KEF R&D

Ci250RRM-THX

CONTENTS

2 Introduction
2 1. KEF’s Philosophy on Loudspeaker Design
3 2. KEF Architectural
3 3. Loudspeaker Models
3 3.1 Ci250RRM-THX
3 3.2 Ci250RRb-THX
4 4. Technology & Performance
4 4.1 Cavity Radiation Control
5 4.2 Low Diffraction LF Aperture
5 4.3 Resonance-free LF Cavity
6 4.4 Tweeter Radiation
8 4.5 4 in. 12th Generation Uni-Q with MAT
8 5. Bespoke Bezel Design
8 6. Summary
9 7. Appendix: Ci Installation: Back Boxes and Filling
10 8. References
11 Specifications and Measurements

Introduction

Ci250RRM-THX represents a new type of three-way architectural loudspeaker for KEF. Existing KEF three-way designs, for example Ci5160REF-THX and Ci3160RL-THX, follow the modified D'Appolito array also found in most of KEF's three-way floorstanding box loudspeakers (Reference 3/5, R5/7/11), with the Uni-Q flanked above and below by the low frequency (LF) drivers. The new Ci250RRM-THX, however, provides a three-way solution in a smaller package by coaxially mounting the Uni-Q in front of a single LF driver. The result is a high-performance architectural loudspeaker that can be easily integrated into the aesthetics of the room, in particular the ceiling.

This paper discusses the new, patent-pending technologies that allow Ci250RRM-THX to deliver exceptional performance, as well as a general insight into KEF's architectural speaker design process at both an acoustic and functional level.

1. KEF's Philosophy on Loudspeaker Design

Loudspeakers are the final stage in the sound reproduction chain. It is ultimately down to the loudspeaker to generate the sound that the listener will hear. While other pieces of audio equipment have clearly defined roles, and it is easier to outline how they would ideally perform, the ideal loudspeaker is more difficult to define. It is simpler to first consider what the complete audio system is trying to achieve. The ideal audio system should be able to recreate a live sonic event so that it is indistinguishable from the original. The listeners should be transported to the environment of the live event. They should be convinced that they are sitting in the actual concert hall in which the live event occurred. They should experience the acoustics of the space, perceive the locations of the instruments, interact with the space and hear the changes in the sound as they turn their heads towards the soloist.

Many recordings are available that never existed as live events, for example, a rock band captured in a studio or music with synthesised instruments. Nevertheless, the same objective applies for these situations: the sonic event that we wish to hear is the one that was envisaged by the musicians and producer. For this to be achieved, there are implications for the fidelity of the replay system: it must not colour the sound with the introduction of distortion or dynamic range compressions; it must have a neutral timbral character, without resonance or imbalance; it should have good temporal resolution such that it does not "smear" the sonic event. Each of these fidelity requirements provide clear targets for the loudspeaker designer.

However, this ideal audio system has two further implications that are more difficult to handle. Firstly, the spatial information of the original event should be captured and replayed. Secondly, the listeners should hear only the acoustic space of the original event and not the acoustic space in which they are located.

Technically, neither stereo nor conventional multichannel playback are sufficient to recreate the exact sound field of an event. However, our perception is not exact: our auditory system builds a scene in our mind based on cues in the signals reaching our ears, such as the relative arrival time and level of the sound at each of our ears. Stereo playback provides a simple means by which the artist or recordist may communicate these cues to the listener. The listener builds a picture of the sonic event in their mind, that is sufficiently able to emotionally connect with the experience of listening to the original.

Loudspeakers must be designed to maximise the communication of these spatial cues. To do this, a loudspeaker must have a response that does not change rapidly with direction. An irregular directivity can result in the loudspeaker communicating spatial cues that conflict with those in the recording.

Controlling the loudspeaker's directivity is also key to avoiding loss of midrange and treble fidelity, which can happen when loudspeakers are placed in a real listening environment. One of the features of our auditory perception is that we are used to hearing sounds that include reflections off close surfaces. Our auditory system can identify the direct sound and separate out reflections to the extent that we do not perceive the early reflections as separate events. The listener will attribute any timbral imbalance in the reflections to the original source. This means that loudspeakers must have a frequency response that is good in all directions, not simply in the direct path to the listener. Loudspeakers must have a smooth and balanced frequency response on-axis and in other directions. If this is achieved, the listeners will be able to "hear through" the room in which they are located and perceive the acoustic space captured in the recorded sound.

In summary, loudspeakers must be designed to have a smooth and balanced response both in terms of frequency and space. The sound from loudspeakers should emanate from the drivers themselves and not from other components, such as resonating panels or openings. The drivers should operate in a well-controlled manner throughout and beyond their band. Loudspeakers should have low distortion and compression and a good temporal response.

"Of all art, music is the most indefinable and the most expressive, the most insubstantial and the most immediate, the most transitory and the most imperishable. Transformed to a dance of electrons along a wire, its ghost lives on. When KEF returns music to its rightful habituation, your ears and mind, they aim to do so in the most natural way they can... without drama, without exaggeration, without artifice."

Raymond Cooke OBE, KEF founder.

2. KEF Architectural

Architectural loudspeakers, also known as custom installation or Ci, have become a large category in home audio. The ability to have sound with limited aesthetic and space impact is very desirable in some applications. In many cases, the need to 'hide' the speakers takes priority over performance.

Architectural loudspeakers are often not placed in ideal locations – they are placed where they can fit, due to architectural limitations, or where they best blend into the room aesthetically. It also becomes quite difficult to implement or even experiment with toe-in angle. Tilting tweeters have been developed to direct high frequency output to a main listening position, however combined loudspeaker response may vary depending on the dispersion characteristics of the high frequency (HF) and mid frequency (MF) drivers and how the tweeter is angled. A tilting tweeter also does not help in situations with multiple seating positions, for example a home theatre, where every seat is ideally delivered a similar balance of sound.

The goal for KEF is to place the performance of its freestanding loudspeakers into the wall or ceiling - 'Hide your speakers, not your sound.' To this end, KEF treats the architectural range of loudspeakers with the same level of novel engineering and design detail as the freestanding loudspeakers, providing high performance whilst remaining as discreet as possible. This includes the development and application of Uni-Q driver arrays across most of the product offering.

