A new loudspeaker design: a case study of an effort to more fully integrate the loudspeaker into the playback room in a musical way.

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Abstract

The authors have been members of a design and development team that has created a new loudspeaker that attempts to resolve several of the primary problems presented by the loudspeaker/room/listener interface, as described in one of the authors’ previous paper. This paper will describe that new loudspeaker, its various new approaches to the interactions between the loudspeaker, the room and the listeners, and a brief review of the research, findings and assumptions underlying its design. The authors hope to have examples of the loudspeaker available for demonstration.

Development of the BeoLab 5 Loudspeaker

The BeoLab 5 is a loudspeaker whose configuration arises out of several disparate research and development threads that are integrated into a functional design topology, a topology that departs significantly from traditional designs. A goal for the loudspeaker that was first articulated in the early development phases and later formally mandated for the design is that the loudspeaker should work to solve as many of the problems facing a domestic consumer loudspeaker as possible.

This led to two concerns throughout the project. The first was that the loudspeaker should exhibit very “musical” behavior, so that it provided as profoundly enjoyable a musical listening experience as possible for its owners, with as few technical intrusions as possible. The second was a concern that one of the authors has called the “Overloaded Bus” problem – the metaphor is a bus that keeps loading more and more payload aboard as the bus progresses, until the bus fails. Considerable care was therefore exercised as development proceeded to prevent this from happening, in spite of the broad array of technologies incorporated in the design.

The following performance areas were addressed:

• High frequency power dispersion and amplitude response

• Low frequency adaptation to the playback room

• Adequate power to provide appropriate acoustic sound pressure levels for listeners

• Robust, reliable and repeatable performance in application

• Operational simplicity and fail-safe protections in application

• Appropriate and functional appearance and build quality for a high quality “musical instrument.”

High frequency power dispersion and amplitude response

Research findings from the Archimedes Project\(^1\,2\,3\,4\) and one of the authors (Moulton)\(^5\,6\) has led to the development of a set of criteria for high frequency loudspeaker performance and to a device suitable for obtaining such performance\(^7\). These criteria were first formally articulated by another of the authors (Pedersen), as
“1) The power response should be as flat and smooth as possible relative to the free field frequency response

“2) Strong floor and ceiling reflections should be avoided

“3) Strong reflection off the wall directly behind the loudspeaker should be avoided”

The device that is used to accomplish this is called an “Acoustic Lens.” It is a scalable reflecting device that fits over a conventional treble dome tweeter or mid-range driver, which is facing upwards. It was invented by Manny LaCarrubba of Sausalito Audio Works, and is licensed to Bang & Olufsen.

Fig. 1. Photo of acoustic lens in prototype form

The effect of the lens is to distribute energy emitted from the driver (which is facing upward) across 180° horizontally and approximately 30° vertically (angled approximately 15° upwards). Other properties of the lens permit the lower crossover point of the driver to be lowered in frequency, extending the effective range of the driver and permitting the relative directivity of the two drivers at the crossover frequency to be evenly matched.
In this plot, the vertical axis represents horizontal polar angle from 180° (top) to –180° (bottom) while the horizontal axis represents frequency (from 1 kHz to 20 kHz). Each contour line represents .5 dB change.

This plot clearly reveals the increasing directivity and diminishing power response of a conventional loudspeaker system as the frequency increases. Also note the interference effects in the 2-4 kHz region. Close examination reveals that by +/-20° off-axis, amplitude varies by as much as 3.5 dB, which is clearly audible.
Fig. 3. Horizontal Directivity Plot of Acoustic Lens

This plot, when compared to Figure 2, reveals the functional effect of the Acoustic Lens. Variance in amplitude over +/- 20° is 1 dB, and at +/-40° is still only 3 dB. Beyond these angular limits, while the amplitude falls off, it does so with comparative uniformity, so that the frequency response does not change greatly, while with a conventional tweeter, the frequency response deteriorates significantly.

A more conventional way to show this is involves displaying the frequency response curves at various angles normalized to on-axis response.
Figure 4 shows the frequency response curves at 10° to 60°, normalized to on-axis, for a conventional high-quality loudspeaker system. This performance is considered excellent.

