KEF R&D

LS60 Wireless

CONTENTS

Foreword

"During KEF's 50th anniversary year we launched the LS50 loudspeaker as a celebration of our 50 years of passive loudspeaker technology and know-how. Today we launch the LS60 Wireless loudspeaker, the culmination of a concerted effort over the past five years to develop new technologies for active loudspeakers.

The LS60 Wireless is a significant product for KEF and it is special to be launching it during the 60th anniversary year. KEF was founded because of Raymond Cooke's belief that loudspeaker performance could be improved through the application of new materials and new technologies. In KEF R&D this is a belief that we still hold; we're very proud of the heritage of our department, and we strive to continue following this same philosophy.

In the last 10 years music consumption has changed beyond recognition, with online streaming becoming common place. This shift has been the catalyst for a resurgence of interest in active loudspeakers. Active loudspeakers have always held the possibility of improved sound quality and are already the de facto standard in most serious public address and studio applications. However, HiFi has always resisted this change, preferring to mostly stick with passive loudspeakers and separates.

Modern passive loudspeakers can give remarkably high performance. One could even argue that the HiFi market's fondness for passive loudspeakers has led manufacturers to develop drivers with extremely refined behaviour as a direct result of the limitations and restrictions of the passive format. Nevertheless, in terms of both absolute performance and flexibility, active has a significant advantage.

The LS60 Wireless is designed to have a small footprint and slim profile so that it can sit comfortably in most people's homes, not requiring special listening rooms or awkward positioning in the room. It provides flexible connectivity – allowing streaming from numerous services, podcasting, internet radio, connectivity for traditional HiFi equipment, Bluetooth sources and TV sound – all the while delivering a scale and quality of sound that is almost unbelievable. We're proud of this engineering feat and excited to bring this product to the market. This white paper outlines some of the technical details and concepts behind the performance."

Dr Jack Oclee-Brown, VP of Technology, KEF Audio.

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 change 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 a good temporal resolution such that it does not "smear" the sonic event. Each of these fidelity requirements provides 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 is 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. Cues such as the relative arrival time and level of the sound at each of our ears. Stereo 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, sufficiently 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 loudspeakers' 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 well 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. Overall Concept

From the outset, the goal of the LS60 Wireless was to create a compact, slim product with a small footprint. Such a product would be more versatile and flexible than a typical HiFi loudspeaker, and not requiring users to make significant concessions to the layout of their rooms. This aim creates a sizeable acoustical engineering challenge, especially because the internal volume of the loudspeaker will be limited. With a passive configuration the resulting performance would be very disappointing. However, an active DSP configuration, along with KEF's unique technologies, enables extremely high performance.

The first and most significant challenge is low frequency performance. The internal air volume of the loudspeaker is quite small, and this means that the acoustical efficiency will be relatively low[1,2]. In order to achieve deep bass, it is necessary to use equalisation to boost the lowest frequencies, and this in turn means that the LF amplifiers must be capable of providing high power and the LF drivers must be able to handle high power.

Ports are often used to increase the low frequency acoustical efficiency in conventional loudspeakers. But this comes at the price of slower transient response, lower acoustical output below the port tuning frequency and potential colouration of the sound from port resonance and midrange leakage. In a loudspeaker with a small internal air volume, ports are especially problematic because, to achieve very low port tuning and high output, the port must be extremely large. Therefore, based on these factors, it was quite clear that the LS60 Wireless should be a closed box loudspeaker.

With a closed box loudspeaker only the LF drivers operate to generate bass output. There is no port radiation to augment output, nor any reduction in cone excursion from the port tuning. Therefore, achieving high output and deep bass becomes a simple matter of three factors:

1. High driver volume displacement (radiating area times driver excursion)
2. Enough amplifier power to reach full excursion and drivers capable of handling this power
3. Equalisation to flatten the loudspeaker response and protection systems to avoid overload and damage

Typical loudspeakers have all drivers placed on the front of the enclosure. But this means that the width of the loudspeaker is linked to the size of the drivers. Maximising the driver area in a conventional layout leads to a wide loudspeaker enclosure and would not achieve the target of a small footprint and slim profile. In addition, the distance from the LF drivers to the midrange driver becomes very large, and this makes it very challenging to seamlessly crossover from the LF section to the MF section.

The natural path for the LS60 Wireless was to use the Single Apparent Source (SAS) driver configuration from the Blade series of loudspeakers. In this configuration four LF driver cones are symmetrically placed on the sides of the loudspeaker enclosure around the Uni-Q driver. This layout is discussed in more detail in section 3.1.1 below. The key aspects of SAS are that it allows larger LF drivers to be used while maintaining excellent directivity, a slim loudspeaker cabinet, and excellent diffraction characteristics.

An early prototype of the LS60 Wireless was constructed in late 2017 to confirm the overall direction. The first listening tests in early 2018 gave the team a first glimpse of the potential of this concept. But it also highlighted that further work was required, especially to maximise the bass output and linearity.

This led directly to the development of the Uni-Core driver and Smart Distortion Control Technology, both of which are described in more detail in sections 3.2.1 and 3.2.3 below.

For the early prototype, the only Uni-Q available with the correct diameter to fit into the slim baffle was from the E-series E301 loudspeaker. This driver was never designed with 3-way operation in mind and is also missing a number of KEF's latest technologies, such as the Tweeter Gap Damper and metamaterial absorber. For the LS60 Wireless a brand new 12th generation Uni-Q was developed and the full details are outlined in section 3.3. Figure 1 shows a small selection of the technologies present.

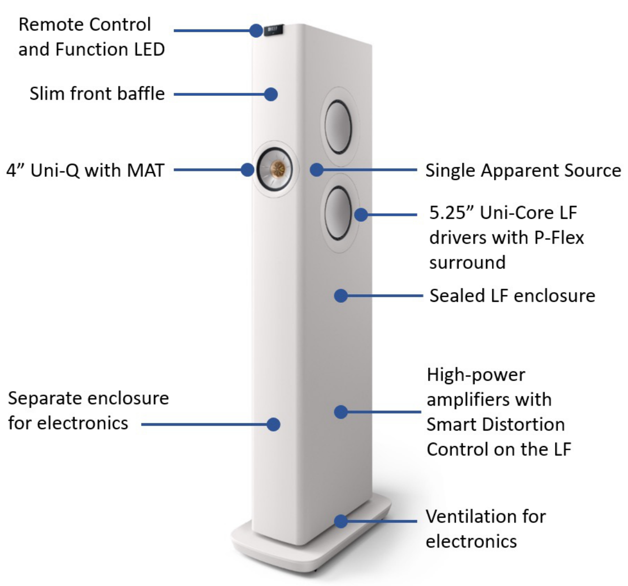


Figure 1. Diagram detailing LS60 Wireless packaging

The next section of the white paper focuses on the various engineering details that work towards the ultimate goal of delivering a new level of performance from a small floorstander.

3. Technology

3.1 External Acoustics and Cabinet Vibration

3.1.1 Single Apparent Source (SAS)

In 2009, KEF introduced the Concept Blade loudspeaker and debuted a new system configuration: SAS (Figure 2). This configuration overcomes many shortcomings found in most conventional loudspeakers.

At low frequencies, the sound wavelength is large compared to the size of a typical LF driver and this means it will radiate sound omnidirectionally, like a stone falling on a pond, even if the driver is placed on the side of the cabinet. With SAS, the acoustical centre of the LF driver array is almost coincident with the Uni-Q, creating a virtual source of sound that comes from one position in space over the entire loudspeaker bandwidth. The LF/MF crossover frequency is adjusted to match the LF driver spacing so that the directivity in the LF to MF crossover region is much more consistent than a conventional loudspeaker. The enclosure width is no longer dictated by the LF drivers. This allows a narrow loudspeaker cabinet combined with a Uni-Q with almost the same diameter as the baffle width. This configuration gives wide horizontal directivity and minimises baffle diffraction. In terms of bass output, the area of the LF drivers can be optimised independently to achieve the required volume displacement and each LF driver cone only handles ¼ of the total LF amplifier power. The midrange on the front baffle operates with low excursion allowing reduced harmonic and intermodulation distortion.

