hand configuration may alter the generated impulse and spectral characteristics [100]. Also, there is considerable variability in spectral shapes of handclaps across individuals. In the same research, the amplitude standard deviations ranged from 0.7 to 5.2 dB across subjects. However it was found that it is possible to improve the repeatability of a handclap if it is produced by the same individual utilizing the exact same hand configuration every time.

Regarding sound pressure levels, a study measured the handclap to be 75.8 dB [102]. In a study by Seetharaman and Tarzia [103] the handclap averaged 26.4 dB above the background level (in a concert hall) with a standard deviation of 4.4 dB across measurements. In the same study however it was noted that signal processing steps can be introduced in order to improve its performance as a sound source. However, the handclap as a sound source does not fulfill ISO 3382-1 requirements for sound pressure levels.

Relating to frequency response, the handclap can be generated in different ways which result in different frequency responses. As stated before, eight clapping modes according to hand configuration were presented in a study by Repp [100]. It can be seen in all frequency responses that a roll-off is evident below 500 Hz. The same is reported in a similar study [102] and is in accordance with Griensiger [71] which states "handclaps suffer from poor low-frequency content". In a study by Fletcher [99], measurements of the sound of nominally flat and cupped natural handclaps were made in an anechoic environment. The author states that "a flat clap produces broad-band sound that typically extends to about 10 kHz while the spectrum of a domed clap usually has a subsidiary maximum somewhere below 1 kHz and then declines with frequency more rapidly than does the flat clap".

In regard to measurements of acoustic parameters, research utilized a handclap as a sound source and a smartphone as a sound recorder [103,104]. The handclap was used mainly as a survey method for these studies to monitor room acoustics. A study by Seetharamn and Tarzia [103] performed measurements of RT. Octave bands measurements above 250 Hz gave consistent results with small deviation, while lower frequencies were unreliable. However, the measurements have to be considered with caution since they were compared with measurements made with a balloon source. Another study by Huang [104] measured acoustic parameters (RT and T_s) in the Bayreuth Festspielhaus. Acoustic parameters were compared with results that were found in the literature and deviations were found that were attributed to reasons such as low SNR and the performance of micro electro-mechanical systems (MEMS) microphones found in smartphones.

In conclusion, the handclap as a sound source does not meet the ISO 3382-1 requirements since it cannot be considered an omnidirectional source and it has low sound pressure levels.

2.5. Inverse Horn Design

An inverse horn design sound source is formed by fitting the diaphragm of a conventional loudspeaker to an aperture hole through an inverted horn for concentrating the acoustical energy. The design was proposed by Polack et al. [105] and is based on the idea that a source of small dimensions is a good approximation of a point source with omnidirectional characteristics. The performance of such a point source depends on the interaction between the loudspeaker and the inverted horn. The careful design makes it possible to construct a very compact omnidirectional sound source satisfying the international standards. The original design has a very irregular frequency response due to the resonances of air generated inside the inverted horn. Cobo et al. [106] proposed applying inverse filtering in order to improve the frequency response of the source. Impulse responses of the source with and without inverse filtering are also presented in this research. It is worth noting that there are commercial implementations of the inverse horn design that fulfill the ISO 3382-1. Also construction of an inverse horn design source through 3-d printing is possible [107].

A similar approach to the inverse horn design is the loudspeaker-pipe sound source [108]. A point source can be formed if a loudspeaker is connected with a waveguide whose exit is small compared with the wavelength. The source is included in this section of the review since it is based on the same idea as the inverse horn design, even if it is not used as much as an alternative to a dodecahedron speaker. The major difficulties that hinder its use are its non-flat frequency response and the reflections between the pipe exit and its interior, but a digitally synthesized input signal can be used to overcome these drawbacks [109]. It has been used for the study of nozzle transmission characteristics [110] and to control internal noise propagation from aircraft engines [108]. It is stated in the ANSI S1.18 standard [111] for determining the acoustic impedance of ground surfaces, that a loudspeaker-pipe source can be utilized. Application for in situ ground impedance measurements can be found in the literature [112].

Considering omnidirectionality, various research and implementations showed that the inverse horn design can fulfill ISO 3382-1 directivity requirements [105–107,113]. In some of the research [106,107,113] inverse filtering was applied for flattening the frequency response but it also had a positive effect on the omnidirectionality of the sound source. Excellent results are presented in research by Cobo et al. [106], where the source, when equalized by inverse filtering, deviates less than ±1 dB in various frequencies. However, it has to be noted that the omnidirectionality of the source depends on the implementation.

Concerning repeatability, since the sound source is utilizing a conventional loudspeaker, it can be assumed that the same sound field is generated for each measurement. Therefore there will be no differences for measured impulse responses of a space, common for measurements conducted with an impulsive sound source.

Regarding frequency response, strong resonances can be seen in figures from various publications [105,106,113]. The amplitude of the resonances deviates more than 20 dB from the flat part of the frequency response [106]. As Ortiz et al. [113] states "it is governed (the frequency response) by the strong influence created by the Helmholtz resonance due to volume compliance and the mass of air in the aperture opening that affords regularly spaced peaks". The frequency of the resonant peaks and harmonics is determined by the volume of the cone. However, to equalize such irregular frequency response arising from resonances of air inside the inverted cone, as mentioned before, Cobo et al. [106] proposed applying inverse filtering. The technique pre-emphasizes the MLS signal driving the sound source so that zero phase or minimum-phase cosine magnitudes are radiated. Applying the proposed inverse filtering has many advantages: it flattens the frequency response, shortens the time response making the signal of the source more adequate for acoustical measurements and improves omnidirectionality. Inverse filtering was also utilized for other inverse horn design implementations [107,113].

