SOUND GOES ROUND: THE QUEST FOR OMNIDIRECTIONAL RADIATION

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1 INTRODUCTION

Omnidirectional sound sources are the preferred source type for room acoustic measurements. Clappers, airbursts, explosive sources and polyhedron loudspeakers can be used to generate an approximation of omnidirectional radiation. Each has limitations on repeatability, spectral content and radiation pattern. This paper traces the history of omnidirectional loudspeakers used for acoustic measurements, provides general design concepts and limitations for these devices, describes an experimental loudspeaker with digital signal processing developed by the author and concludes with a summary of currently available omnidirectional loudspeakers.

2 OMNIDIRCTIONAL SOUND SOURCES

Omnidirectional sources are used in acoustic measurements to approximate a point spherical source (monopole) radiating into 4π space. Both mechanical and electrical sources can be used for acoustic measurements.

Common mechanical sources include clappers (handclaps, hinged wood plates, large books), airbursts (bags, balloons) and explosive sources (starting pistols, firecrackers). These sources have limitations on repeatability, spectral content and radiation pattern where the objective is to produce identical stimuli for each discrete measurement. As such, these sources are often used for 'survey' type measurements.

More precise and repeatable measurements can be obtained by using an amplified loudspeaker that receives an electrical stimulus signal input (pink noise, MLS, swept sine). The de-facto standard loudspeaker is a dodecahedron (12-sided) polyhedron enclosure with a 75 to 150 mm diameter driver installed on each pentagonal face. The deviation from spherical radiation of a dodecahedron loudspeaker causes measurement errors in the early part of the room impulse response used to calculate acoustic parameters per ISO 3382-1 [1, 2, 3].

Two unique omnidirectional loudspeakers have been developed: a multi-cabinet loudspeaker by ITA RWTH at the University of Aachen, Germany and a single driver source, the Brüel & Kjær (B&K) Type 4295 Omnisource Sound Source. The ITA Measuring Loudspeaker uses three cabinets with different sized drivers (300, 125 and 85 mm) for low-, mid-, and high-frequency sound emission. The Omnisource Sound Source uses a single 125 mm driver radiating into a conical coupler terminating at a circular orifice. Additional information can be obtained from the manufacturers.

3 OMNIDIRECTIONAL LOUDSPEAKER DEVELOPMENT

The June 1941 of *Radio Craft* magazine [4] described an omnidirectional sound source utilizing 21 loudspeakers developed by Harry Olson at RCA Laboratories for purposes of comparing subjective sound impressions of directional versus omnidirectional loudspeakers. Curiously, Olson does not describe this loudspeaker in any of his three comprehensive electro-acoustics books.

The need for multiple loudspeakers radiating in different directions to produce a uniform sound field was described in 1951 by Harz and Kösters [5]. A spherical shaped loudspeaker with 32 drivers supplemented by a single larger low-frequency driver in a corner-loaded cabinet was used in the Technical University of Berlin reverberation chamber [6].

The first commercial omnidirectional loudspeaker was the B&K Type 4241 Isotropic Sound Source developed by Viggo Tarnow while at B&K. His research on symmetrical radiation patterns from different solid polyhedron geometries was used as a basis in designing the loudspeaker [7]. The Type 4241 was released in 1974 and remained in production until 1979. The loudspeaker comprised a 200 mm diameter dodecahedron cabinet with nominal 75 mm high-frequency drivers on each face mounted to a pentagonal 0.75 m high wood cabinet housing a 200 mm low-frequency driver crossed over at approximately 1500 Hz. When connected to the B&K Type 2706 Power Amplifier, the radiated sound power level was 100 dB.

Figure 1 shows these early omnidirectional loudspeakers.