Until now, the SAS configuration has only been available in KEF's flagship passive loudspeakers. This changes with LS60 Wireless as the benefits of SAS are perfectly suited to the performance targets of this loudspeaker. This acoustic package, together with a digital crossover, allows the speaker response to have a generally wide directivity that very smoothly narrows in a controlled fashion as frequency increases. The drivers are so well integrated there is virtually no way to tell when the output of one ends and the next one begins.

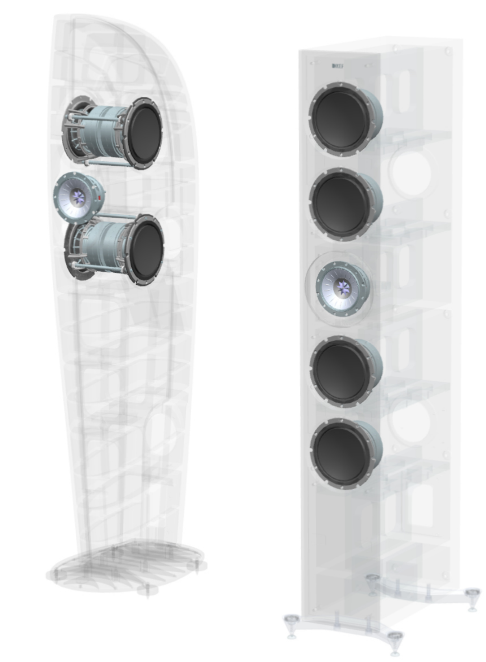


Figure 2. Single Apparent Source and front baffle LF driver configurations as seen in Blade Two Meta and Reference 5 Meta

3.1.2 Cabinet diffraction

At the low-end of their frequency passband the drivers radiation is omnidirectional. When the driver plays, a spherical wave radiates and spreads across the surface of the loudspeaker. As this wave reaches the edge of the cabinet it suddenly expands around the corner. This sudden change in direction creates a secondary sound source at the cabinet edge. As this second wave travels outwards it combines with the direct sound radiated from the driver causing ripples in the measured frequency response. Harry Olsen studied the diffraction effect for various different loudspeaker cabinet geometries [3] and his work is very well known and frequently cited. However, Olsen's study did not include driver directivity, which has a very significant effect [4].

Diffraction can never be totally eliminated, but by optimising driver size and baffle geometry its detrimental effect on the sound can be avoided. The severity of the ripple depends largely on three factors: the size of the driver, the size of the baffle and the size of the baffle edge corner radii. The ideal case is an extremely smooth convex baffle, as featured in the Blade series of loudspeakers. This extreme contouring was not feasible for LS60 Wireless because there is no excess width for large edge radii either side of the Uni-Q. However, diffraction can also be minimised by ensuring that the distance from the outside of the driver to the cabinet edge is as small as possible. This pushes the frequency at which the ripple would occur up to where the driver becomes directional. The lateral radiation is lower and the edge of the baffle is much less exposed to its sound. KEF has used this same solution in other loudspeaker ranges by placing the Uni-Q into a shallow waveguide, the Shadow Flare [5]. In this case, because of the slim width of the baffle, no shadow flare is required.

Figure 3 shows the simulated on-axis frequency response, including the diffraction ripple effect, for a 4" (100 mm) diameter piston at the centre of a square baffle. As the width of the square baffle approaches the driver diameter, the ripple amplitude decreases.

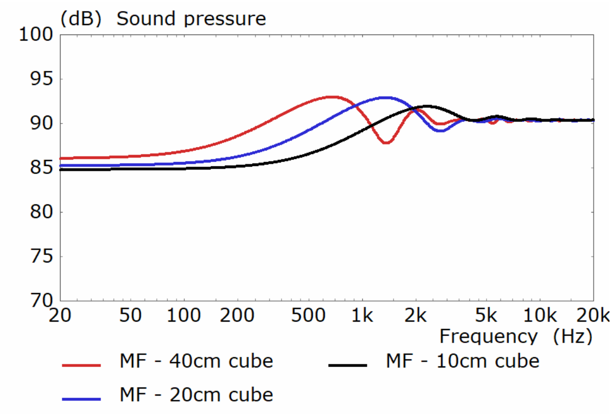


Figure 3. Diffraction effect as square baffle tends to driver diameter

In the case of the tweeter, its directivity is controlled at the bottom of its passband because it is housed inside the midrange cone which acts as a waveguide. This dramatically shadows the edges of the cabinet from the tweeter output, avoiding the effect of diffraction. At higher frequencies, the effect of the midrange cone together with the Tangerine Waveguide keep the tweeter's directivity at a constant angle while shadowing the cabinet edges. Additionally, the small radius on the lateral edges of the cabinet eases the transition into full space for the sound waves that do reach them.

Vertically, the Uni-Q is positioned at a considerable distance from the top edge of the cabinet. Due to the narrow baffle, the edge is narrow and only a small portion of the total sound from the driver reaches it. As a consequence its effect is minimal.

Figure 4 shows the vertical directivity of the system frontal hemisphere at key frequencies. At 390 Hz, where the LF to MF crossover takes place, the enclosure height is larger than an acoustical wavelength yet the directivity remains nearly omnidirectional. When the distance of the Uni-Q to the top edge compares to half of the sound wavelength, at around 800 Hz, the output reaching the edge is already 12 dB quieter. The output continues to drop at a right angle to the speaker axis as frequency increases further obscuring the baffle top edge. Crucially, however, the system's dispersion remains constant at +/- 40 degrees well into the high frequencies.

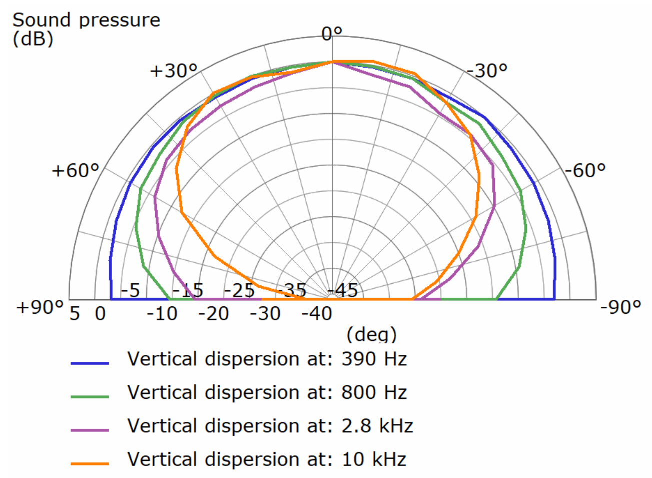


Figure 4. Vertical dispersion front hemisphere at various frequencies - normalised to 0 degrees

3.1.3 Force cancelling

Newton's Third Law states that for every action there is an equal and opposite reaction. This can be applied to the mechanics of a loudspeaker driver. When a voice coil is excited with an electromagnetic force, an equal force pushes the motor in the opposite direction. This force is usually transferred to the cabinet via the driver chassis and results in motion and audible resonances from the cabinet walls.

1984 saw the first commercial use of force cancelling in a loudspeaker with the release of the KEF Reference Model 104/2. More recently this approach has been implemented in products such as the Blade, KF92 and KC62. In this arrangement, identical drivers are mounted back-to-back and their diaphragms move in opposite directions. As the reactive forces are equal in magnitude but opposite in direction, they cancel each other out. This prevents the vibration travelling to the cabinet and thus the resulting audio colouration. An intrinsic design characteristic of KEF's Uni-Core driver technology is its force-cancelling configuration.

Figure 5 shows a comparison of cabinet vibration with and without force cancelling. Both measurements are normalised to the driver's velocity (0 dB) to be comparable. A solid and massive test cabinet with one Uni-Core driver is used and a laser vibrometer is pointed at one of its baffles close to the driver.