The benefits of Uni-Q are the same for architectural as they are for freestanding loudspeakers. Due to the wide, controlled directivity, the 'sweet spot' is exceptionally large. This allows for a larger critical listening area and reduces the negative effects of less-than-ideal placement. For dedicated home theatres, Uni-Q allows the speakers to be positioned in ideal locations in relation to the screen height and seating row positions. The left-centre-right (LCR) channels at the front can be placed at the centre line of the screen, whereas other designs are positioned much closer to ear level. Surrounds and rears can be positioned higher up rather than at ear height, as they can deliver the same balance of sound across all seats in the row.

The three-way rectangular loudspeakers, such as the Ci5160 and Ci3160 formats in both Ci-REF and Ci-R series, use a driver arrangement inspired by Joseph D'Appolito's work with midwoofer-tweeter-midwoofer (MTM) arrangements. MTM eliminates the lobing effect prevalent with coplanar loudspeakers that have the tweeter situated above the midrange driver by placing a midrange driver both above and below the tweeter. However, due to the driver interaction in the crossover region caused by the distance between the tweeter and midrange, vertical dispersion is decreased. By using a Uni-Q array at the centre, the flanking drivers are now low frequency (LF) drivers, and the crossover region is sufficiently low that the associated wavelengths are much longer than the distance between the LF drivers and the Uni-Q, restoring the vertical dispersion.

The use of Uni-Q and adopting the same engineering philosophy also extends to a consistent tonal balance, allowing for the different speaker ranges to be mixed within both home theatre and whole-home audio systems, across both architectural and freestanding loudspeakers, dependent on the specific requirements of the installation and listener.

3. Loudspeaker Models

3.1 Ci250RRM-THX

Ci250RRM-THX represents KEF's first coaxial three-way loudspeaker. The constituent drivers can be further specialised than in a two-way, owing to the reduced bandwidth each driver needs to cover. It utilises a 250 mm (10 in.) LF driver, as well as a coaxially mounted 100 mm (4 in.) 12th Generation Uni-Q driver array with MAT (Metamaterial Absorption Technology). This Uni-Q is the same as was developed for the LS60 Wireless, which can be read about, in more detail, in the relevant white paper [1].

As with all KEF architectural loudspeakers, it is not described as a 'music' or 'home theatre' loudspeaker – it is equally at home in both kinds of system whether as stereo, surround bed channels or Dolby Atmos.

Ci250RRM-THX's measured performance has also allowed it to achieve THX® Certified Ultra. This covers strict requirements including low distortion, high output and smooth, balanced off-axis performance.

3.2 Ci250RRb-THX

Whilst not a focus of this paper, a similar sized round architectural subwoofer has also been developed – Ci250RRb-THX. With twice the diaphragm area of Ci200QSb-THX, Ci250RRb-THX makes for an ideal partner for Ci250RRM-THX in both 2.1 and multichannel applications. In addition, the use of a KEF KASA500 system amplifier can even allow a listener to create a four-way system design using the onboard DSP.

Ci250RRb-THX has also met the requirements for THX® Certified Ultra performance when used in conjunction with the KEF KASA500 DSP amplifier. A single KASA500 driving a pair of Ci250RRb-THX will provide the required performance for THX Select, whilst THX Ultra is achieved when a single KASA500 drives four Ci250RRb-THX subwoofers.

4. Technology & Performance

During the development of Ci250RRM-THX, KEF engineers identified several issues with the traditional three-way coaxial driver arrangement, especially in the critical midrange passband. Starting from a foundation of mounting a Uni-Q driver in front of an LF driver (Figure 1), these issues were progressively tackled. The key was developing technologies that would address the performance problems, without negatively affecting the output of the LF driver. The resultant technologies – the patent-pending Cavity Radiation Control and the Low Diffraction LF Aperture – and their effects are described in the following sections.

4.1 Cavity Radiation Control

To deliver a three-way loudspeaker design in an architectural situation whilst maintaining ease of installation, the use of coaxially arranged drivers has become prevalent, especially when a speaker is destined for placement in the ceiling. There are two main ways of approaching this concept:

1. A concentric driver arrangement, where a centrally placed tweeter is surrounded by a midrange driver, which is in turn surrounded by a low frequency driver. This requires the voice coil for the low frequency driver to be extremely large and heavy, which affects the low frequency performance and renders the arrangement expensive.

2. A coaxial driver arrangement, where a traditional LF driver is placed behind a mounting that contains a concentric tweeter/midrange driver array (Figure 1.). In this arrangement, the mounting method used allows for low frequency sound from the rear LF driver to vent into the room. In addition, the LF driver can have a larger radiating area and a smaller voice coil, enhancing low frequency performance and decreasing cost respectively. These benefits have made this approach far more common than the concentric driver arrangement.

In the coaxial arrangement, the tweeter and midrange driver are mounted in an airtight housing which is positioned a distance away from the LF driver. This distance is important, as it allows the LF driver cone to move and output low frequency sound efficiently. It also creates a cavity between the LF driver and the housing of the midrange driver and tweeter.

KEF engineers found that the resulting cavity causes several resonances, which are determined by the size and shape of the cavity. These resonances were found to significantly affect the midrange passband response. As an example, the arrangement shown in Figure 1 exhibits an irregular response between 600Hz-2kHz, which is seen in Figure 2. A significant dip of up to 30dB can be seen at 860Hz, as well as a 'glitch' at approximately 1.9kHz. Finally, there are significant aberrations at the top of the midrange response coupled with a lack of consistent behaviour between the off-axis measurements.