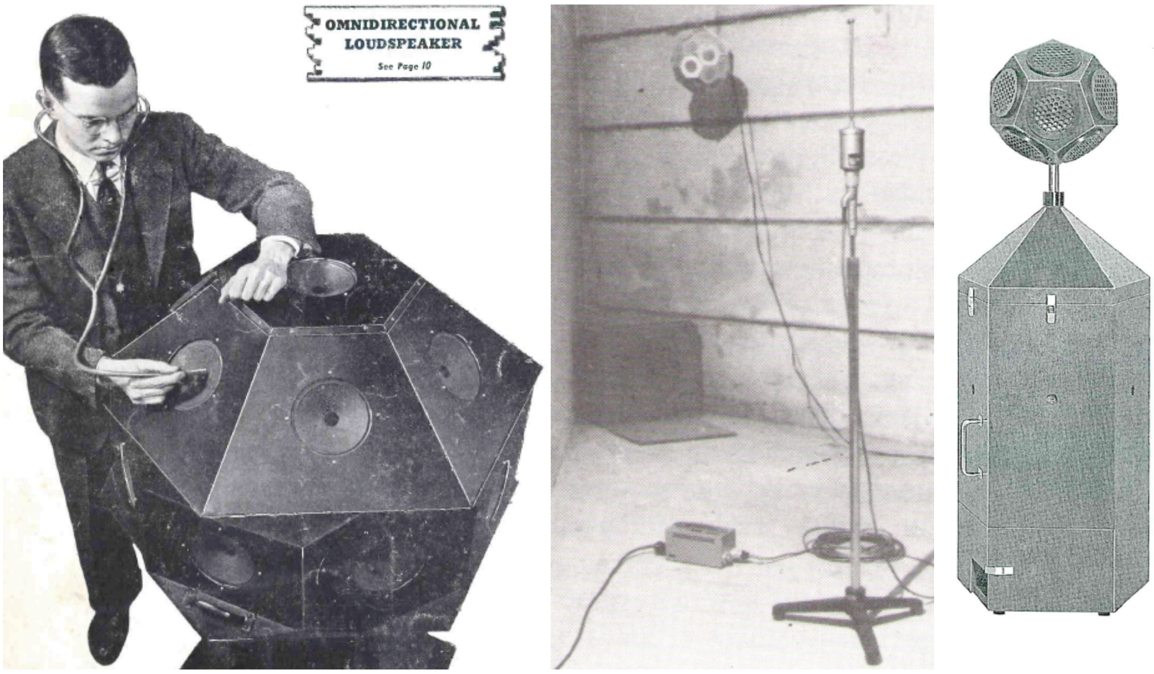


Figure 1. Early omnidirectional loudspeakers: RCA 21 driver unit circa 1941 (left); 32 driver unit with low-frequency corner-loaded cabinet at the University of Berlin circa 1951 (center) and B & K Type 4241 Isotropic Sound Source circa 1974 (right). Photo used with permission from Brüel & Kjær.

Replacing the B&K Type 4241 in 1983 was the Type 4224, an integrated sound source complete with noise generator, amplifier and 300 mm driver housed in a single cabinet. While not marketed as an omnidirectional source, the unit had reasonably good isotropic radiation when used with its inverted diffusing cone centered over the driver.

Norwegian Electronics (later Norsonic), released the NOR-213 dodecahedron loudspeaker in 1993, believed to be the first commercial full-range single enclosure omnidirectional loudspeaker.

In 1997 B&K released the Type 4296 OmniPower™ Sound Source dodecahedron loudspeaker.

Acoustics Engineering used an icosidodecahedron (32-sided) polyhedron enclosure for their Pyrite omnidirectional sound source, released in 2003, later distributed by B&K in 2005 as the Type 4292 OmniPower™ Sound Source. This was updated in 2010 as the Type 4292-L OmniPower™ Sound Source using neodymium magnet drivers to affect a 5 kg weight reduction over the Type 4292.

Figure 2 shows some current and past omnidirectional loudspeakers.

Figure 2. Omnidirectional loudspeakers (left-to-right): ITA Measuring Loudspeaker; Norsonic NOR-276; Norwegian Electronics NOR-213 and B&K Type 4296. Photo used with permission from ITA RWTH Aachen University.

Presently, there are 19 omnidirectional loudspeakers available from 16 manufacturers, although one manufacturer has rebranded another manufacturer's product. Sizes range from 275 to 450 mm in overall diameter with drivers between 75 and 150 mm in diameter.