Relating to sound pressure levels, 85 dB in each one-third-octave band between 100 Hz and 5 kHz and 102 dB full band was measured [105]. A little higher sound pressure levels can be found in a commercial implementation [114]. The inverse horn design has lower levels than traditional omnidirectional sources (dodecahedron speakers). However, since signals such as MLS [106,113] are usually utilized for acoustic measurements with the inverse horn design, synchronous averaging can be applied, thus enhancing the signal-to-noise ratio.

In regard to measurements of acoustic parameters, research where the inverse horn design was utilized as an alternative source and results obtained were compared with measurements with a dodecahedron speaker or another source could not be found in the literature. Since the source fulfills ISO 3382-1 requirements then it should provide similar results for the measurement of acoustic parameters compared with dodecahedron speakers. However, the inverse horn design was used as an omnidirectional source according to the ANSI S1.18 standard [115] for the measurement of ground impedance in a study by Cobo et al. [106].

In conclusion, the inverse horn design as a sound source meets the ISO 3382-1 criteria since it fulfills the requirements for omnidirectionality and emits acceptable sound pressure levels. Considerations should be taken in order to avoid contamination by background noise in acoustic measurements, especially in the low-frequency range.

2.6. Wooden Clapper

An impulsive sound can be created if two plates of wood are struck against each other. A study by Sumarac-Pavlovic et al. [116] created and measured a specially designed wooden clapper intended to operate as a source for acoustic measurements. The clapper consists of two identical parts connected by a hinge, allowing the two parts to revolve around the same axis. However, the shape of the waveform of the wooden clapper does not have the typical N-shape found in other impulsive sounds. It is more complex and represents a short intrinsic reverberation process lasting some few tenths of milliseconds. According to the classifications found in the literature, a clapper impulse can be considered as reverberant impact pulse waveform with B-duration of about 15 ms [117].

According to a research, the justifications that prompted its use as a sound source was the experimental estimations of impulse responses of old wood churches located at remote places (no road, no electricity) where none of the standard sound sources could be used [118]. The source was also used for the measurement of classroom acoustics [60]. Also, a wooden clapper can be used as an acoustic source for survey acoustic measurements through the use of a smartphone app [102].

Considering omnidirectionality, measurements performed in an anechoic environment showed that the proposed source does not fulfill the requirements of the ISO 3382-1. The polar diagrams presented in the study indicate that the deviations from omnidirectionality at the lower octave bands at central frequencies of 125, 250 and 500 Hz in both planes are within ±3 dB, above the ISO 3382-1 limits. However, the radiation of the wooden clapper is within the standard limits at higher frequencies.

Concerning repeatability, the variations of the impulse levels are relatively small if the clapper is operated by a trained person. They are within the limits of ±1–2 dB in all octave bands.

Regarding sound pressure levels, octave spectrum levels of the clapper impulse level at 1 m distance are ranging from (about) 72 dB (low-frequency range) to 100 dB. As the authors' state "measurements performed in rooms located in urban environments, where the ambient noise level was higher, showed that the dynamic range in the octave band at 125 Hz might be insufficient and that the measurement results have to be considered valid for the octave band at 250 Hz and higher".

Relating to frequency response, the authors present only the octave spectrum levels, in which the source seems to have a roll-off below 250 Hz. Similar roll-off was found for a wooden clapper in another study [102].

In regard to measurements of acoustic parameters, research where the wooden clapper was utilized as an alternative source and results obtained were compared with measurements with a dodecahedron speaker or another source could not be found in the literature.

In conclusion, the wooden clapper as a sound source does not meet the ISO 3382-1 sound source requirements since it cannot be considered an omnidirectional source and also does not have sufficient sound power in the low-frequency range.

2.7. Shotshell Primer

Shotshell primers contain a small amount of explosive, which is ignited inside of a tube by compressing its back section, crushing the explosive mixture. The tube directs the hot gas away from the holder region, the effective sound source being at the end of the tube where the gas expands out thus creating an impulsive sound. Research by Don et al. [119] has investigated the properties and design of a shotshell primer as an impulsive source. The source has also been used for measuring the effects of moisture content on soil impedance [120] and for the measurement of sound barrier attenuation [59].

Considering omnidirectionality, according to a polar graph presented in the research by Don et al. [119], the source appears to not fulfill the recommendations of ISO 3382-1. It is found experimentally that the sound field is conically symmetric around the axis formed by the tube.

Concerning repeatability, due to differences in the primers, small variations were measured in the peak levels typically by ±1 dB. Hence the source appears to have acceptable repeatability.

Regarding sound pressure levels, changes in the level tube can produce peak levels from 140 to 150 dB approximately. Increasing the tube length from 0.5 m to 2 m caused the peak level to drop by 10 dB. A number of different brands of primers have been tested with the peak level characteristics vary slightly, depending on the amount of explosive.

Relating to the frequency response, a normalized frequency spectra presented by the authors contains energies at frequencies between 100 Hz and 10 kHz, with the maximum intensity around 1 kHz. However, there is a steep roll-off in the low- and the high-frequency range.

In regard to measurements of acoustic parameters, the accuracy of measurements with a shotshell primer as an acoustic source has not been compared with measurements with a source that fulfills the ISO 3382-1 standard. However, as mentioned before the source have been used for measuring the effects of moisture content on soil impedance [120] and for the measurement of sound barrier attenuation [59]. For the measurements of sound barrier attenuation, the experimental results were compared with predictions from a variety of approximate and exact diffraction theories which allowed the attenuation to be determined with an accuracy of 1 dB. For the measurement of real and imaginary components of soil impedance, good agreement was obtained between measured and calculated values.

In conclusion, the shotshell primer as a sound source does not meet the ISO 3382-1 sound source requirements since it cannot be considered an omnidirectional source and also does not have sufficient sound power in the low-frequency range.