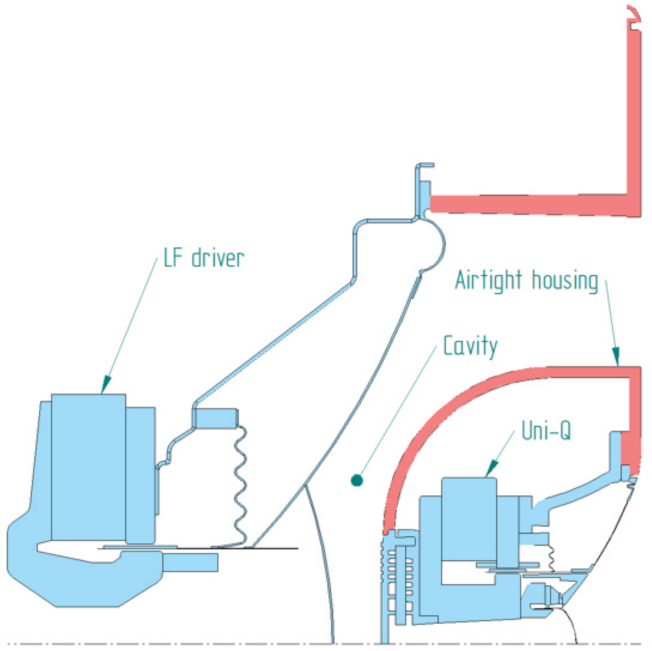

Figure 1. Classic arrangement of a tri co-axial driver: the midrange driver is in a closed box

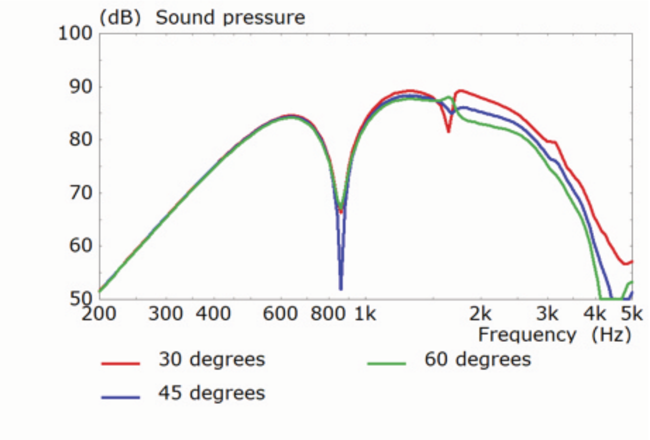

Figure 2. Midrange frequency response associated with Figure 1 (FEA modelled)

One way to decrease the amplitude of the cavity resonances is by packing the cavity with acoustic damping material. This, however, creates additional challenges. The LF output pathway would be constricted, increasing turbulence and resistance. This results in a decrease in low frequency output and system efficiency.

A patent-pending method has been devised for taming the cavity resonances without restricting bass performance and efficiency – Cavity Radiation Control. Rather than using an airtight mounting pod, the rear of the midrange driver is left open, effectively creating a dipole arrangement (Figure 3.) The rearward sound from the midrange driver is channelled into the cavity and onwards into free space through the annular gaps around the Uni-Q mounting.

The far-field response of the midrange is therefore made up of both the front firing and the rearward sound waves of the midrange driver, creating an acoustical short circuit. Figure 4 shows the effect - the 30dB dip at 860Hz has been removed, making for a much smoother response at the lower end of the frequency scale.

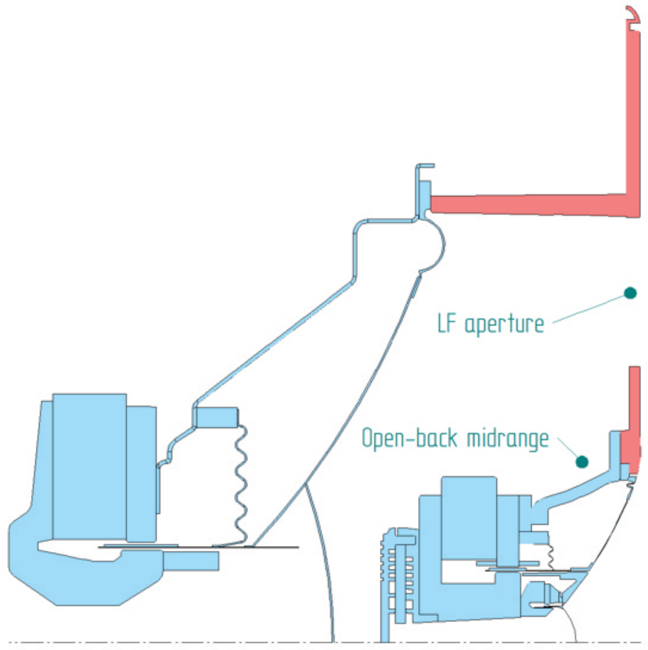

Figure 3. Cavity Radiation Control

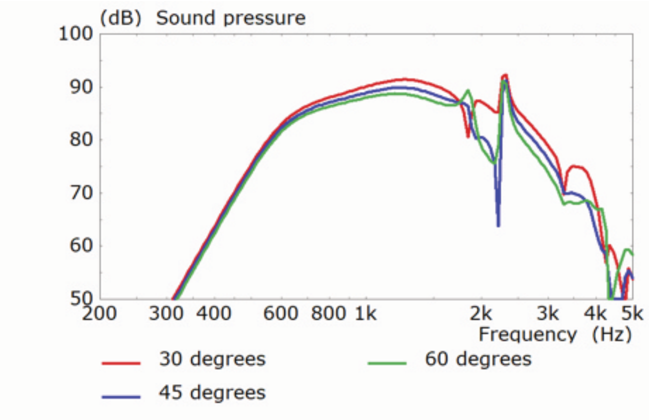

Figure 4. Midrange frequency response associated with Figure 3 (FEA modelled)

4.2 Low Diffraction LF Aperture

In a three-way coaxial arrangement, a ring-shaped aperture is required to allow the output of the bass driver to radiate into the room. However, this breaks the continuity of the MF/HF driver baffle resulting in resonances above 1kHz. The effect of this can be seen in Figure 4, at around 2.1kHz.

Figure 5 shows a section of the final design, where the mounting pod has been carefully profiled, smoothly transitioning from the midrange cone and the aperture in a similar way to how KEF Blade and LS50 Meta loudspeakers feature curved cabinet surfaces. A ring of melamine foam has also been added on the other side of the ring-shaped aperture to reduce reflections and scattering.