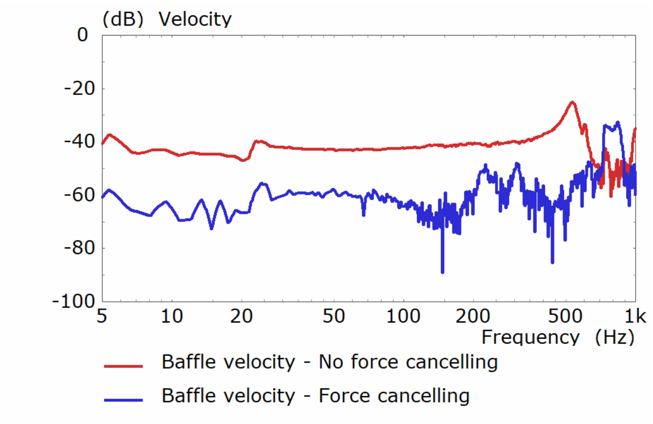


Figure 5. Effect on cabinet vibration with (drivers same polarity, blue) and without (drivers opposite polarity, red) force-cancelling operation

In one case (Figure 5, red curve), the two drivers in the Uni-Core are connected with the opposite polarity, meaning they move in the same direction, thus causing the cabinet to move as one lump of mass in the opposite direction and the cabinet walls to resonate in a higher-order mode around 500 Hz. This is representative of the vibration behaviour occurring when a driver moves against the cabinet in a regular speaker. The relative movement of the baffle to the driver is at –40dB, or 100 times lower, which might seem low. However, in a normal speaker, the cabinet outer panel area can easily equal several times the driver's radiating area and when excited it will likely generate audible sound. As an example, a Reference 5 Meta cabinet has 25 times the outer surface area of its 4 LF drivers.

In the second case (Figure 5, blue curve), the two drivers are connected with the same polarity and thus moving in opposite directions, as they would be in a force-cancelling configuration. The cabinet therefore barely moves. The attenuation in cabinet vibration is an astounding -20 dB broadband. This is equivalent to increasing cabinet mass in a non-force-cancelling system by a factor of 10.

Force cancelling, combined with decoupling of the Uni-Q driver (see section 3.3), allows the LS60 Wireless to have extremely low cabinet wall motion, ensuring everything the user hears is the output of the drivers - the cabinet itself is silent.

3.2 LF Drivers

3.2.1 Uni-Core

The four LF drivers in LS60 Wireless are arranged into two Uni-Core units. Each Uni-Core (Figure 6) is a very slim 4.3" (110 mm) deep unit housing two 5.25" (130 mm) diameter long-excursion LF drivers that share the same motor.

Figure 6. One of the two Uni-Core LF units found in LS60 Wireless

Uni-Core was debuted in the KC62 subwoofer, but in fact the invention was for the LS60 Wireless project. The very first prototype of the LS60 Wireless used four conventional 4.5" (115 mm) LF drivers. The performance showed promise but the bass output and extension was not satisfactory. A target of 3dB higher bass output was set, achieved with a LF driver radiating area increase of 13% combined with an excursion increase of 27%. This presented an issue as within the cabinet width the space was fully utilised. Many ideas were discussed and the Uni-Core was among them: to combine the two back-to-back motors into a single circuit to energise both voice coils. There was initially some hesitation over this approach because it presented some difficult challenges: so that the two voice coils do not collide they would have to be of different diameters but should have matched behaviour, and the natural magnetic circuit arrangement would mean the current orientation in the coils might result in significant electro-magnetic coupling between the coils.

Figure 7. Comparison of LS60 Wireless width achieved with Uni-Core (left) and width achieved with back-to-back LF drivers with equivalent excursion (right)

However, all other suggested ideas presented issues too, and initial exploratory simulations into the Uni-Core configuration were started. The early results were surprising: most of the concerns were unfounded or the arrangement naturally compensated for them. Uni-Core was given the green light and development of the LS60 Wireless LF drivers started.

LS60 Wireless demonstrates the true potential of Uni-Core by pushing the compromise between cabinet dimensions and sound performance further than any other loudspeaker. Figure 7 shows how the use of a Uni-Core in this case helped shed 1.2" (30.5mm) from the baffle width compared to using back-to-back LF drivers of the same excursion.

There are two basic principles behind the idea of Uni-Core. The first is the use of a shared motor between two drivers, that is a single magnetic circuit energising the two voice coils. The second principle, the one instrumental to the depth of the driver array, is the use of a different diameter for each voice coil. By doing this and using the space between the two coils to install a mounting ring for the motor T-Yoke, the two voice coils can overlap when they move backwards and considerable depth is saved (Figures 8,9).

Figure 8. Cross-section of Uni-Core driver found in LS60 Wireless

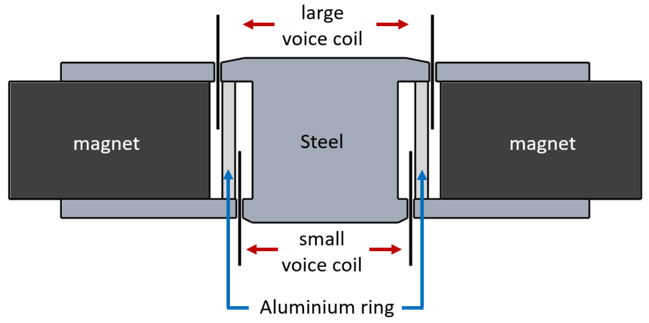


Figure 9. Schematic of the Uni-Core motor found in LS60 Wireless

Despite the asymmetry of the motor and the two different voice coil sizes, for Uni-Core to function correctly it is essential that both drivers behave almost identically. If this is not the case then Single Apparent Source will not function correctly, and force cancelling will not be achieved. This means that the motor force factor (BL), the stiffness of the suspensions (Kms) and the moving mass (Mms) should be as similar as possible for both drivers.

The issue of motor force factor (BL) matching can be elegantly dealt with by the arrangement. The motor force factor is determined by the length of voice coil wire immersed in the magnetic gap (L) multiplied by the magnetic flux density crossing the gap (B). If both coils are given the same number of layers of wire, and the same winding height, the larger coil has a greater length of wire immersed the magnetic gap, but the magnetic flux density in this gap is naturally lower due to the larger gap circumference. The opposite occurs on the smaller voice coil and with some careful design the BL of the two coils can be extremely close. With optimal shaping of the steelwork using FEM modelling, it is possible to ensure BL remains matched under large excursion too. Figure 10 and Figure 11 show the flux density B(x) and force factor BL(x) functions respectively for both drivers in the Uni-Core.

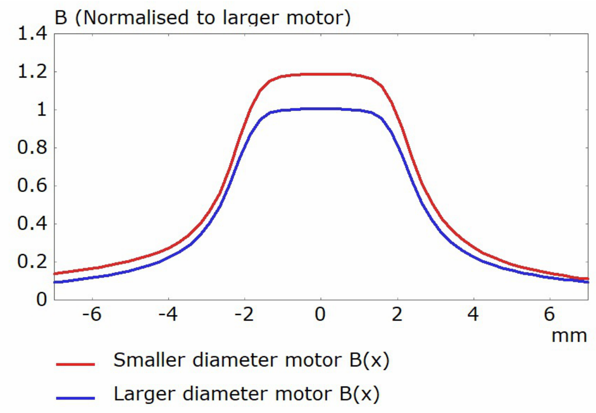


Figure 10. Comparison of B(x) for the two motors in the Uni-Core driver array

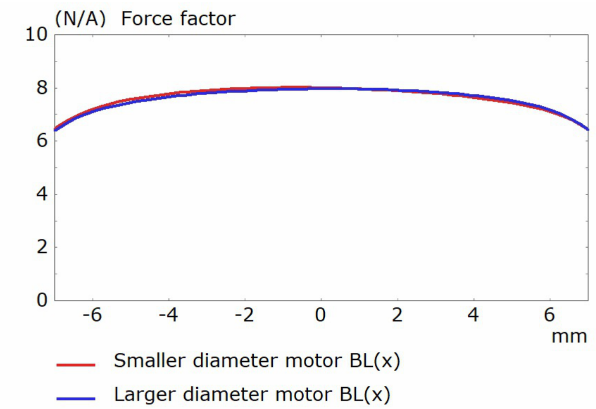


Figure 11. Comparison of BL(x) for the two motors in the Uni-Core driver array

Besides matching the force factor of both coils, there was also significant concern over the inductive behaviour of the Uni-Core arrangement. To minimise distortion in a loudspeaker motor, it is critical that the voice coil inductance is low and does not vary with coil position or current level. In Uni-Core there is the further complication that the mutual inductance of the two overlapping coils must be considered too. However, it was found that the inductance behaviour of Uni-Core could be controlled very effectively due to two major effects [6]:

1. The circuit reluctance is higher and inductance is lower than a conventional motor, due to the presence of two voice coil gaps.