2.8. Rotation of a Directional Speaker

A sound source utilizing a common directional speaker through rotation and measurements in different placements was proposed and evaluated [43,121]. The source mimics the sound field emitted by a dodecahedron speaker by breaking it down in twelve different sound fields created from a single speaker for twelve different placements of the speaker (similar to the twelve positions of the faces of a dodecahedron speaker) [121]. Measurements were performed for every placement of the speaker and as a final step, the measurements were superimposed (the impulse responses) creating a single impulse response. In the following study [43], different common directional loudspeakers were used for creating an omnidirectional sound field for impulse response measurements and different placements of the loudspeakers were performed (different rotations of the loudspeakers for a total sum of twelve, twenty-six and fourteen positions).

Considering omnidirectionality, evidence from the research [43] indicated that utilization of different directional speakers results in different directional characteristics of the created sound field. Two-way design speakers that were used in the study employing a tweeter driver have a higher directivity in the high-frequency range compared with typical driver speakers. Hence, differences in the sound field created were detected which resulted in variations in the measurement of acoustic parameters. Another aspect of the results showed that a higher number of speaker placements possibly resulted in better omnidirectionality in the high-frequency range. The results indicated that the design of an appropriate directional speaker can potentially form a sound field with omnidirectional characteristics that fulfill the ISO 3382-1 sound source requirements.

Concerning repeatability, since a conventional speaker is utilized, it can be assumed that the same sound field can be generated for every set of measurements if the exact same placements of the speaker are performed. Therefore, there will be no differences for measured impulse responses of a space, common for measurements conducted with an impulsive sound source.

Regarding sound pressure levels, the suggested source can reach high levels that depend on the directional speaker that can be used. Also, since signals such as MLS and ESS can be utilized for acoustic measurements with the rotation of directional speakers, synchronous averaging can be applied thus enhancing the signal-to-noise ratio.

Relating to frequency response, signal energy tends to be evenly distributed across a wide range of frequencies in the case of a directional speaker of good quality. Hence, if a common directional speaker with a flat frequency response is utilized for the proposed method, then the emitted sound could presumably also approach a flat frequency response.

In regard to the measurement of acoustic parameters, measurements with a dodecahedron speaker and the proposed source were assessed in order to quantify the results. Evidence from these studies [43,121] point toward the idea that RT and EDT can be measured with the proposed source with excellent accuracy compared with measurements with a dodecahedron speaker. RT measurements showed a mean absolute error of less than 0.08 s, compared with measurements with a dodecahedron speaker. Results for C_{80} and definition (D_{50}) showed also a satisfactory accuracy but not as much as the results for the RT and EDT. A possible explanation might be that the differences in the sound fields created between the dodecahedron speaker and the proposed method are more profound in the early stages of the measured impulse responses for each case. Hence, since C_{80} and D_{50} parameters are an indication of early-to-late arriving sound energy, these differences affect the measurement of C_{80} and D_{50} more than the measurement of RT and EDT.

In conclusion, the rotation of an appropriate directional speaker can potentially form a sound field with omnidirectional characteristics that fulfill the ISO 3382-1 sound source requirements. However, that still remains to be verified.

2.9. Ultrasound Piezoelectric Transducer (Spherical Distribution)

An omnidirectional acoustic source can be realized consisting of a spherical distribution of hundreds of small ultrasound transducers [23,122]. The transducers emit audible sound thanks to the parametric acoustic array phenomenon which was first proposed by Westervelt [123]. In the parametric acoustic array phenomenon, an ultrasonic wave is emitted from a piezoelectric transducer, consisting of an ultrasonic carrier modulated with the desired audible signal. Thanks to nonlinear propagation effects in air, the primary field gets naturally demodulated, resulting in a strongly focused beam of audible sound.

Most utilizations of the parametric acoustic array phenomenon have been devoted to exploiting the highly focused beams that can be generated through planar arrays of piezoelectric transducer such as the audio spotlight applications [124]. However, it was not until the work of Sayin et al. [122] that it was used for the generation of omnidirectional sound fields instead of focused ones. A continuation and improvement of the work were provided by Arnela et al. [23]. Results from these two studies and implementations are going to be presented in the following paragraphs.

Considering omnidirectionality, measurements in an anechoic chamber with the ultrasound piezoelectric transducer (spherical distribution) [23] fulfilled the ISO 3382-1 requirements above 1 kHz and performed better than a dodecahedron speaker in the high-frequency range above 2 kHz. However, the directivity index deviations revealed that the source below 800 Hz does not fulfill the ISO 3382-1 sound source requirements. Similar results for omnidirectionality were reported for the prototype ultrasound piezoelectric transducer (spherical distribution) [122].

Concerning repeatability, since the source is using ultrasound piezoelectric transducers, it can be assumed that the same sound field can be generated for every measurement. Therefore there will be no differences for measured impulse responses of a space, common for measurements conducted with an impulsive sound source.

Regarding sound pressure levels, the source prototype [122] reached 90 dB SPL. Measurements presented for generation of pure tones [23] showed levels ranging from 46 to 59 dB for the ultrasound piezoelectric transducer for different octave bands. The sound source clearly has lower SPLs than the dodecahedron for all the frequencies. However, the authors state that in future works, broadband signals such as sine sweeps will be evaluated to get higher sound pressure levels and to characterize the source according to current regulations.

Regarding frequency response, measurements performed in octave bands [23] and 1/3 octave bands [122] indicate that the source experiences difficulties to generate strong sound pressure levels for the low-frequency range.

In regard to measurements of acoustic parameters, there are no results displayed, however the authors state [23] that in the future "the behavior of the source when performing acoustic tests in buildings, such as the RT of a room or the airborne sound insulation of a partition, will also be examined".