Figure 5 shows the same data for a BeoLab 5.

Figure 6 shows the on-axis amplitude response and power response of the BeoLab 5.

The net result of this performance is that early lateral reflections from the loudspeaker to the listener have essentially the same frequency response as the direct sound, with constrained high-frequency content from reflections from the floor, ceiling, and wall behind the loudspeakers, in support of the criteria given above.
The full reasoning regarding why such performance is desirable is well beyond the scope of this paper. Suffice it to say that there is a significant and diverse body of evidence to support the use of these criteria. It is also worthy of note that similar behavior is obtained from many other musical instruments.

**Low frequency room adaptation**

The low-frequency room problem has proved to be daunting. In a simple sense, the room in which the loudspeaker is placed is a fundamental part of the loudspeaker system. Variations in the room, or in speaker or listener location in the room introduce significant changes in low frequency timbre of the loudspeaker.

Traditional solutions to this have been to equalize loudspeaker performance so that it is suitable for a specific point in the listening room, known as the “sweet spot.” One of the authors (Pedersen) has developed an alternative approach to this problem. As Pedersen states:

“Systems that are based on a measurement of the transfer function from the input of the loudspeaker to the output of an omnidirectional microphone try to measure the complete multidimensional system with a 1 dimensional measurement followed by a 1 dimensional filtering/equalization. At the very position of the microphone these systems do solve the problem when the evaluation is performed using an omnidirectional microphone, i.e. the measured transfer function to the microphone does approximate the target filter response.

“However, if the listening position is changed or the system is evaluated by other means than an omnidirectional microphone then the conclusion could be different. The choice of target function seems to be non-trivial in these systems, and the optimal target function might be a function of the whole system: loudspeaker position, loudspeaker directivity, room size, listening position, etc.

“The Adaptive Bass Control (ABC) system addresses the 1 dimensional problem of equalizing the acoustic power output of the loudspeaker to match the acoustic power output in a reference loudspeaker position in a reference room. This requires a 1 dimensional measurement and a 1 dimensional equalization filter, which is the case in an ABC system.”

In the Adaptive Bass Control system, the acoustic power output across the bass spectrum is matched to a reference acoustic power output selected by the designers, an optimum acoustic power output. The acoustic power output is found by determining the radiation resistance of the loudspeaker at its desired position. The radiation resistance is determined by taking a measurement of the force acting on the loudspeaker diaphragm from the sound field and a measurement of the diaphragm velocity. From these two measurements, the mechanical radiation resistance can be calculated.

These two measurements are done sequentially with a single microphone at two different points in space. The microphone is included in the loudspeaker system and is moved approximately 4 cm. (from 6 to 10 cm. from the diaphragm), using a servo motor. Calculation is done in the loudspeaker electronics. The entire process takes about 1 minute per speaker, and is entirely automated.

“The Adaptive Bass Control (ABC) system generates an equalization filter, which yields a much more constant timbre between different listening rooms and loudspeaker positions at low frequencies. An additional advantage is that ABC improves the timbre everywhere in the listening room – it is not limited to a predetermined listening position.” This quality of the technique in turn yields a far more flexible and musical outcome and performance than do more traditional solutions. It is suitable for the general array of musical listeners and corrects for both major anomalies in bass response and for changes that have occurred in the playback space since installation.

**Adequate power**

The BeoLab 5 is a 4-way powered loudspeaker. For the lower and upper bass systems, the enclosures have small sealed volumes (29 and 5 liters respectively), in order to maintain the desired footprint and height.
At the same time, adequate acoustic power was desired to effectively mimic the loudness of orchestral and rock/heavy metal performance.

The design goal was to obtain full bandwidth musical performance to 108 dB SPL for short-term sustained periods, with peak levels up to 120 dB SPL, for listeners in a large room, at 3 meters from a stereo pair of BeoLab 5 loudspeakers.

This required three separate strategies:

- sufficient power available for each driver in the loudspeaker,
- a strategy to deal with the problems of thermal compression, and
- a strategy to protect the drivers and amplifiers from damage due to overloads.