2. Uni-Core requires a non-ferrous tube part, located between the two coils, to support the inner pole of the motor system. Constructing this part in aluminium means that it can double as a shorting ring, which reduces total inductance and inductance modulation.

Since the voice coils are of different diameter, some moving parts around them must be different as well, namely the suspensions and cones. The suspension stiffness, both in resting position and under excursion, had to be matched between both drivers by means of careful FEM optimisation of their geometry. Figure 12 shows a comparison of driver mechanical stiffness along displacement Kms(x) for the two driver suspensions, where it is shown they have been successfully matched.

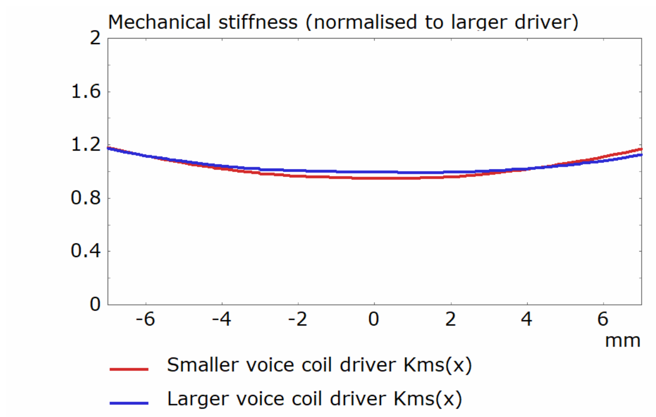


Figure 13. Comparison of Kms(x) for the two drivers in the Uni-Core driver array

3.2.2 P-Flex surround

When a relatively large piston pushes on a small air volume, the pressure built up will try to escape the cabinet any way it can. The weakest path for this air to push out is the soft rubber surround of the driver. Common LF surrounds are simple half-roll designs, which are successful in allowing the linear movement of the driver while keeping it centred and sealed, but are easily deformable by the pressured air trying to escape the cabinet. This problem is frequently encountered in subwoofers, and the common solution is to use a very thick material for the half-roll. This allows it to withstand higher pressures but adds significant mass and stiffness, restricting the driver efficiency and typically increasing distortion.

KEF's solution is the P-Flex surround, which debuted in the KC62 subwoofer. P-Flex is a three-dimensionally pleated surround that doesn't restrict the pistonic movement of the driver or add mass but withstands the extreme pressures inside the cabinet. The design of the P-Flex surround in LS60 Wireless has been further refined compared to the version in KC62. Figure 13 shows the 2nd generation P-Flex surround found in the LF Uni-Core drivers in LS60 Wireless.

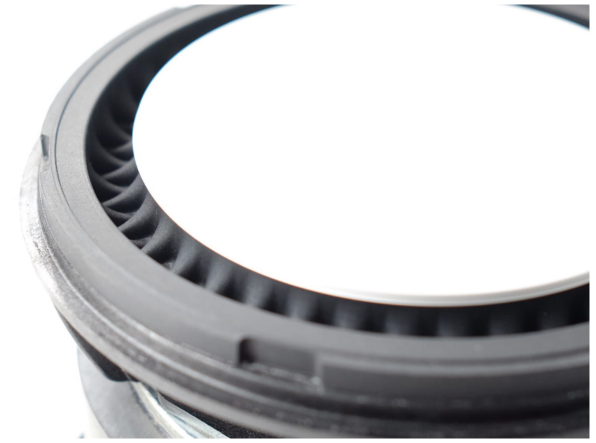


Figure 13. Close-up detail of the P-Flex surround in the LS60 Wireless Uni-Core

Figure 14 shows a comparison of the P-Flex surround and a regular half-roll surround of equivalent excursion. A FEM simulation shows that at high excursion the half-roll design buckles under the internal pressure from the air in the enclosure. This buckling deformation results in a series of distortion mechanisms related to stiffness, mass and radiating area modulation as well as the actual noise of the rubber buckling. The three-dimensionally pleated shape of the P-Flex surround allows it to unroll freely in both directions by having a low stiffness against the driver displacement at the same time it provides a much greater geometrical stiffness against the internal air pressure from the LF enclosure acting on its inner wall as the driver moves.

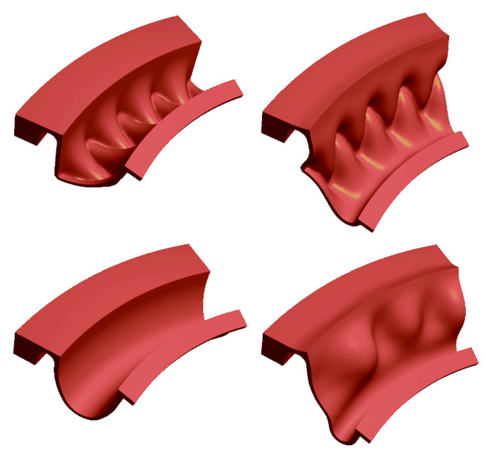


Figure 14. Cross-section of the LS60 Wireless P-Flex surround showing pleated geometry (top) and regular half-roll surround showing buckling at high excursion (bottom)

For a more detailed explanation on P-Flex, the reader can refer to the KC62 white paper [6].

3.2.3 Smart Distortion Control Technology (SDCT)

The LS60 Wireless relies on DSP equalisation to extend the low frequency response. There are no ports and all sound is produced by driver movement. The internal air volume in the LF chamber is approximately 12.5 Litres. The peak volume displacement produced by the four LF driver cones is around 0.28 Litres. This means that, when the drivers are visibly moving, the cabinet volume is significantly modulated. Unchecked, this would lead to significant bass distortion that would degrade the sound quality.

The LS60 Wireless uses KEF's proprietary active distortion reduction system, Smart Distortion Control Technology (SDCT), to linearise the loudspeaker output. SDCT is a hybrid system (Figure 15) that indirectly senses cone velocity from the voice coil current, which is then fed into a negative feedback loop. The second component is a DSP model of the driver, which applies pre-correction to compensate for residual non-linearities. This method provides a major reduction in distortion and is a key tool for a small speaker to produce deep, loud and clean bass.

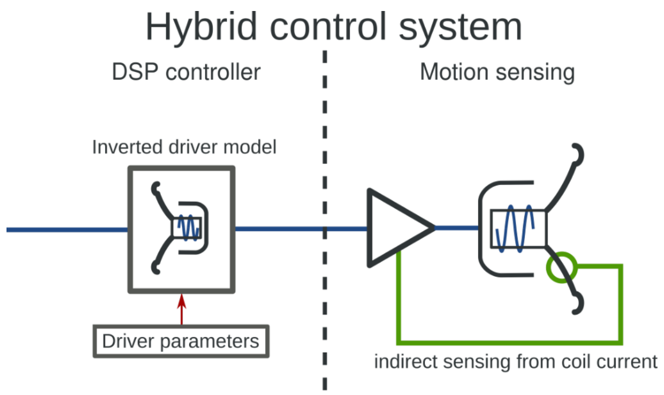


Figure 15. Block diagram of Smart Distortion Control Technology's hybrid control system

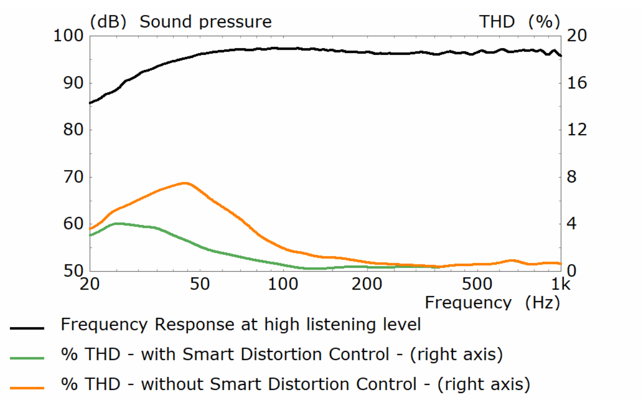


Figure 16. THD reduction at high listening levels with Smart Distortion Control Technology

Figure 16 shows the improvement in distortion when SDCT is applied to the system. The version of SDCT applied in the LS60 Wireless has been further refined compared to the original version in KC62. Besides the cabinet volume nonlinearity, a number of additional distortion mechanisms are also modelled and compensated for by the DSP distortion controller.