In conclusion, the ultrasound piezoelectric transducer (spherical distribution) does not meet the ISO 3382-1 omnidirectionally requirements in the low-frequency range. Also, considerations should be taken in order to avoid contamination of background noise in acoustic measurements, especially in the low-frequency area. However, the omnidirectionality of the source in the high-frequency range can possibly be utilized in conjunction with other acoustic sources.

2.10. Ring Radiator

An omnidirectional sound source consisting of two electrodynamic drivers, positioned face-to-face at a short distance (10 to 40 mm) has been proposed by Kruse et al. [125,126]. The drivers are equipped with smooth conical cabinets which are filled with damping material. Sound is emitted from the edge of the cavity which has a ring-shaped form. Different cabinet design, driver size and driver arrangements have been considered for the sound source. Results from the aforementioned studies are presented in the following paragraphs.

Considering omnidirectionality, measurements of directivity (250 to 12000 Hz) were performed for the proposed sound source in an anechoic chamber [125]. The directivity patterns were determined by playing back white noise and calculating the 3rd-octave spectra, recorded at 3 m distance with 2° resolution. Results are presented for a source with two 5 cm drivers and a source with two 12 cm drivers both at a distance of 20 mm. As the authors state "a closer inspection of the data reveals a maximum variation of ±4 dB up to 8 kHz for the 5 cm drivers" [125]. Greater variation is observed for the 12 cm drivers. Results for directivity can also be found in [126] for 5 cm drivers. The aforementioned results for the ring radiator seem very promising. However, it is not clear if the source fulfills the ISO 3382-1 omnidirectionality requirements. A study should be conducted according to the specifications of ISO 3382-1 directivity measurements and also in more planes.

Concerning repeatability, since the sound source is utilizing conventional electrodynamic drivers, it can be assumed that the same sound field is generated for each measurement. Therefore there will be no differences for measured impulse responses of a space, common for measurements conducted with an impulsive sound source.

Regarding sound pressure levels, a sound pressure of 107 dB at 1 m distance was measured [126] when driving the loudspeakers at their maximal specified power with pink noise between 150 Hz and 6 kHz. Self-built sources by the authors were able to generate 100 dB (small source) and 106 dB (medium source) [125].

Relating to frequency response, figures presented at [125,126] demonstrate strong peaks at 2.5 kHz. As authors state: "At about 2.5 kHz, a resonance can be observed associated with the diameter of the cavity enclosed by the loudspeakers". Experimentation showed that this resonance can be reduced by placing a sheet of damping material in the cavity. Authors state that inverted filtering could be applied to smooth the frequency response. Also a roll of below 150 Hz is observed, which may be justified by the frequency response of the drivers.

In regard to measurements of acoustic parameters, there are no results displayed in the research. However a problem concerning the impulse response that could possibly affect the measurement of acoustic parameters was identified by the authors [125]: "A problem was the impulse response, which in case of the medium (size) source indicated decay times in excess of 30 ms at 10 kHz. At high frequencies, the distance between the two drivers is no longer small compared to the wavelength, and waves emitted from one chassis will be reflected at the other on". The authors provided a solution by inserting a small piece of acoustic foam into the space between the two drivers, thus dampening axial wave propagation and lowering the decay times to a maximum of 12 ms at 2.5 kHz.

In conclusion, the ring radiator seems to have omnidirectional characteristics that can potentially fulfill the ISO 3382-1 requirements. However, that still remains to be verified. Also, the source can produce adequate sound pressure levels for acoustic measurements.

2.11. Explosive Mixture of Acetylene Gas with Air

An explosive air–gas mixture has been investigated as an impulse source by Jambrosic et al. [91]. The reaction of calcium carbide with water produces acetylene as the explosive gas and calcium hydroxide as the byproduct. In the study, the air–gas mixture was stored in a container with a soft ball as sealant.

Relating to sound pressure levels, the source reached 164.9 dB at 1 m. Measurements were performed outdoors and not in an anechoic chamber due to safety reasons.

Concerning frequency response, the source produced more than sufficient sound pressure levels in the entire frequency range of interest, with a superior low-frequency spectral content as well. The explosive mixture of acetylene gas had higher sound pressure levels in the low-frequency range than firecrackers, gunshots or balloons measured in the same study.

Regarding omnidirectionality, repeatability or measurements of acoustic parameters, the authors did not provide any results.

Finally, concerning the fulfillment of ISO 3382-1 requirements, the explosive mixture of acetylene gas with air seems to create a satisfactory sound pressure level in the whole spectrum and especially in the low-frequency range but there are no data concerning the omnidirectionality of the source. However, due to the fact that the source is of the impulsive type it is possible that an omnidirectional sound field can be created. However, the applicability of the source in real life measurements is doubtful due to practicality and safety reasons.

2.12. Compressor Nozzle Hiss

In a study by Szlapa et al. [86], a compressor with a small-diameter nozzle producing a hiss noise was used as a sound source. The compressor nozzle hiss was employed as a broad-band noise for the interrupted noise method, described in ISO 354 [11].

Considering omnidirectionality, four microphones were arranged symmetrically around the source at 2 m distance. As the authors state [86], relative ranges of the maximum sound levels revealed a mean value of around 2.7%. However, measurements were performed in a room and not in an anechoic chamber.

Concerning repeatability, the authors state that the general features generated by the source remained unchanged.

Relating to frequency response, measurements performed in 1/3 octave bands, up to 40 kHz in different rooms. Results reveal that the maximum may lie in the 40 kHz band or even at a higher frequency. The characteristic of the frequency response of the source which extends well beyond the human hearing range, and can possibly be used for animal studies. Also, the authors state that the maxima of the source are very likely to be distributed bimodally, with the second maximum occurring at 125–160 Hz with values being significantly lower than that at 40 kHz. However, the source has significant low levels in the low-frequency range.