Figure 6 shows the resulting midrange frequency response. The irregularities above 2.1kHz have been effectively managed, creating a much smoother response at the top of the operating band of the midrange driver. This arrangement also minimises port noise from the annular gap and maintains low frequency output.

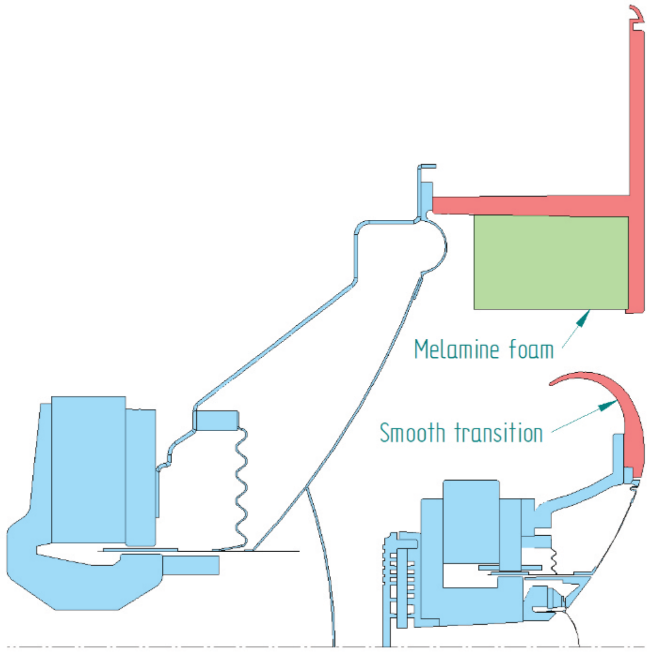

Figure 5. Low Diffraction LF Aperture added to Cavity Radiation Control

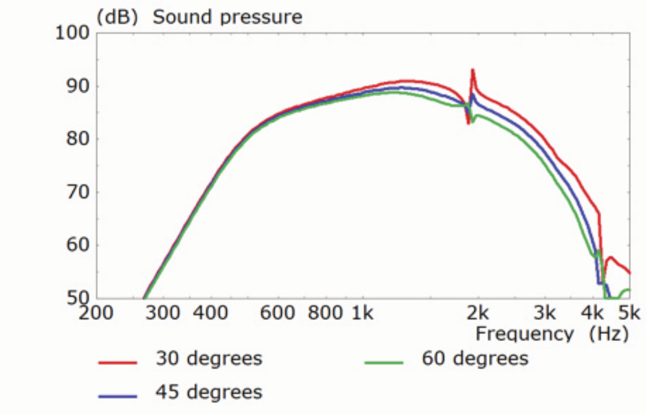

Figure 6. Midrange frequency response associated with Figure 5 (FEA modelled)

4.3 Resonance-free LF Cavity

The residual glitch observed in the response in Figure 6 at 1.9 kHz is caused by a cavity resonance mode. Figure 7 shows this resonance through a visualisation of a Finite Element Analysis simulation of the sound pressure in the LF cavity. There is an area of zero pressure with maximum particle velocity located around the midrange motor system at this frequency.

To deal with this cavity resonance, a ring of melamine foam has been positioned around the MF driver motor to coincide with the lowest pressure and highest air particle velocity region of the resonance. Figure 8 shows a section of the speaker with the ring included. This placement does not affect any low frequency elements, but effectively suppresses the cavity mode. Figure 9 shows the resulting midrange frequency response without the irregularity at 1.9kHz.

The combined design features presented so far deliver a well-behaved midrange response, free from unwanted resonances, whilst avoiding any restriction of the output of the low frequency driver. Additionally, the frequency responses both on- and off-axis show exceptionally well-controlled performance across the measured listening window.

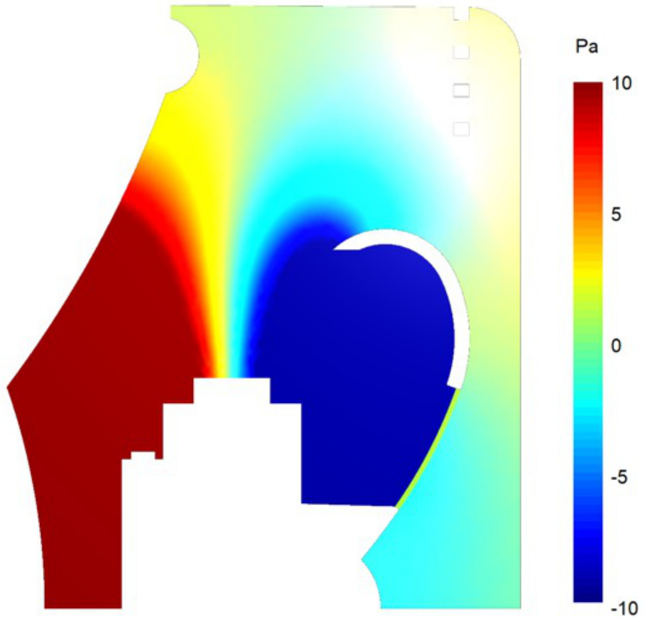

Figure 7. Midrange pressure distribution at 1.9kHz

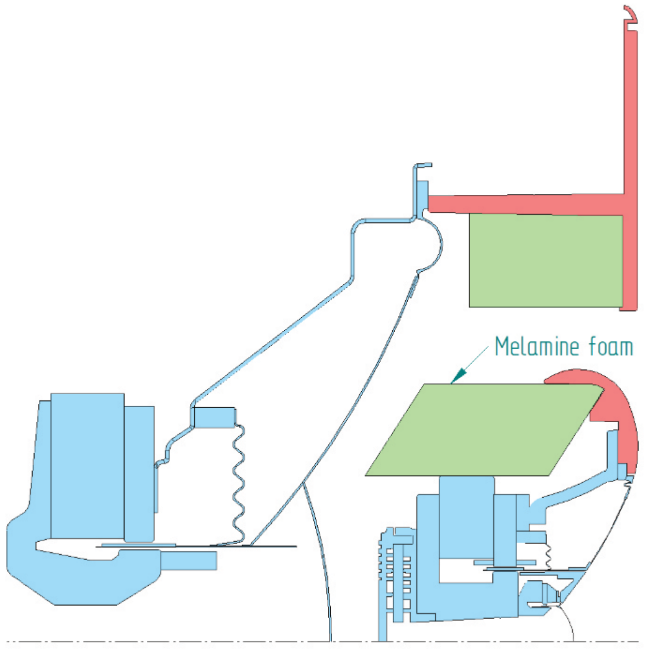

Figure 8. Cavity Radiation Control, Low Diffraction LF Aperture and Resonance-free LF Cavity combined