Appendix A summarizes available omnidirectional loudspeakers and key physical and electro-acoustic parameters. The listed manufacturer's websites provide more comprehensive information.

4 OMNIDIRECTIONAL LOUDSPEAKER THEORY

The primary objective of an omnidirectional loudspeaker is to emit spherical wavefronts with equal magnitude across a wide frequency range. Polyhedron loudspeaker geometries tend to radiate as multi-directional sources, not as omnidirectional sources, above the cut-off frequency.

Loudspeaker angular radiation is a function of the individual driver response, driver spacing, interaction between drivers and enclosure geometry. These factors result in frequency-dependent radiation patterns depicted in a polar diagram as magnitude versus angle.

Typically, omnidirectional loudspeakers exhibit spherical radiation below a cut-off frequency between 1000 and 1600 Hz that depends on the driver and enclosure dimensions. Above the cut-off frequency, radiation narrows, becomes less uniform and lobes appear in the polar diagram, most noticeably at the driver locations.

A driver cone can be approximated as a simple piston in an infinite baffle with all segments vibrating in phase with equal volume velocity. The limit for omnidirectivity for a single driver is $ka < 1$, where (k) is the wave number ($2\pi/\lambda$) and (a) is the driver radius. The upper limit for omnidirectivity, with narrowing coverage without generating radiation pattern side lobes is approximately $ka < 3.8$. Table 1 summarizes idealized driver sizes where omnidirectional radiation occurs for $1 < ka < 3.8$ at various frequencies above the typical cut-off limit.

Table 1. Theoretical Driver Radius Size for Omnidirectional Radiation, mm		
Frequency, Hz	ka = 1	ka = 3.83
1000	50	180
2000	25	90
4000	12.5	45
8000	6.25	22.5

Common 75 and 150 mm diameter drivers used in omnidirectional loudspeakers generally do not fulfil all requirements for spherical radiation based on the simplified ka relationship with the exceptions at 1000 and 2000 Hz when ka = 3.83, which exhibits a narrowing coverage pattern.

As frequency increases, driver size must decrease to maintain omnidirectional radiation. Real drivers do not always follow the ideal pistonic motion from which the ka theory is based. Measuring the polar pattern of a single driver can be helpful to understand how coverage varies as a function of frequency and at what frequency the coverage starts to narrow. Often the radiation pattern exhibits lobing before the first cone break-up mode frequency occurs.

Besides size, driver selection should also consider: (1) high sensitivity; (2) power handling; (3) frequency bandwidth; (4) low power compression to maintain constant acoustic output and linear frequency response and (5) low Qts and Vas (Thiele-Small parameters) to minimize enclosure volume. Few 75 to 150 mm full-range commercial drivers satisfy all of these parameters.

Smaller drivers maintain omnidirectional radiation to higher frequencies, but power handling and acoustic output are reduced. Larger drivers have better low-frequency extension, increased power handling and higher acoustic output, but high-frequency omnidirectional radiation diminishes.

Acoustic sources with the same input signal will have a complex output determined by the interaction of the radiated wavefronts. The sources can be identical drivers or different size drivers coupled to a crossover network, where both drivers radiate a common portion of the passband. The source interaction results in three general trends: (1) increased low-frequency output due to mutual coupling of like devices, non-uniform mid-to-high frequency response and (3) deviation from omnidirectional radiation above the cut-off frequency.

Two drivers facing the same direction that vibrate in phase and are separated by a finite distance (d) generate a predicable interference pattern. When $d < \lambda/4$ the sources combine resulting in nearly omnidirectional radiation. As the separation distance increases, the radiation angle progressively decreases. At $d = \lambda/2$, source directivity narrows to approximately 30°, but without interfering off-axis lobes. Starting at $d = \lambda$ and larger source spacings, off-axis lobes result with more lobes generated at larger driver spacings while the on-axis radiation remains narrow. With polyhedron shapes, drivers face in different directions so simple two source theory is not fully applicable, particularly at higher frequencies where less coverage overlap occurs from adjacent drivers. Table 2 summarizes the range of driver spacings for omnidirectional radiation at various frequencies above the typical cut-off limit.