3.2.4 Intelligent Bass Extension

There is important content present in music recordings below the common cut-off frequency of most loudspeakers. This is where subwoofers usually take over by filling in the reproduction down to 20 Hz.

With conventional loudspeakers, the bass extension is determined by the driver and enclosure design. The LS60 Wireless takes a different approach and relies on high volume displacement drivers, high power and DSP equalisation to extend the low frequency response. Provided there is both linear driver excursion and amplifier power available the bass extension can be extended as far as the user requires. When "Extra" bass extension mode is selected, the LF section has a frequency range extending down to 26 Hz at normal to high listening levels. When higher music listening levels are required, an algorithm activates in the DSP and dynamically controls the output to keep the LF drivers safe from mechanical damage and distortion. There has been extensive research done in this project to ensure this transition is smooth when listening to music, so as not to detract from the listener's enjoyment. Figure 17 shows the frequency response of LS60 Wireless across the LF region for various signal levels.

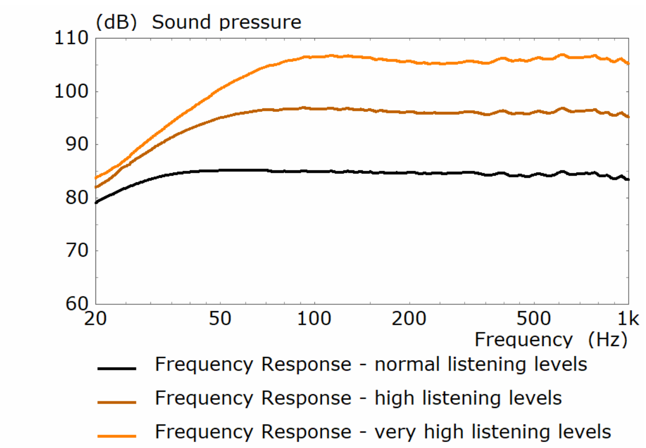


Figure 17. System frequency response showing iBX dynamic bass extension for normal, high and very high listening levels

3.3 New 4" 12th Generation Uni-Q

Since its inception in 1988, there have been over fifty Uni-Q designs spread over 12 generations. The core premise is the same across all iterations – a two driver array that provides a point source with wide, controlled directivity – but each Uni-Q is carefully optimised according to the system it is integrated into.

The LS60 Wireless is a 3-way loudspeaker and the Uni-Q is only required to replay MF and HF signals. Many KEF loudspeakers use a 3-way configuration and most use a 5.25" diameter Uni-Q with a 1" (25 mm) tweeter.

To suit the design goals of the system, the LS60 Wireless required a new smaller Uni-Q with a 4" (100mm) diameter (Figure 18), while still maintaining the high level of performance typical of the 5.25" Uni-Qs.

Figure 18. 4" Uni-Q

Figure 19 shows a cross section of the newly developed Uni-Q for LS60 Wireless. This is a 12th generation Uni-Q and incorporates many key KEF technologies.

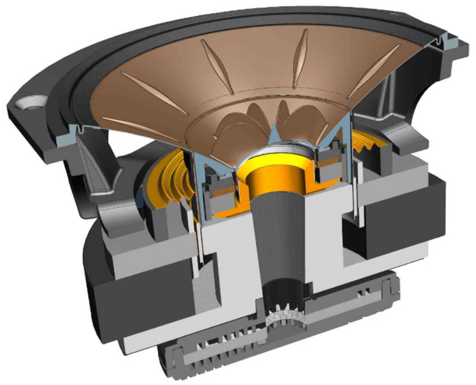


Figure 19. Cross-section of the 4" Uni-Q

The MF driver cone is aluminium and uses KEF's proprietary Cone Neck Decoupler technology to control the breakup. This is a technique that KEF has been refining for more than 10 years, providing a hybrid cone with the benefits of a rigid metal cone without the traditional drawbacks of severe breakup [7, p.15].

The MF cone radiating area is slightly lower than the more usual 5.25" (130 mm) Uni-Q drivers, so in order to maintain high output capability it was important to allow larger excursion than typical on most MF drivers. This is handled through careful design of the motor system. The surround and suspension were also designed to allow more cone movement than typical for a MF driver. The suspension was made narrower than typical ones to minimise its moving mass and move its resonance frequency out of the midrange passband [8].

The HF driver uses an aluminium dome, with a profile carefully designed to achieve optimal performance in the Uni-Q configuration along with a high breakup well above the audio bandwidth [5, p.22, 9]. As with the MF driver, due to the slightly smaller radiating area, special attention was paid to maximise the excursion. Firstly, in the design of the motor and secondly by using a very soft silicone rubber surround. A Tangerine Waveguide sits in front of the tweeter dome, widening the directivity and increasing sensitivity at high frequencies [7, p.14, 10, p.201].

The key feature of a 12th generation Uni-Q is the inclusion of a Tweeter Gap Damper to control sound from the tweeter that passes into the gap between the tweeter and midrange driver. This patented technology was first introduced in the R Series in 2018 [8, p.5]. The configuration of the motor system in the LS60 Wireless Uni-Q is different and consequently it was necessary to rearrange some of the parts around the tweeter gap to incorporate the absorber, as shown in Figure 20.

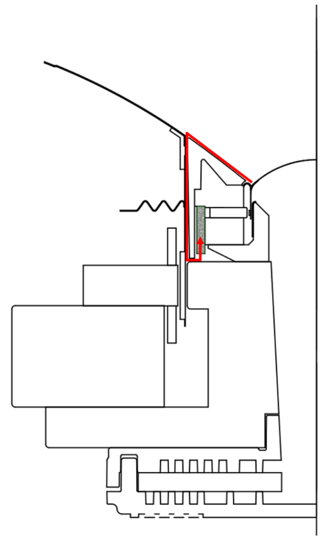


Figure 20. LS60 Wireless Uni-Q section showing Tweeter Gap Damper

The LS60 Wireless Uni-Q also includes the very latest KEF technologies. Firstly, the rear sound from the tweeter is controlled using KEF's patented Metamaterial Absorption Technology (MAT) [7, p.2, 11]. For the LS60 Wireless a smaller MAT absorber disc (Figure 21) has been designed and in the centre of the new motor system a large conical waveguide carries sound from the back of the tweeter dome to the absorber. The overall absorption of the rear wave from these two elements exceeds 99% from 840Hz upwards.

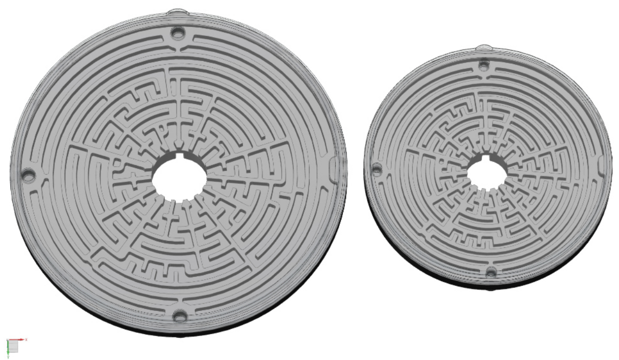


Figure 21. MAT found in the Blade Meta and Reference Meta Uni-Q vs. MAT found in the LS60 Wireless Uni-Q

The new Uni-Q chassis, shown in Figure 22, also incorporates the integrated vibration decoupling scheme first seen on the Reference and Blade Meta loudspeakers. This important detail ensures that very little vibration from the Uni-Q motor reaches the cabinet, avoiding cabinet wall movement and secondary radiation that could colour the sound [8, p.9].

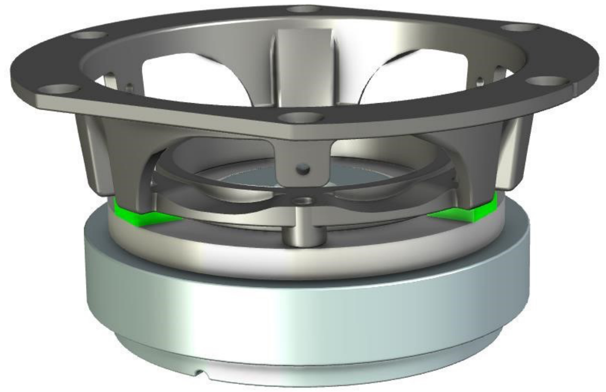


Figure 22. Uni-Q decoupling chassis arrangement showing the chassis attached to the motor through the spring elements and the damping material highlighted in green

3.3.1 MF and HF motor details

Multiphysics Finite Element Modelling (FEM) tools were extensively used to ensure the linearity of both motors at high excursion. Figure 23 shows a cross section of the MF and HF motor arrangement with magnetic flux density as a heat map. The steelwork geometry has been optimised through FEM to be saturated near the voice coil to reduce BL modulation due to the influence of the voice coil's own AC magnetic field. Two long aluminium rings have also been positioned at either side of the MF voice coil gap and their size has been optimised to reduce inductance and inductance modulation even at high excursion. Similarly in the HF motor a long copper conductive sleeve covers the motor pole [8, p.6]. Figure 24 shows the relatively flat force factor along the MF voice coil's long excursion BL(x).