Power is provided by Bang & Olufsen’s proprietary ICE Power Class D switching amplifiers. These are highly efficient, small in size, require little cooling, and yield high power output. As a result, the actual amplifier power available for each loudspeaker is very high, at:

Tweeter: 250 Watts
Mid-range: 250 Watts
Mid-bass: 1,000 Watts
Lower bass: 1,000 Watts
Total power per speaker: 2,500 Watts
Total power per stereo pair: 5,000 Watts

This configuration provides adequate power output to manage both the desired sustained levels and peak levels mentioned above. These levels deserve some comment. The measured level of 108 dB SPL at 3 meters is done with 2 loudspeakers playing uncorrelated pink noise. Allowing for reverberant energy, one loudspeaker will therefore generate a sustained level of ca. 102 dB SPL at 3 meters, or 111 dB SPL at 1 meter, with peaks as high as 121 dB SPL. This is approximately 15 dB higher than conventional loudspeakers as described in the earlier paper, and roughly equivalent to the concert hall levels encountered with acoustical performance. It is still 10-15 dB below the sustained levels that can be obtained by a rock or heavy metal band in live performance. In listening trials, the BeoLab 5s obtained subjective loudness levels that satisfactorily mimicked (and may have replicated) the sound pressure levels obtained by large acoustical ensembles.

**Thermal compensation and protection**

Thermal compression occurs as a function of heat buildup in the drivers, causing acoustical output to drop as temperature rises. Each driver has a thermal sensor built in. The output of the two low frequency drivers is increased as temperature increases, by up to 4 dB, in order to make short term compensations for thermal buildup in the drivers.

In addition, a thermal protection model using the same sensors is also in place to attenuate each driver if and when it reaches dangerously high temperatures, for a fail-safe protection system.

**Robust, reliable and repeatable performance in application**

A requirement for the BeoLab 5 was that it maintain high standards of consistency in operation, and require no particular maintenance. Also, it was felt to be necessary to be able to restore a BeoLab 5 to its original performance specifications in the field, in the event of any driver or electronic malfunction or failure.

Because of the requirement for DSP and significant computational capacity in order to implement ABC, it was determined to manage all electronic adjustments in the digital realm, including “linear phase”
crossovers, equalization and time correction for each driver, global equalization and assembly quality control.

This means that, in manufacture, each driver can be measured and its performance documented. During the quality control phase of manufacture, the loudspeaker is trimmed in the digital realm to a tolerance of +/- .25 dB in comparison with the reference BeoLab 5. The DSP manipulations needed to do this are recorded and archived, along with all of the driver values. An RS-232 port is available on each BeoLab 5, so that in the field, in the event that service is required, the loudspeaker can be restored to its original reference values. If a driver is replaced, the DSP is re-trimmed to bring that driver into compliance with the original specification.

There are two implications to this. First, each BeoLab 5 is matched to the reference unit to a tolerance that is effectively within the threshold of audibility for the various difference limens for amplitude change at frequency, which is to say that the differences between units are essentially inaudible. Second, the DSP block, coupled with appropriate documentation, makes it possible to maintain each BeoLab 5 to that specification as it ages. This is done without the need for intervention by the owner/user (other than to seek assistance), including diagnostics or adjustments.

In combination with the Adaptive Bass Control and the Acoustic Lens Technology, the BeoLab 5 stereophonic or surround arrays can be placed as needed and listened to from a wide range of positions with satisfactory and pleasurable timbral and musical results. No adjustments need to be undertaken by the end user.

**Appropriate and functional appearance and build quality for a high quality “musical instrument.”**

The appearance of the BeoLab 5 is based on the physical requirements of the acoustic lenses. From these, the final appearance has been determined, including a symbolic reference to the suspended cymbal with the brushed aluminum diffraction guide plates.

**Conclusion**

The BeoLab 5 represents an attempt to globally address the various issues presented by room interface at both high and low frequencies, power, reproducibility, and musical instrument gestalt in a single integrated loudspeaker system. Listening tests to date support its performance quality and ability to provide an significantly enhanced musical listening experience. The authors believe that, as a unique single design, the BeoLab 5 works more effectively in a wider range of listening rooms than any other loudspeaker designed to date.


10 ibid

11 ibid

12 ibid