Table 2. Theoretical Driver Spacing for Omnidirectional Radiation, mm		
Frequency, Hz	d = λ/4	d = λ/2
1000	75	150
2000	37.5	75
4000	19	37.5
8000	9.5	19

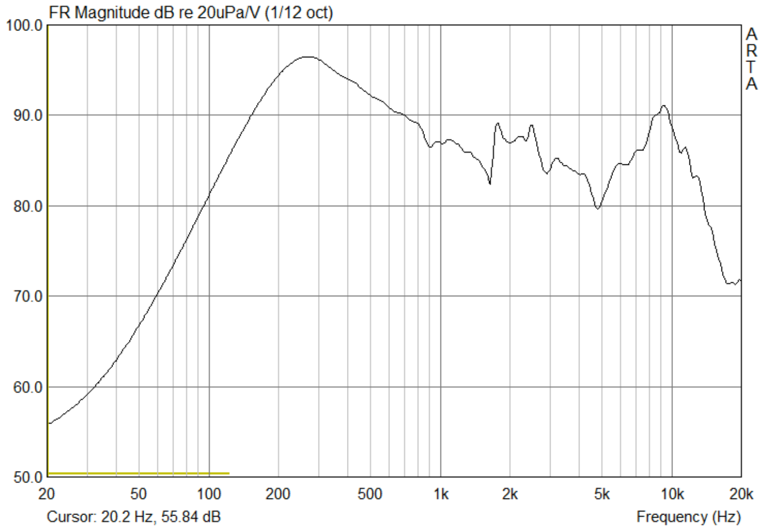
Omnidirectional loudspeakers using 75 and 150 mm diameter drivers cannot be spaced sufficiently close to fulfil the driver spacing requirements for spherical radiation at frequencies above 1000 Hz for $\lambda/4$ spacing and above 2000 Hz at $\lambda/2$ spacing.

At low-frequencies, where cabinet dimensions are less than $\lambda/4$, mutual coupling between drivers occur, resulting in a 10logN acoustic power increase. As frequency increases, mutual coupling decreases because drivers are a larger fractional wavelength apart and do not efficiently couple. An 8 dB increase below 250 Hz due to mutual coupling is typical for dodecahedron loudspeakers. This is beneficial as it offsets the limited low-frequency output of the small drivers that are typically used.

At mid-to-high frequencies, the driver radiation pattern narrows and driver spacing increases relative to wavelength. The outputs from different acoustic sources combine with different phases that depend on propagation distance and radiation angle and cause complex interference with numerous on- and off-axis directional lobes. A lesser consideration is edge diffraction due to the travelling high-frequency waves across the driver baffle that can also affect frequency linearity and directional response.

Above the cut-off frequency radiation narrows and between 1600 and 2000 Hz polar pattern lobes become evident.

Figure 3 shows the frequency response and polar diagram for a dodecahedron loudspeaker of nominal 330 mm overall diameter with 100 mm drivers. The effects of mutual coupling, non-uniform mid-to-high frequency response and high-frequency directional lobing can be seen.



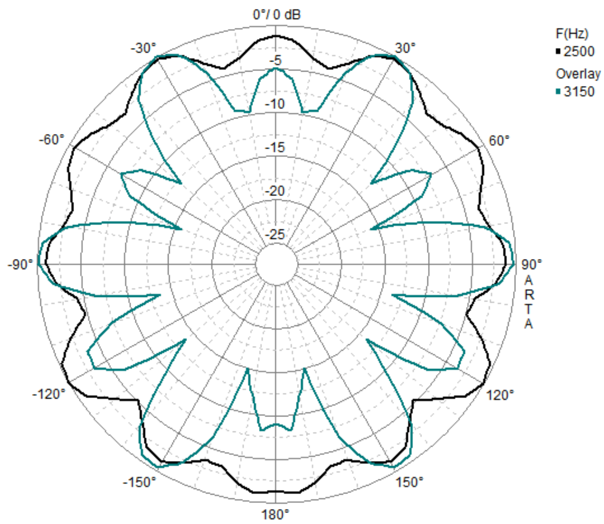


Figure 3. Dodecahedron loudspeaker frequency response (top) and 2500 and 3150 Hz polar responses (bottom).