3.4 System

3.4.1 Amplification

One important advantage of an active loudspeaker is that the amplifiers for each driver may be specially designed according to the specific signal characteristics each will see. To gain a better insight into the requirements, KEF R&D performed a statistical analysis on an extensive library of more than 40,000 pieces of real music. This study provided new data on the spectral amplitude and crest factor in different frequency bands. Crest factor is the ratio between the peak and average amplitude of a signal. Low and midrange frequency content tends to be continuous with a low crest factor. As frequency increases the crest factor raises considerably.

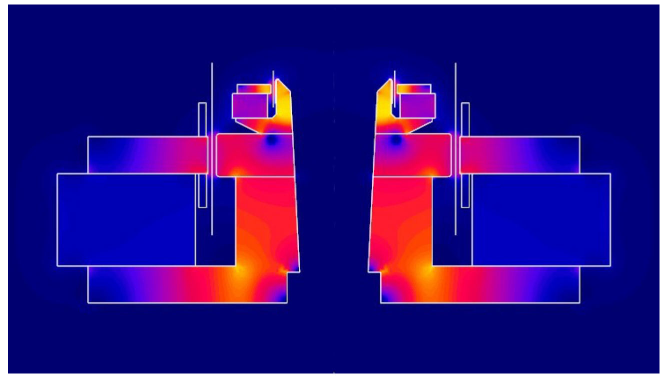


Figure 23. Uni-Q motor system magnetic circuit

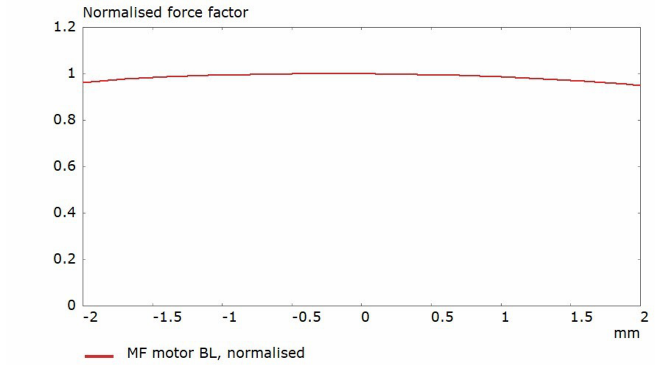


Figure 24. BL(x) of the LS60 Wireless midrange motor

Figure 25 shows an example calculation of the crest factor across five midrange and high frequency bands for a sample of 1800 music files.

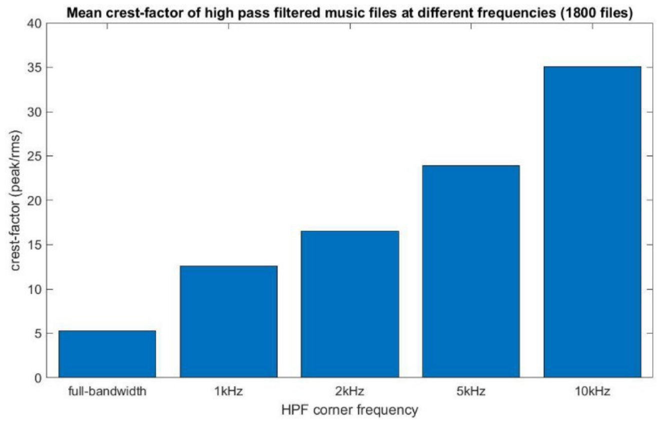


Figure 25. Calculation of mean crest factor by frequency band on statistical sample of music

For an active loudspeaker, this means that the LF amplifier must be capable of providing continuous power output. A HF amplifier, however, needs to provide only very low levels of continuous output, but still be capable of outputting extremely high instantaneous power peaks.

KEF have developed a sophisticated software simulation tool that mimics the end-to-end signal path in the loudspeaker, including details such as the DSP processing, the frequency response of the drivers and the complex load that the drivers present to the amplifiers. Using this tool the exact power requirements for each section can be calculated for a range of different musical genres. This provides detailed power statistics for each driver that can then be used in the design and specification of the corresponding amplifiers. The result of this analysis on the LS60 Wireless was that a 500W amplifier was required for the LF portion, 100W for the MF and 100W for the HF.

Based on the bandwidth and signal statistics a hybrid amplifier class arrangement was selected. The LF section of the system demands high amplifier power to deliver clean bass output. The MF section also requires high continuous power output on certain demanding tracks. Along with the constraint of housing the electronics in a separate enclosure at the bottom of the cabinet, this requires thermal efficiency to be a priority and hence Class D amplifiers were selected for these sections. Class D amplifiers are highly efficient due to their high-speed transistor switching design and their sound quality can be at a level required for high-fidelity reproduction.

The HF section has very different power statistics. Only low continuous output is required but the amplifier must have the ability to deliver sudden large peaks. High bandwidth is also an important consideration for true High-Res support. For this reason a class AB amplifier was selected. Class AB amplifiers have a much lower efficiency than Class D, but the thermal power generated is reasonably low under these signal conditions. Class AB has the added advantage of wide HF bandwidth and of not requiring an output filter.

The reason behind the high-power specification for both MF and HF amplifiers, especially the HF one, is due mainly to the crest factor of music at the intended frequency passband. Ensuring the amplifiers have the rail voltage available to supply the power to amplify a sudden sharp peak in the signal is crucial to avoid harmonic distortion. The KEF Class AB design was revised from LS50 Wireless II to further reduce distortion.

Finally, the LF amplifier features an indirect voice coil current feedback sensing loop as part of the Smart Distortion Control Technology devised to dramatically reduce distortion together with a DSP control algorithm.

3.4.2 Phase correction

In a multi-way loudspeaker, the audio signal is divided into multiple frequency bandwidths by the crossover and then passed to the individual drivers. The sound that the listener hears is the acoustical summation of the individual driver responses. A major aim in loudspeaker design is for the output from the individual drivers to sum to give a reasonably flat overall frequency response and this aim has received a huge amount of attention in the history of loudspeaker engineering. Quite rightly, most of the focus is on the magnitude response of the loudspeaker. The human ear is extremely sensitive to deviations in the magnitude response and it is a critical aspect to get right in any high-performance loudspeaker. Much attention is also paid to the relative phase between different driver outputs, because, if this is incorrect, then the summed response will suffer from interference between drivers.

The relative phase between driver outputs also has an important effect on the directivity of most loudspeakers too. However, the overall phase response of the loudspeaker is traditionally ignored and most loudspeakers have significant overall phase distortion. There are good reasons that this effect has been overlooked. Firstly, the human ear is relatively insensitive to phase distortion compared to magnitude distortion. Secondly, even though the phase distortion effect is known by many, in a passive or analogue active loudspeaker there is very little that can be done to address it.

Phase Correction, as found in LS50 Wireless II and LSX, compensates for phase distortion by pre-filtering the signal through a special type of all-pass FIR filter. This filter has the reverse phase characteristics to the phase error introduced by the crossover and compensates for the system's phase distortion, ensuring sound at all frequencies reach the listener at the same time.

With Uni-Q, as all frequencies radiate from a single coherent source, the phase relationship between the MF and HF drivers stays consistent in all directions. This makes it an ideal candidate for phase correction. The LS50 Collection white paper [7] discusses why the Uni-Q is an excellent case for the application of phase correction. LS60 Wireless, being a 3-way design, required the expansion of phase correction into a third driver section. SAS makes this possible. Since the distance of the four LF drivers to the Uni-Q is minimal and the arrangement is symmetrical, phase correction can be easily implemented following the same scheme as in LS50 Wireless II.