Regarding sound pressure levels, measurements for the compressor nozzle hiss revealed 92 dB (A-filtered) while for the same study 133 and 126 dB were measured for a gunshot and a balloon burst respectively for the same configuration. Again the measurements were performed in a room.

In regard to the measurement of acoustic parameters, RT presented by the authors shows higher deviation in the low-frequency range for the nozzle compared to measurements with balloons and gunshots. However, in the mid and high and frequency range, the results appear to be similar.

In conclusion, there is not enough evidence concerning the omnidirectionality of the compressor nozzle hiss fulfilling the ISO 3382-1 requirements. Also, the source does not have sufficient sound pressure level in the low-frequency range.

2.13. Directional Speaker

Directional, electrodynamic (direct-radiator type) speakers have been used as a source for acoustic measurements [75,127–129]. An electrodynamic or moving-coil loudspeaker is an electromagnetic transducer for converting electrical signals into sounds [130]. There are two principal types of loudspeakers: Those in which the vibrating surface (called the diaphragm) radiates sound directly into the air (direct-radiator type), and those in which a horn is interposed between the diaphragm and the air (horn type). The direct-radiator type is the most common one and it is used in home and car entertainment, mobile devices and in public-address systems.

Directional speakers are not alternative sources to a dodecahedron speaker since it is well documented that they are not omnidirectional [131]. However, they have been used as a sound source for acoustic measurements due to low cost, convenience and also for speech intelligibility measurements. Therefore they have been included in this review. Referring to the research that utilized the source due to low cost and convenience: “simplification in the measurements due to technical limitations” (Acoustics of Orthodox Churches [127]) and “this paper objective assessment of the room’s acoustics, using simple low-cost equipment and available software” (Experimental methods [75]).

Directional speakers have also been used for the determination of speech intelligibility. The IEC 60268-16 [65] (International Electrotechnical Commission) specifies objective methods for rating the transmission quality of speech with respect to intelligibility and requires a mouth simulator having similar directivity characteristics to those of the human head/mouth. Commercial implementations are available. A study by Soeta et al. [128] utilized an electrodynamic speaker in order to investigate the effects of the style of the liturgy on acoustic parameters. In the study, it was stated “a directional sound source might be a better approximation than an omnidirectional sound source for the purpose of the present research”. The same approach was followed by Brezina [129] for the measurement of intelligibility and clarity of speech in Romanesque churches and by Dordevic et al. [132] for an Orthodox church.

Considering omnidirectionality, directional speakers do not fulfill ISO 3382-1 directivity requirements for the sound source. Directivity patterns can be found in Beranek and Mellow [131] or in specifications of commercial implementation. As Beranek and Mellow state: "above the frequency where $ka = 2$ (k is the wavenumber and a is the radius of the diaphragm of the speaker, usually between 800 and 2000 Hz), a direct-radiator speaker can be expected to radiate less and less power". The rate at which the radiated power would decrease, if the cone were a rigid piston, is between 6 and 12 dB for each doubling of frequency. This decrease in power output is not as apparent directly in front of the loudspeaker as at the sides because of directivity. That is to say, at high frequencies, the cone directs a larger proportion of the power along the axis than in other directions.

Concerning repeatability, it can be assumed that the same sound field can be generated for every set of measurements. Therefore there will be no differences for measured impulse responses of a space, common for measurements conducted with an impulsive sound source.

Regarding sound pressure levels, the suggested source can reach high levels that depend on the speaker that will be used. Also, since signals such as MLS and ESS can be utilized for acoustic measurements, synchronous averaging can be applied thus enhancing the signal-to-noise ratio.

Relating to frequency response, signal energy tends to be evenly distributed across a wide range of frequencies in the case of a directional speaker of good quality. Hence, if a common directional speaker with a flat frequency response is utilized for the proposed method, then the emitted sound could presumably also approach a flat frequency response.

In regard to the measurement of acoustic parameters, both a directional speaker and a dodecahedron speaker were used in a number of studies [133–135] for comparison purposes. In a study by Jambrosic et al. [133], speakers of different directivity and size were used (near-field monitor, sound reinforcement loudspeaker, active subwoofer). RT measurements were performed in three acoustically different spaces (acoustically treated listening room, reverberant corridor and theatre) and compared with measurements with an omnidirectional source. Deviations can be observed in the results with the largest measured in the reverberant corridor. The authors state: "if the room has an irregular shape or its surfaces are very reflective, the results are again significantly different from the ones obtained using the omnidirectional speaker as a referent source". In a study by Wallace and Harvie-Clark [135], RT measurements were performed in a multipurpose hall with a directional speaker and an omnidirectional one. Significant differences were measured if the directional speaker was used in one orientation only, compared with the omnidirectional speaker. However, measurements averaged made with the directional speaker pointing both horizontally and vertically, more accurately represent the results obtained with an omnidirectional speaker. In another study by the National Physical Laboratory (NPL) [134], a large recording studio and a small control room were given to participants to perform acoustic measurements. Among others, the effect of sound source was evaluated. Different sources were used (omnidirectional source, array speakers and directional speaker). Little variations were found in the high-frequency range. However in the low-frequency range, larger variations were found which is unexpected since directional speakers have better omnidirectionality in this range.

In conclusion, a directional speaker does not meet the ISO 3382-1 requirements since it cannot be considered an omnidirectional source.

2.14. Laser-Induced Air Breakdown

One of the many uses of pulsed lasers is to generate acoustic pulses in the air beside solid and liquid media [136,137] which can be used as a source for impulse response measurements within the audible bandwidth [138,139]. An acoustic point source can be generated by focusing a pulsed laser beam to rapidly heat the air at a focal point which produces a small expanding plasma ball. Plasma is formatted "through the cascade process caused by electrons emitted from atoms and molecules that have absorbed multiple photons through a multi-photon process when a laser beam is focused in a gas. A portion of this plasma energy is used to create a shock wave, which is the sound source generated by laser-induced breakdown" [139].