5 OMNIDIRECTIONAL LOUDSPEAKER DESIGN OBJECTIVES

Loudspeaker omnidirectivity and its effect on room acoustic parameter measurements has been a frequent subject of conference papers and literature publications. Research has included theoretical modeling of omnidirectional loudspeaker radiation and pragmatic measurement applications. From these, conclusions on omnidirectional loudspeaker design have been described. While not an exhaustive list, several conclusions reflecting aspects of this research can be applied to designing a full-range single enclosure omnidirectional loudspeaker:

1. The cut-off frequency progressively increases and high-frequency level variation becomes greater for higher-order polyhedron geometries with fixed effective radii [7];
2. Other polyhedron shapes exhibit omnidirectional properties and the tetrahedron (4-sided) shape with equal midradius performs better than the dodecahedron shape at certain frequencies [8];
3. The dodecahedron geometry produces the most omnidirectional radiation [9];
4. The acoustic output is less for lower order polyhedra since fewer drivers are used [8];
5. Driver interference across the enclosure is more significant than driver radiation characteristics in reducing omnidirectional radiation [9];
6. Drivers and baffle dimensions that are similar in size extend the frequency range of omnidirectional radiation by raising the cut-off frequency [9];
7. Maximizing the driver opening angle, which effectively defines the diameter of the vibrating piston, lowers the summation of acoustic output contributions from adjacent drivers and reduces lobing interferences [9];
8. Driver equalization can reduce group delay variations within a given bandwidth to minimize low-frequency group delay from affecting the room impulse response that is time-windowed before filtering [2].

A full-range single enclosure omnidirectional loudspeaker design involves a series of compromises in selecting driver and enclosure parameters, no different than any other loudspeaker project. Ideally, the loudspeaker will provide: (1) omnidirectional radiation to 5657 Hz and low-frequency extension to 88 Hz based on ISO 3382-1; (2) high acoustic output; (3) minimal linear and non-linear distortion products; (4) maximum 5 dB level variation between adjacent 1/3 octave bands and (5) overall dimensions and weight suitable for field use.

6 NEW OMNIDIRECTIONAL LOUDSPEAKER CONCEPT

All commercial dodecahedron loudspeakers are essentially ‘12 drivers in a box’. Inspection of product frequency and polar response data show the same general trends as in Figure 3. Some data indicate less deviation in frequency and directional responses, but this could be due to data smoothing and not to intentional design optimization of omnidirectional radiation.

The concept of a two-way loudspeaker, with one driver handling the low-frequencies and a second driver handling the high-frequencies would seem to offer benefits in raising the cut-off frequency and thus improve omnidirectivity at high-frequencies. Options include a separately spaced woofer and tweeter or a coaxial driver.

A prototype omnidirectional loudspeaker, shown in Figure 4, has been developed and tested by Acoustical Design Collaborative, Ltd. While not finalized, the prototype shows differences – some better and some worse – in frequency and polar response directivity compared to the conventional dodecahedron loudspeaker.

Figure 4. Prototype omnidirectional loudspeaker.

The loudspeaker enclosure, designed using CAD and solid modeling software, is an icosidodecahedron shape less than 400 mm overall diameter comprising 12 pentagonal and 20 triangular faces. The enclosure geometry was selected to permit mounting separate low- and high-frequency drivers. Each pentagonal face has a 100 mm woofer and each triangular face has a 25 mm tweeter. Drivers are standard commercial products selected for high sensitivity and power handling.

The loudspeaker is bi-amplified and uses DSP to adjust the frequency response, crossover type, slope and driver passband. Initial settings were based on the published driver parameters.

Testing was performed using ARTA acoustic measurement software version 1.8.5 [10]. Directional response was measured by mounting the loudspeaker 2 m above the floor in a large room and rotating the loudspeaker in 5° increments from 0° through 360°. Frequency sweeps were used as the test stimulus. The impulse response was windowed to process only the direct sound. Due to the physical size of the room, the frequency resolution below 125 Hz was not valid, but this was not of concern since the objective was to understand the frequency response and angular radiation above 1000 Hz.