Using a theoretical model of 2-way and 3-way crossovers with 4th order Linkwitz-Riley acoustic transfer functions as an example, it can be shown how a 3-way design further benefits from phase correction. In the example shown in Figure 26, when the frequency for a 2-way crossover is around 3 kHz, the group delay observed is around 0.2ms. Adding a third way to operate below 400 Hz results in additional and considerable group delay of up to 1.5ms that can be more noticeable particularly during the start and stop of signals.

Figure 27 shows the measured impulse response of the LS60 Wireless with Phase Correction on and off respectively. The improvement in the time response to the impulse signal is readily apparent, particularly reducing ringing after a few milliseconds. This feature is enabled by default in the KEF Connect app's EQ and can be disabled using "Expert Mode".

3.4.3 User Equalisation

The LS60 Wireless's response has been carefully balanced to provide a neutral timbral balance and realistic musical reproduction in a medium to large acoustically treated room. DSP allows the flexibility of offering frequency response settings to further tailor the user listening experience based on their listening room acoustics.

EQ modes are provided to help the user do this. Wall Mode, Treble Trim and three Bass Extension modes. Figure 28 shows the three Bass Extension modes "Extra", "Standard" and "Less".

The app also allows for the addition of subwoofers to the system, with the flexibility for a single or dual subwoofers playing the combined left and right channel content as well as separate stereo subwoofers.

In terms of integration, "Basic" mode offers an easy-to-use menu of stepped options, with adjustment provided to control the low-pass filter frequency to the subwoofer where a high-pass filter is applied to the speaker accordingly. Low- and high-pass filter frequency preselected values are provided for pairing various KEF subwoofers to help the user as a starting point to easily approach the best integration in their room.

"Expert" mode provides a much more customisable option – the separation of the low- and high-pass filters (subwoofer and speaker, respectively). This allows the user to factor in the variables pertaining to their setup – room geometry, treatment, distance between speakers and subwoofers, and the listening position.

The details of the signal path from input selection to power amplifier output are similar in principle to the ones in LS50 Wireless II and diagrams describing these can be found in its white paper [7, p. 19]. A few key differences to note is the addition of a DAC and amplifier for the LF section as well as Smart Distortion Control Technology.

Figure 29 shows a snapshot of the Expert Mode in the KEF Connect app.

4. Summary

LS60 Wireless is the result of years of research and development, culminating in the most advanced active loudspeaker system to leave the assembly line of KEF, still working upon the foundations set by founder Raymond Cooke in 1961. Using SAS as a starting point, a clear path of acoustic design challenges emerged. Through the adaptation of existing technologies, and the development of new ones, these challenges have been met.

LS60 Wireless follows KEF's main design philosophy goals: a smooth and balanced response both in terms of frequency and space; sound that emanates from the drivers themselves and not from panels or openings; drivers that operate in a well-controlled manner throughout and beyond their band; and low distortion and compression, as well as a good temporal response.

The result is a floorstanding active wireless loudspeaker system that blends high performance, connectivity and aesthetics in a small footprint, combining all three for the increasing number of people who are looking for an exceptional audio experience.

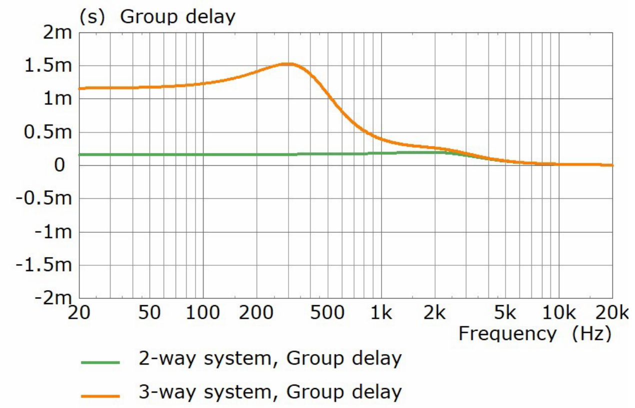


Figure 26. Theoretical group delay for 2-way and 3-way system with 4th order Linkwitz-Riley acoustic filter slopes

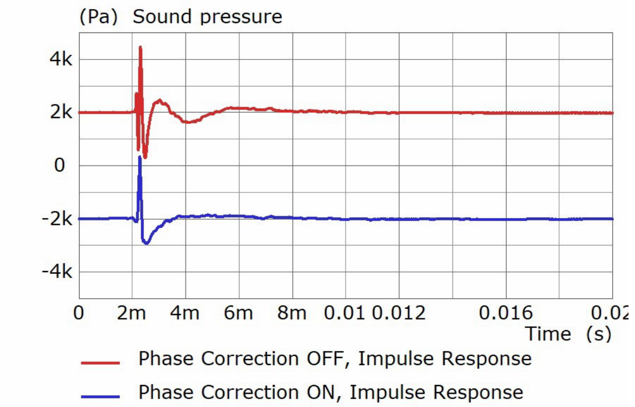


Figure 27. LS60 Wireless impulse response with and without Phase Correction (+/-2 kPa offset)

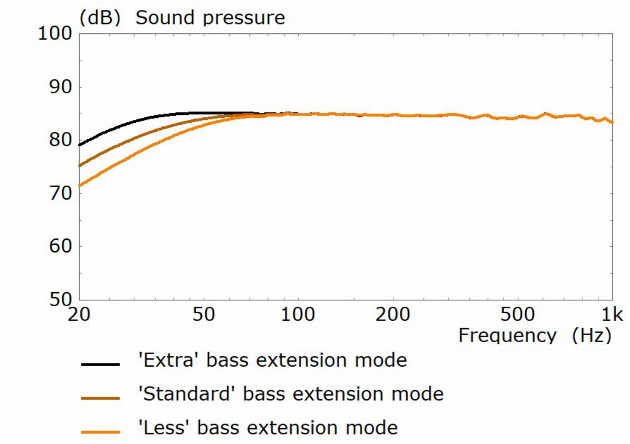


Figure 28. LS60 Wireless bass extension modes

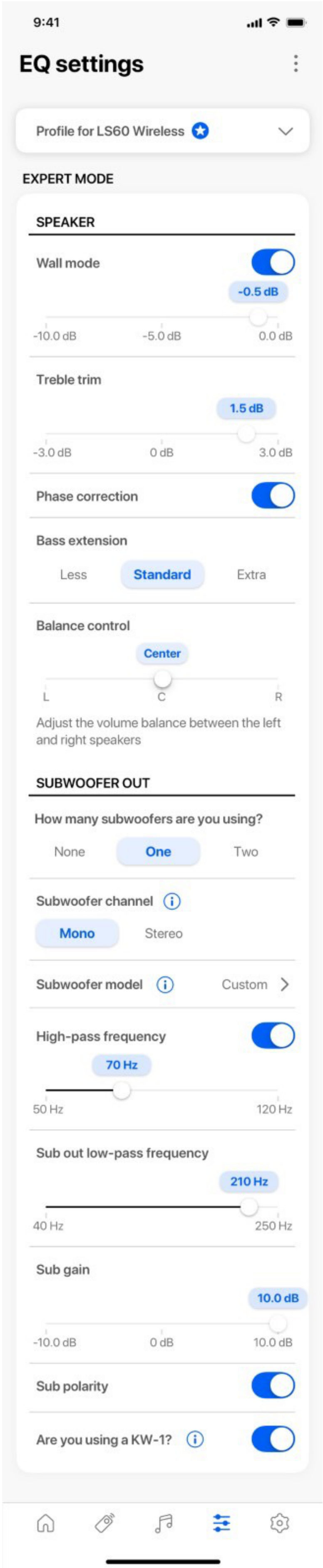


Figure 29. KEF Connection user interface in Expert mode for LS60 Wireless

5. References

[1] R. H. Small, "Vented-Box Loudspeaker Systems-Part 1: Small-Signal Analysis," *J. Audio Eng. Soc.*, vol. 21, no. 5, pp. 363–372, Jun. 1973.

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

[3] H. F. Olson, "Direct Radiator Loudspeaker Enclosures," *J. Audio Eng. Soc.*, vol. 0, no. 1, pp. 34–64, Nov. 1951.

[4] G. Perkins, "Modelling loudspeaker cabinet diffraction," presented at the IOA Reproduced Sound conference, Oct. 2014.