Referring to research, in a study by Bolanos et al. [138], the source was used for the measurement of the impulse response of a room. The accuracy of the results was assessed by comparison with impulse responses measured with a custom-made spherical loudspeaker and a directional loudspeaker. In a study by Hosoya et al. [139], the source was validated by measuring the resonant frequencies (from the impulse response) of a very small space and comparing them with those computed by a theoretical model. The source is also proposed for scale model work [140,141].

Considering omnidirectionality, measurements were performed in an anechoic chamber for directivity in octave bands at 1 m (10° resolution) [140]. The central frequencies were 75 kHz, 37.5 kHz, 18.75 kHz, 9.375 kHz, 4.6875 kHz and frequencies below 3.125 kHz. The results present an omnidirectional pattern for all frequency bands. The maximum difference in energy level is less than 1 dB within the range from 0° up to 90° for all frequency bands. In a subsequent study by the author [138], the magnitude response of the pressure pulse measured along 0°, 45° and 90° directions deviates by less than 0.5 dB at frequencies above 10 kHz, and no noticeable differences were found at frequencies less than 10 kHz. In a study by Hosoya et al. [139], the point sound source was generated in an anechoic box were twelve microphones (30° differences) were placed 80 mm from the sound source. The average power spectra measured at each point was presented showing small differences.

Concerning repeatability, a study by Bolanos et al. [140] measured twenty consecutive pulses at a distance of 0.8767 m. The waveform shape was conserved between emissions and only small sound level differences were evident. This was also true for other source–receiver distances. The standard deviation of the peak values of 20 repetitions was less than 0.3 dB for all measurement distances. In subsequent research [138], the standard deviation for the magnitude response of the pressure pulse at 1 m averaged over 100 measurements was less than 0.8 dB for all frequencies. The authors state: "The repeatability of laser-induced breakdown (LIB) depends mainly on the laser configuration, but other parameters, e.g., dust, may affect the generation of LIB and consequently produce deviations in the waveform from pulse to pulse". However, in another study [139] it is stated that: "as the laser pulse energy increases, the sound pressure of the point sound source generated by LIB increases, also the reproducibility decreases and the fluctuations become apparent".

Regarding sound pressure levels, the peak pressure value of the LIB was measured in a study [140] at 0.8 m and was approximately 360 Pa (145 dB). In another study [139] three levels of laser pulse energy were used: 335.9 mJ, 798.2 mJ and 990.9 mJ. As the laser pulse energy increased, the sound pressure of the point sound source generated by LIB increased. Different time responses of sound pressure generated by LIB ranged from to 480.3 Pa (147.6 dB) to 698.9 Pa (150.87 dB). It was also found that the amplitude of the sound pressure varies depending on the spot radius.

Relating to frequency response, differences were found among the research [139,140], possibly due to different implementations. In a study by Bolanos et al. [140], the magnitude response has its maximum at 20 kHz, a rising edge of 6 dB/octave for frequencies below 10 kHz and a decay edge of approximately 10 dB/octave for frequencies between 30 and 120 kHz. In a study by Hosoya et al. [139], the frequency response appears to be more even.

In regard to measurements of acoustic parameters, results and comparisons with other sources such as dodecahedron speakers were not found in the literature. However, a comparison between the impulse responses obtained with a dodecahedron speaker, a directional speaker and an LIB can be found in [138]. The impulse response obtained with LIB shows distinct reflections in contrast with measurements with the spherical loudspeaker. The authors justify this fact due to interference with reflections produced by the different driver elements in the spherical loudspeaker. The authors state: "The LIB presents characteristics close to an ideal point source thus providing an accurate measurement of the impulse response of the acoustic system". Therefore differences in the impulse response in regard to measurements with a dodecahedron speaker are to be expected according to the research. The results of these differences in acoustic parameter measurements have not yet been explored.

In conclusion, a LIB can form a sound field that can potentially have omnidirectional characteristics that fulfill the ISO 3382-1 requirements. However, that still remains to be verified. The LIB appears to be a very promising acoustic source for practical acoustic measurement applications.

2.15. Electric Spark Source

An electric spark discharge may be used as an impulse sound source for acoustic measurements [142,143]. The principle is based on the generation of an electric discharge by applying a high voltage between two electrodes. On the electrical breakdown of the air gap, heat is generated in the spark, causing a rapid expansion of the core gas [142]. This expansion results in the propagation of a shock wave which is the primary source of sound [144]. Following the initial shock, the air in the region of the core is raised in temperature above the ambient and the cooling of this air results in a secondary wave of lower frequency and intensity. Steel electrodes with variable radius can be used combined with a variable gap.

Electric spark sources have been mainly used as a source for scale models for the simulation of acoustic phenomena [145]. The most common scale model application being auditorium acoustics [146] while it has also been used for the study of sound propagation in urban areas [147]. Electric spark sources have also been used for the acoustical spectrometry of sound propagation through air-filled porous materials [148]. In addition, the acoustic properties of an absorbent material have been measured with a high voltage spark discharge as an impulse source [149]. Finally, high energy spark discharges have been used in studies for the measurement of impulse responses and acoustic parameters in spaces [150,151].

Considering omnidirectionality, a study by Ayrault et al. [145] showed that the behavior of spark discharges and their acoustic radiation depends greatly on the electrodes gap. Polar plots measured in an anechoic chamber for different electrode gaps showed that the overpressure (maximum pressure of the impulse) is reduced 2.5 dB at 90° (compared to 0°) and 4.4 dB for electrode gaps of 5 mm and 20 mm respectively. The authors did not present polar plots for smaller electrode gaps. In a similar study, polar plots presented by Hidaka et al. [152] showed a sufficient omnidirectionality. However, the authors showed results only for 5, 10 and 20 kHz without presenting details how the measurements were performed. It has to be noted that the research was implemented for scale models which require higher frequencies. Finally, a study by Shibayama et al. [153] presented high correlation between theoretical and experimental directivity patters of a spark discharge. However, results are presented for frequencies above 20 kHz. The study also presents high correlation between the estimated sound pulse waveforms and the measured ones for different directions.