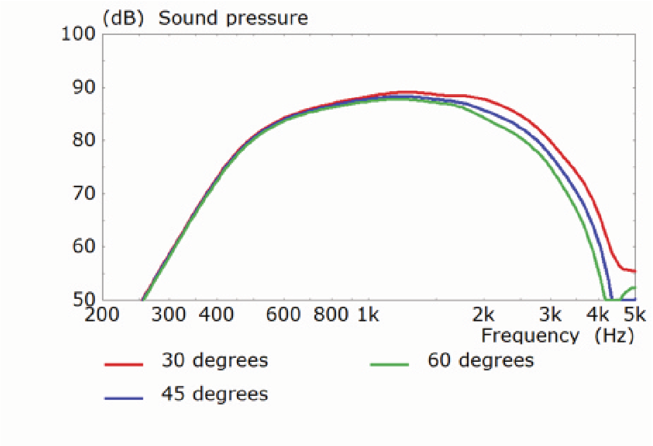

Figure 9. Midrange frequency response associated with Figure 8 (FEA modelled)

4.4 Tweeter Radiation

Whilst primarily designed to improve midrange performance, the features described in the previous section also benefits the radiation of the tweeter. Figure 10 shows the tweeter frequency response associated with Figure 1 – the traditional three-way coaxial design. Whilst generally well controlled throughout, there are irregularities which are caused by the sharp edge of the midrange baffle, where the low frequency aperture begins. The final design, as shown in Figure 8, introduces the rounded and smoothed transition of the baffle into the aperture, and results in the tweeter response shown in Figure 11. The response is far smoother, and better controlled across the off-axis measurement window.

The following figures show the effect of the previously discussed technologies at 4kHz (Figures 12,13) and 8kHz (Figures 14,15). Figure 12 shows that the traditional design from Figure 1 suffers from significant, yet uneven pressurisation within the cavity at 4kHz. As these resonances superimpose themselves upon the sound emanating from the front of the driver, the result is the irregular response in Figure 10.

With the final design, as shown in Figure 8, the performance obtained has been improved, as shown in Figure 13. The pressurisation within the cavity at the measured frequencies is far more homogenous than before, which leads to far less interaction with the sound radiating from the front of the loudspeaker. Referencing Figures 14 and 15, the same result is attained at 8kHz. Comparable results can be observed throughout the working bandwidth of the tweeter, hence the overall improvement and observable smoothness of the tweeter response.

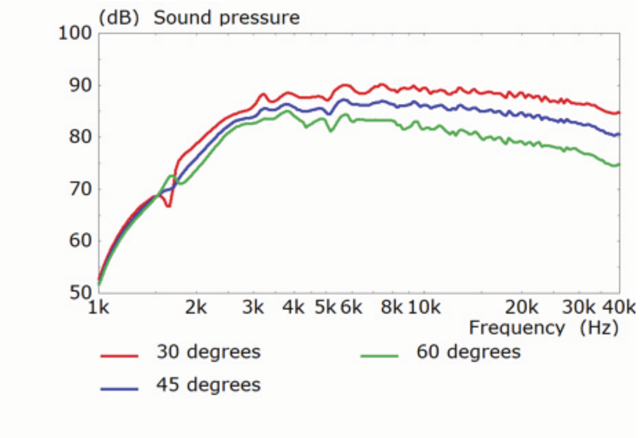

Figure 10. Tweeter response associated with Figure 1 (FEA modelled)

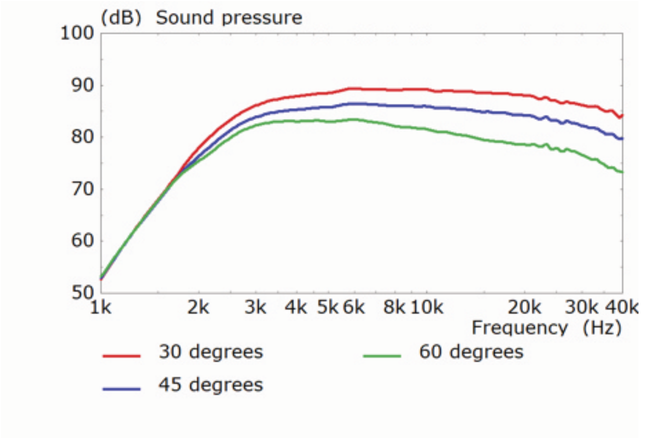

Figure 11. Tweeter response associated with Figure 8 (FEA modelled)