[5] "The Reference (white paper)." KEF R&D, May 2014. [Online]. Available: http://www.kef.com/uploads/files/THE_REFERENCE/REF_White_Paper_preview_path_200514.pdf

[6] "KC62 (white paper)." KEF R&D, Jan. 2021. [Online]. Available: https://ca.kef.com/pub/media/documents/kc62/21-KEF-KC62-UniCore-Sub-WhitePaper.pdf

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

[8] "BLADE, THE REFERENCE (white paper)." KEF R&D, Feb. 2022. [Online]. Available: https://images.salsify.com/image/upload/s--Qrnn1ggt--/3bbba8edc0ece49267553efe3b4df80705d3a377.pdf

[9] M. Dodd, "Optimum Diaphragm and Waveguide Geometry for Coincident source Drive Units," presented at the Audio Engineering Society Convention 121, Oct. 2006. Accessed: Jan. 21, 2016. [Online]. Available: http://www.aes.org/e-lib/browse.cfm?elib=13720

[10] J. Oclee-Brown, "Loudspeaker compression-driver phase-plug design," Doctoral Thesis, University of Southampton, 2012. Accessed: Jun. 22, 2014. [Online]. Available: http://eprints.soton.ac.uk/348798/

[11] S. Degraeve and J. Oclee-Brown, "Metamaterial Absorber for Loudspeaker Enclosures," presented at the Audio Engineering Society Convention 148, May 2020. Accessed: May 10, 2022. [Online]. Available: https://www.aes.org/e-lib/browse.cfm?elib=20758

LS60 Wireless

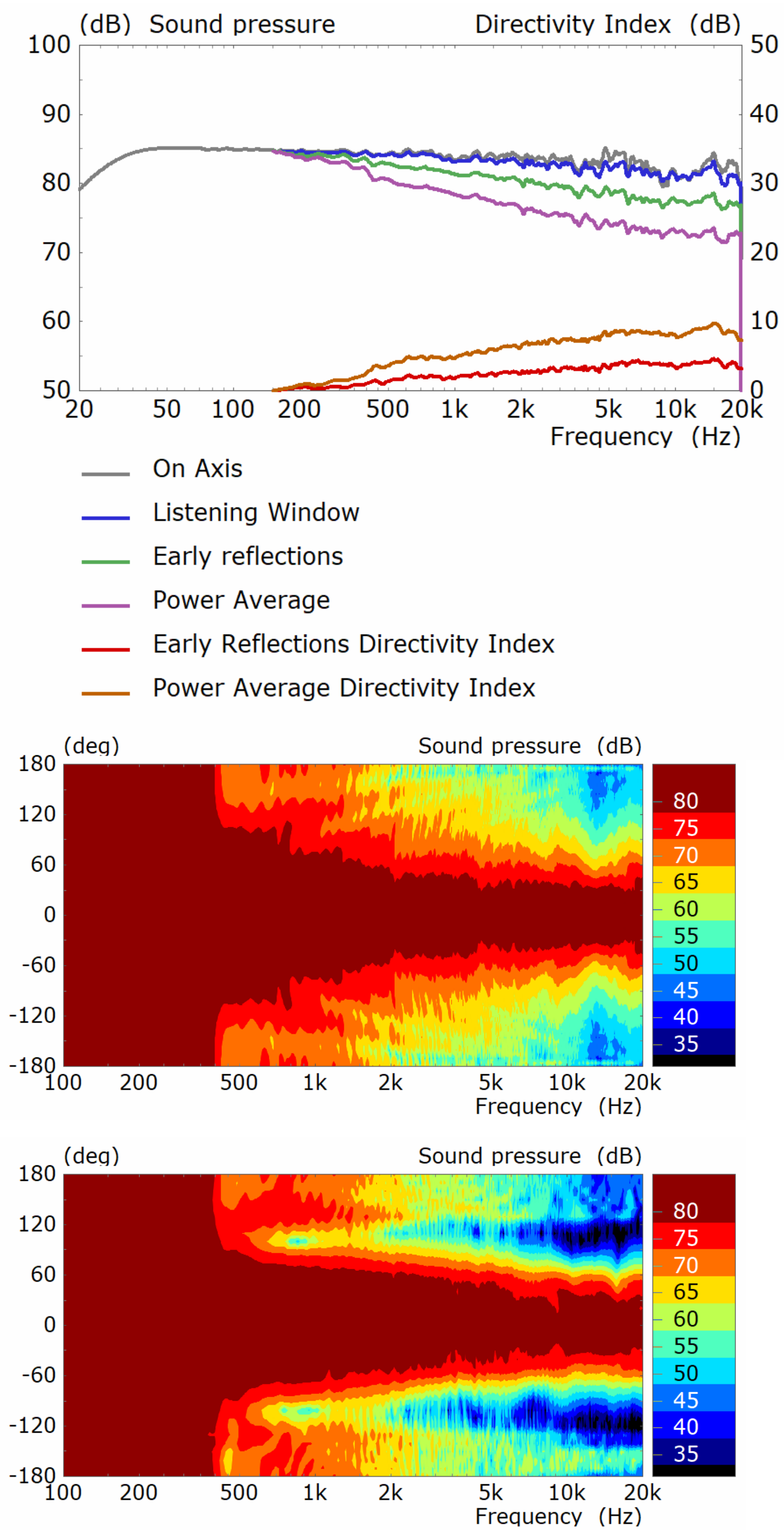
Model Information, Specifications and Measurements

LS60 Wireless

Three-way Single Apparent Source Active Loudspeaker System

Model	LS60 Wireless	
Drive units (per speaker)	Uni-Q Driver Array: HF: 19 mm (0.75 in.) vented aluminium dome with Metamaterial Absorption Technology# MF: 100 mm (4in.) aluminium cone Uni-Core Force Cancelling Driver: LF: 4 x 135 mm (5.25 in.)	
Frequency range (-6dB) measured at 85dB/1m	26 Hz – 36 kHz *Depends on EQ settings	
Frequency response (±3dB) measured at 85dB/1m	31 Hz – 24 kHz *Depends on EQ settings	
Amplifier output power (per speaker)	LF: 500W MF: 100W HF: 100W	
Amplifier class (per speaker)	LF: Class D MF: Class D HF: Class AB	
Max SPL measured at 1m	111 dB	
Wireless streaming features	AirPlay 2, Google Chromecast, ROON Ready, UPnP Compatible, Bluetooth 4.2	
Streaming services	Spotify via Spotify Connect, Tidal via Tidal Connect, Amazon Music, Qobuz, Deezer, QQ Music via QPlay, Internet Radio, Podcast *Depends on services availability in different countries	
Input resolution	Network up to 384kHz/24bit Optical up to 96kHz/24bit Coaxial up to 192kHz/24bit HDMI up to 192kHz/24bit *Depends on source resolution	
Interspeaker connection	Wireless: all sources resampled to 96kHz/24bit PCM Wired: all sources resampled to 192kHz/24bit PCM	
Supported format (all inputs)	FLAC, WAV, AIFF, ALAC, AAC, WMA, MP3, M4A, LPCM and Ogg Vorbis	
Supported format (network)	MQA, DSD	
Dimensions (HWD per speaker)	1090 x 212 x 394 mm (42.9 x 8.3 x 15.5 in.) with plinth 1042 x 130 x 321 mm (41.0 x 5.1 x 12.6 in.) without plinth	
Weight (per set)	62.4 kg (138 lbs)	
Power input	100 – 240VAC 50/60Hz	
Power consumption	450W (operating power) <2.0W (standby power)	
	Primary speaker	**Secondary speaker**
Inputs	HDMI eARC TOSLINK Optical Digital Coaxial Analog RCA USB Type A (service) RJ45 Ethernet (network) RJ45 Ethernet (interspeaker)	USB Type A (service) RJ45 Ethernet (interspeaker)
Output	RCA Subwoofer output	RCA Subwoofer output
Wi-Fi network standard	IEEE 802.11a/b/g/n/ac IPv4, IPv6	-
Wi-Fi network frequency band	Dual-band 2.4 GHz / 5 GHz	-

#Metamaterial Absorption Technology is a joint development with Acoustic Metamaterials Group.



LS60 Wireless Spinorama (top) and dispersion plots - horizontal (middle) and vertical (bottom)

KEF