Concerning repeatability, in a study by Hidaka et al. [152] the sound pressure waveforms of the spark discharge sound source (superposed 64 times) were presented with fairly good results. However, in the study, it is stated that "a waveform with high repeatability and big sound energy are incompatible conditions". In a study by Ayrault et al. [145], in order to establish repeatability, measurements were performed 40 times. The standard deviation of the pressure measurements was found not to decrease significantly with a greater measurements number. Cabot et al. [150,151] in his studies for the measurement of impulse responses in rooms, states that "an electric spark discharge provides the best combination of intensity, repeatability, reset time and portability". In a study by Picaut and Simon [147], a good reproducibility was obtained as small deviations were found in the spectrum for different discharges. However Qin and Attenborough [136] state about the variation of electric spark discharges that: "first, there can be significant variations in the spark waveforms from spark to spark under the same testing conditions. This is the result of temporal variations in the breakdown potential, randomness of the air breakdown channel between the electrodes, and vibration of the electrodes". In the same study, the relative variation of the peak pressure, defined as the standard deviation divided by the average pressure, was found less than 3% for laser generated acoustic shocks but about 9% for the acoustic signals from the electric sparks.

Regarding sound pressure levels, in a study by Ayrault et al. [145] up to 140 dB SPL at 1 m from the source were measured. In another study and implementation by Wyber [142], sound pressure levels reached 133 dB.

Relating to frequency response, figures are provided in Shibayama et al. [153], Latham [154], Hidaka et al. [152], Cabot et al. [151] and Picault and Simon [147]. Spectra reveal that spark sources tend to be lacking in low-frequency energy. Also, the shape of the spectrum seems to have a roll-off starting at about l0 kHz.

In regard to measurements of acoustic parameters, while systems utilizing electric spark charges for measurements of acoustic parameters were proposed and implemented [150,151], measurements and comparison were not presented.

In conclusion, results so far about the electric spark source show that it is not omnidirectional in the audible frequency range, thus it does not fulfill the ISO 3382-1 requirements. Also, the source does not provide sufficient sound pressure levels in the low-frequency range.

3. Discussion

Fifteen sources have been identified in the literature which can be used as alternative sources to a dodecahedron speaker for acoustic measurements. The majority of the sound sources (9) are of the impulsive type: balloons, guns, firecrackers, handclaps, wooden clappers, shotshell primers, an explosive mixture of acetylene gas with air, laser-induced air breakdowns and electric spark sources. Four acoustic sources utilize an electrodynamic loudspeaker: Inverse horn design, rotation of directional loudspeakers, ring radiators and directional loudspeakers. One study utilizes piezoelectric transducers through spherical distribution. Finally, one study used a compressor nozzle hiss. A categorization of the sources according to whether they are impulsive or continuous is presented in Table 4.

Table 4. Categorization of the sources.

Source Categories	Sources
Impulsive	Balloon, gun, firecracker, handclap, wooden clapper, shotshell primer, an explosive mixture of acetylene gas with air, laser-induced air breakdown, electric spark source
Continuous	Inverse horn design, rotation of directional loudspeaker, ring radiator, directional loudspeaker, piezoelectric transducers through spherical distribution, compressor nozzle hiss

According to ISO 354 [11] and ISO 3382-1 [8], the methods for measuring RT and acoustic parameters can be classified to the interrupted noise method and the integrated impulse response method. A further classification presented in ISO 354 separates the integrated impulse response method into the direct and the indirect method. An extensive description of the methods can be found in the aforementioned standards. All the impulsive sources can be utilized in the direct integrated impulse response method. All the sources which employ an electrodynamic loudspeaker and the source of piezoelectric transducers through spherical distribution can be utilized in the indirect integrated impulse response method. Those sources can also be utilized in the interrupted noise method. The compressor nozzle hiss can only be employed in the interrupted noise method.

A summary of the features examined for the sources (omnidirectionality, repeatability, adequate sound pressure levels, even frequency response, accuracy in measurement of acoustic parameters and fulfillment of ISO 3382-1 sound source requirements) is presented in Table 5. A blank in the table implies that this feature has not been studied or that there is insufficient data to draw conclusions. The table has been created to present a general overview of the characteristics of the sources. However, the data in the table should be evaluated with caution and in conjunction with the corresponding research. Determining whether a source can be utilized and the expected accuracy that can be achieved in the measurements requires deeper knowledge. For example, in the case of the balloon as a sound source, we note that RT can be measured (except in the low-frequency range). This holds true but the accuracy of the measurements will be affected by the background noise in each frequency band as well as the shape and characteristics of the measuring space as it is stated in the presented research.

Table 5. Features of acoustic sources.