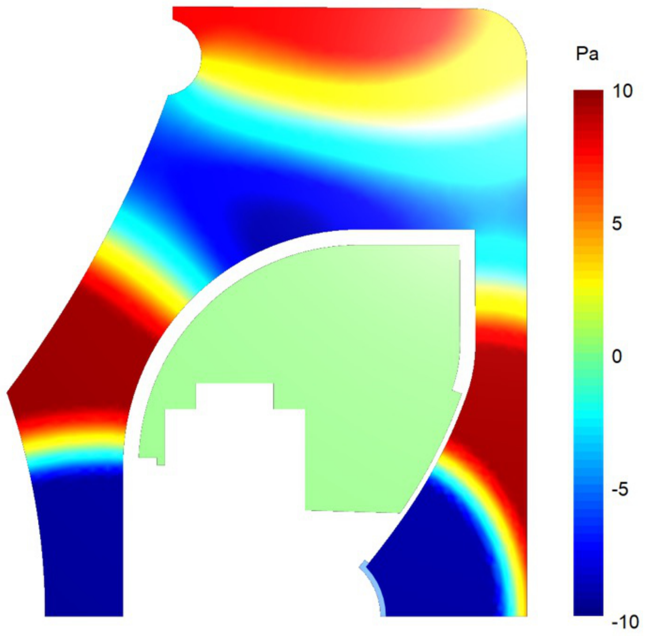

Figure 12. Tweeter pressure distribution at 4kHz associated with Figure 1

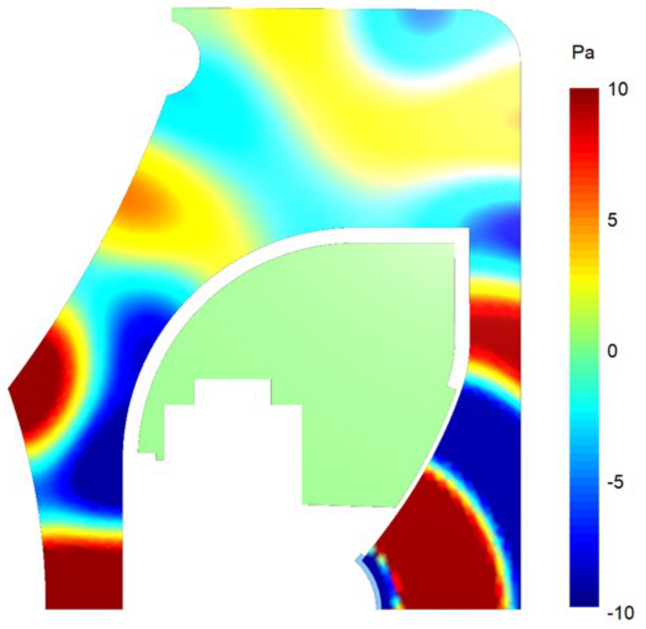

Figure 14. Tweeter pressure distribution at 8kHz associated with Figure 1

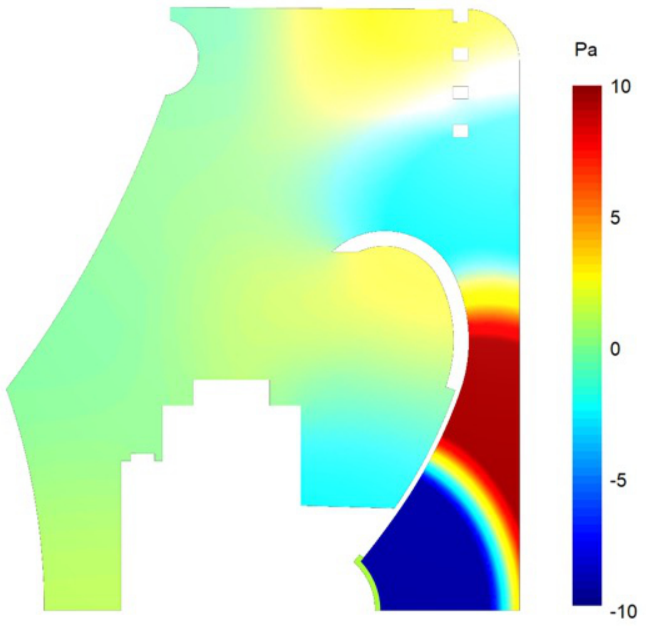

Figure 13. Tweeter pressure distribution at 4kHz associated with Figure 8

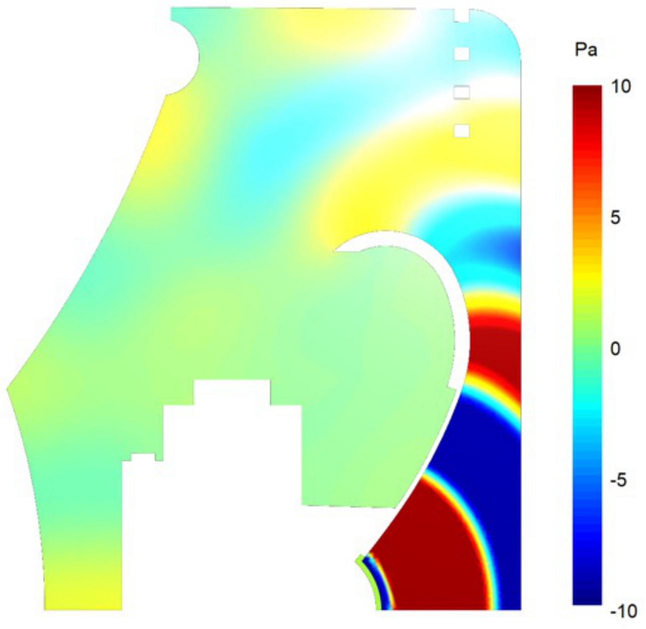

Figure 15. Tweeter pressure distribution at 8kHz associated with Figure 8

4.5 4 in. 12th Generation Uni-Q with MAT

Ci250RRM-THX uses the 100mm (4 in.) Uni-Q driver developed for the LS60 Wireless active speaker system. As part of the 12th Generation Uni-Q, it shares some features found in R Series (2018), LS50 Collection, and Blade and Reference Meta. The following is a list of various standout technologies, alongside references for where detailed explanation of how they work may be found:

1. Metamaterial Absorption Technology (MAT) - A maze-like disc that absorbs 99% of the tweeter back wave, avoiding its reflection back into the tweeter dome, reducing distortion [2]
2. Tweeter Gap Damper – first developed for R Series (2018), this technology features an acoustically damped chamber that reduces the resonance caused by sound travelling over the gap that sits between the tweeter housing and midrange cone [3]
3. Flexible Decoupling Chassis – developed for Blade and Reference Meta, this feature deals with the issue of a vibrating chassis when the driver is decoupled from the cabinet. [4]

The full complement of features can be found in section 3.3 of the LS60 Wireless white paper [1].

5. Bespoke Bezel Design

The mechanical and industrial design of Ci250RRM-THX, like with all KEF products, is a tightly collaborative effort between the design, acoustic and manufacturing teams. Everything must fit together to deliver the best acoustic performance, alongside other design and installation features.