A dodecahedron loudspeaker was built using the same woofers and tested to serve as a basis of comparison to the icosidodecahedron prototype.

Preliminary conclusions suggest the following:

1. Both loudspeakers have 12 main radiation lobes;
2. The tweeter response for the prototype is not evident on the polar diagrams between 2000 and 4000 Hz which initially was thought would improve omnidirectivity;
3. From 1000 to 4000 Hz the dodecahedron has better omnidirectivity than the prototype;
4. Above 4000 Hz the prototype has better omnidirectivity than the dodecahedron;
5. The prototype satisfies the omnidirectivity defined in ISO 3382-1;
6. The prototype has 6 to 8 dB greater acoustic output between 2000 and 8000 Hz that overcomes the low- and high-frequency imbalance occurring in the dodecahedron.

At present it is not known if the polar response anomalies are due to the initially selected DSP settings, individual driver directional response, driver spacing, complex interaction between drivers, different driver acoustic centers or some combination of parameters.

Future acoustic testing will generate 3-D directivity balloons for the low- and high-frequency drivers at 2° angular resolution from which separate generic loudspeaker library (GLL) files will be created to be used with the AFMG EASE SpeakerLab program.

As a design tool, the SpeakerLab program enables viewing the frequency and polar responses of the woofers and tweeters separately [11]. This will help determine physical and electronic modifications to improve the prototype's performance. Different signal processing parameters (crossover frequency and type, slope, passband, frequency equalization, polarity and signal delay) can be input to view the resulting response changes.

The objective for the prototype is to improve upon omnidirectional radiation over the standard dodecahedron. Optimizing the driver parameters to increase the cut-off frequency and reduce the magnitude of polar response lobing may be possible by separately adjusting the electrical input signals to the woofers and tweeters. Modifications to enclosure size may also improve performance.

7 REFERENCES

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11. EASE SpeakerLab Software, Ahnert Feistal Media Group, Germany. www.ease.afmg.eu.

APPENDIX A CURRENT OMNIDIRECTIONAL LOUDSPEAKERS

Company	Model	Physical		Electrical		Sound Power	Contact
		Size (mm)	Weight (kg)	Power (W)	Driver Size (mm)	(dB re 1pW)	
AVM	DO-12	450	18	600	125	120	www.en.alava-ing.es
Brüel & Kjaer	4292-L	390	8	300	125	122	www.bksv.com
BSWA Tech	OS002	300	10	200	100	115	www.bswa-tech.com
CESVA	BP012	400	14.5	600	125	123	http://www.cesva.com
Delta OHM	HD 2050	385	9	540	125	180	www.deltaohm.com
ITA RWTH	ITA Measuring Loudspeaker [1]	N/A	N/A	300	300	125	gkb@akustik.rwth-aachen.de
				1200	125	137	
				120	85	116	
Lange	D12A [2]	335	7	650	140	122	www.langeloudspeakers.com
Larson Davis	BAS001	N/A	N/A	500	N/A	119	www.larsondavis.com
Lookline	D103 [2]	270	6	N/A	100	118	www.lookline.com
	D203 [2]	375	9.5	300	130	122	
	D303 [2]	375	11.5	600	130	123	
Müller-BBM	MDOD	250	4.1	220	N/A	120	www.muellerbbm.com
Norsonic	NOR-276	355	9	200	150	120	www.norsonic.com
Ntek	OMNI	350	12.8	350	125	123	www.ntek.it
NTi Audio	DS2	350	12.8	350	125	123	www.nti-audio.com
Outline	GSR	380	10	1600	125	121	www.outline-audio.ro
Qsources BVBA	Qohm	260	3.5	800	100	122	www.qsources.be
	Qom	420	15	200	125	120	
Real Acoustix	Real Dodec	N/A	N/A	400	125	132	www.realacoustix.com

Notes
1. Separate low-, mid- and high-frequency enclosures with outboard amplifiers and DSP.
2. Internal amplifier, DSP and RF remote control.