	Sources	Omnidirectionality	Repeatability	Even Frequency Response	Adequate Sound Pressure Levels	Accuracy in Measurement of Acoustic Parameters	Fulfillment of ISO 3382	Featured References
1	Balloon	No	No (yes under conditions)	No	Yes (no in the low-frequency range)	No (yes for RT except low-frequency range)	No	[47,52,55,56,67–78]
2	Gunshot	No	Yes (under conditions)	No	Yes (no in the low-frequency range)	No (yes for RT except low-frequency range)	No	[53,54,71,76,77, 79–92]
3	Firecracker	Possibly Yes	Yes (slight deviations)	No	Yes (no in the low-frequency range)	Possibly yes	Possibly yes	[26,44,45,49,68, 75,88,93–98]
4	Handclap	No	No	No	No	No	No	[71,73,99–104]
5	Inverse horn design	Yes	Yes	Yes (through inverse filtering)	Yes	Yes	Yes	[105–115]
6	Wooden clapper	No	Yes (under conditions)	No	Yes (no in the low-frequency range)	-	No	[60,102,116–118]
7	Shotshell primer	No	Yes	No	Yes (except low-frequency range)	-	No	[59,119,120]
8	Rotation of directional speaker	-	Yes	Yes	Yes	Yes (for RT)	-	[43,121]
9	Ultrasound Piezoelectric Transducer	No	Yes	No	No	-	No	[23,122–124]
10	Ring radiator	Possibly yes (under conditions)	Yes	No	Yes	-	-	[125,126]
11	Explosive mixture of acetylene gas with air	-	-	Yes	Yes	-	-	[91]
12	Compressor Nozzle Hiss	-	-	No	No	No	-	[86]
13	Directional Loudspeaker	No	Yes	Yes	Yes	No (yes for RT under conditions)	No	[75,127–135]
14	Laser-induced air breakdown	Possibly yes	Yes	No	Yes (no in the low-frequency range)	-	-	[136–141]
15	Electric spark source	No (depends on the implementation)	Yes	Yes (depends on the implementation)	No (depends on the implementation)	-	No	[142–152]
-	Dodecahedron	Yes	Yes	Yes (depends on the implementation)	Yes (depends on the implementation for low-frequency range)	Yes	Yes	[26–42]

Data from this review indicate that besides dodecahedron speakers, other sound sources that fulfill ISO 3382-1 requirements are inverse horn designs and possibly firecrackers. However, for firecrackers there is no research that has been carried out according to the specifications of ISO 3382-1 for the measurement of omnidirectionality. Other sound sources that can potentially fulfill ISO 3382-1 source requirements are the rotation of a directional speaker, ring radiator and laser-induced breakdown.

Uses and Future Work

The primary use of this review is to present the acoustic sources alternatives to a dodecahedron speaker, so that the reader can obtain a broad perspective of the literature and the available choices as well as their most important features. Hopefully the review will help the researcher, the acoustic consultant and the sound engineer for the appropriate choice of acoustic source according to the acoustic measurement.

The review may also be useful for selecting a suitable source for performing acoustic measurements with minimum cost. As stated in the introduction, a dodecahedron speaker is the most expensive equipment in an acoustic measurement setup. Some of the low-cost sources that were presented are the balloon, firecracker, handclap and rotation of directional speaker. The reader can be informed about the aspects of each method, the accuracy that can be achieved, as well as details of the appropriate application.

Another possible use of this review is to help identify research gaps. As presented in Table 5, there are gaps in the description of characteristics for many acoustic sources. Also, some features of the sources have not been explored in the best possible way. For example, a common feature not studied in all sources is omnidirectionality according to the specifications described in ISO 3382-1. Finally some sources such as the rotation of a directional speaker, ring radiator and laser-induced air breakdown are promising and justify further research.

An option for future research is also the combination of sources for acoustic measurements. For example, research has shown that some sources have better omnidirectionality at high frequencies (e.g., firecracker) and could be combined with sources that have better omnidirectionality and higher-pressure levels at low frequencies (e.g., dodecahedron speaker) for a better excitation of a space.

Finally, we hope that this review will be useful in relevant areas where acoustics measurements are necessary. As mentioned in the introduction, an acoustic source is essential for the measurement of HRTFs which are important for auralization purpose in many fields such as virtual and augmented reality. This review can possibly be useful for researchers working in those fields.

4. Conclusions

Relevant studies have been presented in this review concerning acoustic sources alternatives to a dodecahedron speaker. Fifteen sources were identified in the literature. The majority of them are of the impulsive type: balloons, guns, firecrackers, handclaps, wooden clappers, shotshell primers, an explosive mixture of acetylene gas with air, laser-induced air breakdowns and electric spark sources. Four acoustic sources utilize an electrodynamic loudspeaker: inverse horn design, rotation of directional loudspeakers, ring radiators and directional loudspeakers. The two final sources are a compressor nozzle hiss and piezoelectric transducers through spherical distribution. Emphasis was placed on features such as omnidirectionality, repeatability, adequate sound pressure levels, even frequency response, accuracy in measurement of acoustic parameters and fulfillment of ISO 3382-1 sound source requirements. Elements about the generation of sound and the impulse response were also presented where they were available.

Results from this review have shown that besides dodecahedron speakers, other sound sources that fulfill ISO 3382-1 requirements are inverse horn designs and possibly firecrackers. Sources that can potentially fulfill ISO 3382-1 source requirements are the rotation of a directional speaker, ring radiator and laser-induced breakdown. Reviewing the literature has led us to conclude that there are alternative sound sources that in some occasions can provide usable results concerning the measurements of acoustic parameters. This study has identified research gaps which can be a fruitful area of future work. A possible way for future research could be the combination of different sources for acoustic measurements. Finally, we hope that this review will be useful in relevant areas such as the measurement of HRTFs which are important for auralization purposes.

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Abbreviations

The following abbreviations are used in this manuscript:

ANSI	American National Standards Institute
C_{80}	Clarity
D_{50}	Definition
DI	Directivity Index
DIN	Deutsches Institut für Normung
EDR	Effective Decay Range
EDT	Early Decay Time
ESS	Exponential Sine Sweep
G	Source Strength
HRTF's	Head-Related Transfer Functions
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LIB	Laser-Induced Breakdown
MLS	Maximum Length Sequence
NPL	National Physics Laboratory
RT	Reverberation Time
SNR	Sound to Noise Ratio
STD	Standard Deviation
T_s	Centre Time

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