Not only is the area surrounding the Uni-Q of critical acoustic importance, but so is the geometry of the slotted grille section that surrounds the low frequency aperture (Figure 16). During early rapid prototyping using resin, it was found that even minor dimensional changes in these areas for cosmetic or structural reasons greatly impacted acoustic performance. The challenge, therefore, was to produce a lightweight, robust mechanical design that conformed to the computer-modelled acoustic system design, whilst incorporating the design language and common features found across the architectural range (see Appendix). The team decided on the use of lightweight polymer mouldings for the main structural components, which allowed the brief to be fulfilled.

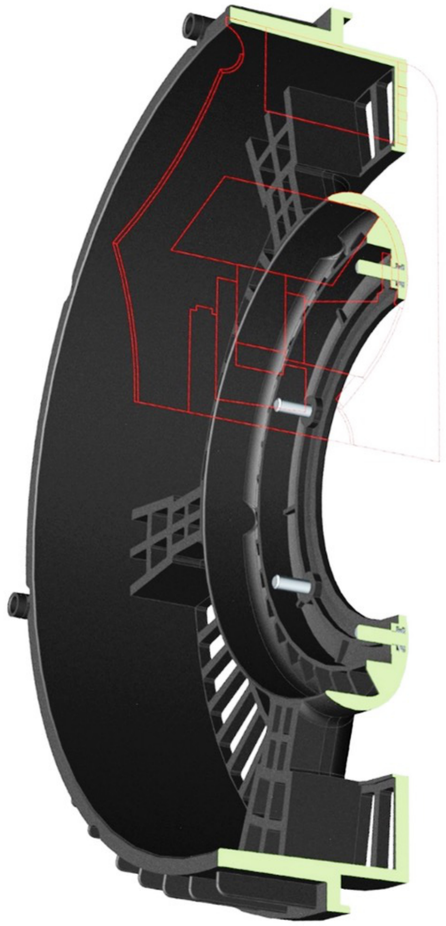

Figure 16. Image showing section of the final acoustic simulation geometry in red, and the resulting mechanical CAD design used for the Uni-Q housing tooling

6. Summary

The development of new technologies to solve long-standing issues is at the very heart of the Ci250RRM-THX architectural loudspeaker. As discussed in earlier sections, KEF speakers must be of the highest performance and suitable for any application, whether designed as a traditional cabinet based loudspeaker, or for custom installation. The role of the loudspeaker does not change between these scenarios, which is why the philosophy does not change.

Through solving the intrinsic issues of the three-way coaxial format, Ci250RRM-THX delivers exceptionally high performance, making for a worthy addition to the product range.

7. Appendix: CI Installation: Back Boxes and Filling

It is well understood that low frequency extension, sensitivity and cabinet size are directly related [5]. For example, to achieve lower extension whilst maintaining or increasing sensitivity, cabinet size must be increased. The air volume within a speaker cabinet acts as a spring – as the driver moves inwards, the air becomes compressed, and the smaller the air volume, the higher the stiffness. The driver itself also has a stiffness provided by the suspension and surround, and the system stiffness is the sum of the air volume and driver stiffness.

When designing an architectural speaker, it must be decided whether to utilise a backbox or an infinite baffle design. If designing for use with a backbox, then the stiffness of the system must be considered. As some of the stiffness will be contributed to by the air volume, then the stiffness of the driver must be reduced to compensate. The limited cabinet size will result in reduced low frequency extension, sensitivity, or both.

All KEF architectural loudspeakers are designed as infinite baffle, with all the required stiffness built into the driver. This means that no stiffness reinforcement is required from the finite and fixed air volume provided by a backbox. Instead, the installer can focus on ensuring that the enclosure is of a large enough size to take advantage of the low frequency output capabilities of a KEF architectural loudspeaker.

This makes installation straightforward – by using the enclosure, the only consideration for installation is mounting depth of the speaker. Backboxes can add considerable mounting depth, which may require building out from an existing wall, losing floor space in the process.

To provide maximum flexibility, KEF publishes a 'Ci Cabinet Volume' table modelled. This table lists all current KEF architectural models and provides a minimum enclosure volume for 'Reasonable' and 'Ideal' bass response. The volumes are calculated so that the final bass response meets a certain level of flatness when the enclosure is empty: 1dB overshoot for 'Reasonable' and 0.5dB overshoot for 'Ideal.' The use of wadding material, such as polyester fibre in the enclosure can help smooth the overshoot. Ci250RRM-THX is specified as requiring an 80L enclosure for 'Reasonable' bass and 150L for 'Ideal.'

Figure 17 shows Ci250RRM-THX in three scenarios – an infinite enclosure, an empty 150L enclosure and a 150L enclosure totally filled with polyester fibre. The infinite enclosure shows the smoothest response with the deepest extension, with a -6dB point of 28Hz. When placed into the empty 150L enclosure, the -6dB point has increased to 31Hz, with a 0.5dB boost in the response at 60Hz. Filling the enclosure with material smooths the response, whilst maintaining 31Hz at -6dB.

Figure 18 shows the same, except using the 80L enclosure. The infinite enclosure response is the same as the previous figure. In the empty 80L enclosure, the -6dB point is now 34Hz, with a more pronounced 1dB boost at 60Hz. When the 80L enclosure is filled, the response smooths out. Going into a smaller enclosure than this is not recommended as both the low frequency extension and degree of overshoot will rise. The larger the overshoot, the more wadding material is required, the space for which cannot be provided by the ever-reducing cabinet volume.

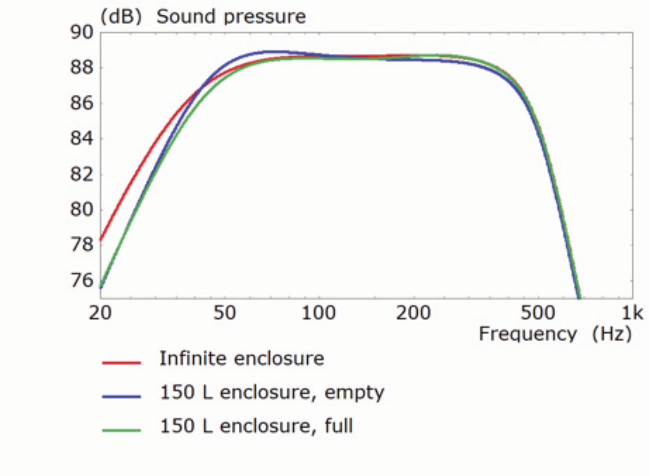

Figure 17. Effect of the 'ideal' enclosure volume on the Ci250RRM-THX woofer frequency response

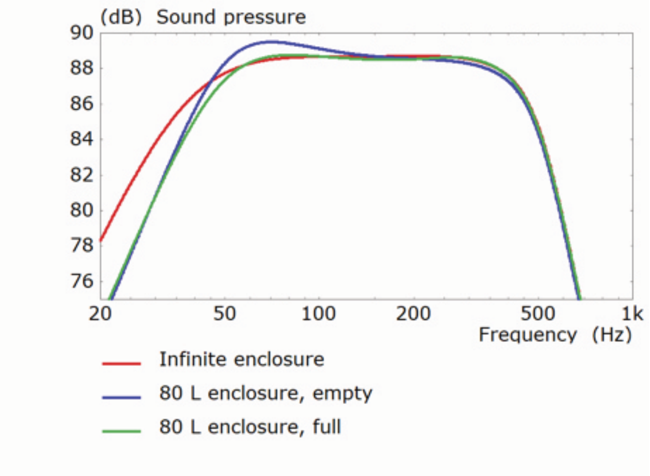

Figure 18. Effect of the 'reasonable' enclosure volume on the Ci250RRM-THX woofer frequency response

8. References

[1] "LS60 Wireless (White Paper)." KEF R&D, Apr. 2022. [Online]. Available: https://assets.kef.com/product-support/ls60-wireless/LS60W_Whitepaper.pdf

[2] "LS50 Meta, LS50 Wireless II (White Paper)." KEF R&D, Oct. 2021. [Online]. Available: https://assets.kef.com/pdf_doc/LS50WII/KEF-LS50Meta-LS50WirelessII-WhitePaper.pdf

[3] "R Series 2018 (White Paper)." KEF R&D, Oct. 2018. [Online]. Available: https://assets.kef.com/uploads/cm/r2018_whitepaper_en.pdf

[4] "Blade Meta, Reference Meta (White Paper)." KEF R&D, Feb. 2022. [Online]. Available: https://assets.kef.com/documents/reference/KEF_Blade_Ref_Meta_Tech_Paper.pdf

[5] R. H. Small, "Closed-Box Loudspeaker Systems Part I: Analysis," *J. Audio Eng. Soc.*, vol. 20, no. 10, pp. 798–808, Dec. 1972.

[6] "KEF Ci Cabinet Volume Table." KEF R&D [Online]. Available: https://assets.kef.com/uploads/files/en/series_pdf/Ci_Minimum_Cabinet_Volume.pdf

Specifications and Measurements

Ci250RRM-THX
Three-way Coaxially Arranged Architectural Loudspeaker

Model		Ci250RRM-THX
Series		Ci-R Series
Nominal impedance		8Ω
Sensitivity (2.83V/1m)		89dB
Frequency response (±6dB) open-backed		28Hz - 20kHz
Frequency range (-10dB)		20Hz - 45kHz
Nominal coverage		120°
Max SPL		111dB
Crossover frequency		540Hz, 2.6kHz
Drive units	LF	250mm (10in.)
	MF	100mm (4in.) Uni-Q
	HF	19mm (0.75in.) vented aluminium dome with Metamaterial Absorption Technology[1]
Recommended amplifier power		50 - 250W
Recommended high-pass filter (Hz)		30 - 60Hz
Product external dimensions	Diameter Ø	346mm (13.62in.)
	Depth	175mm (6.89in.)
Cut-out dimensions	Diameter Ø	300mm (11.81in.)
Net Weight		6kg (13.2lbs)
Mounting depth from surface		168mm (6.62in.)
Optional rough in frame		-
Ideal rear volume		150L
Minimum rear volume		80L
THX certification		THX® Certified Ultra
Safety and Regulatory Compliance		IP64
Ceiling thickness (Maximum)		30mm (1.18in.)
Ceiling thickness (Minimum)		6mm (0.24in.)

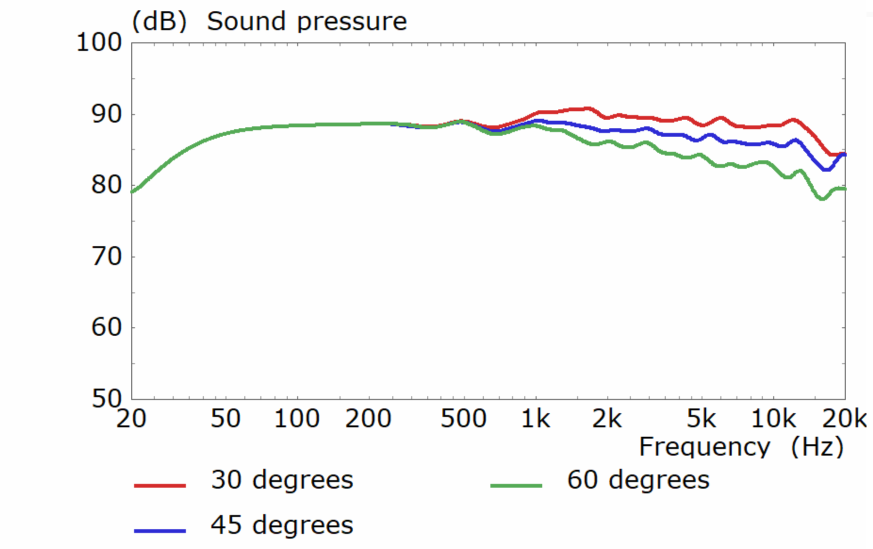

Figure 19. Measured frequency response of Ci250RRM-THX at various off-axis positions