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DIRECT RADIATING PHASE PLUG FOR RING RADIATOR TWEETER

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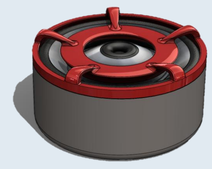
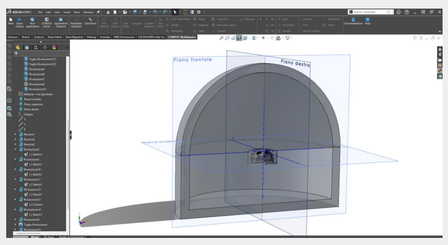
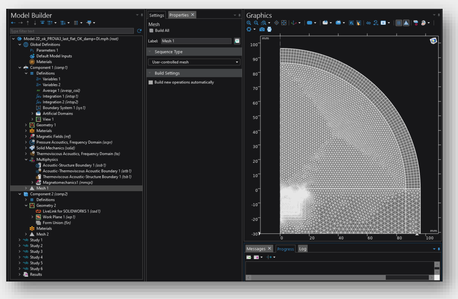


The two most commonly used membrane profiles for sound reproduction of the high frequency audio band are the dome shape and the annular shape. The annular (also known as ring) shape has some different basic design features if compared to a dome with the same outer size. For example, the annular membrane permits a smaller voice coil diameter, potentially reducing the total moving mass while limiting power dissipation. However, it includes a second surround involved in displacement and the presence of the added surround implies that the resulting emitting surface is slightly smaller than that of the dome.
Another key point is that the annular shape doesn't suffer from the soft dome apex anti-phase behavior above the breakup frequency, but it is characterized by a side anti-phase behavior. Anyway, a direct radiating high frequency transducer using a ring-shaped diaphragm is called ring radiator tweeter and it can offer interesting acoustic performances.
COMSOL Multiphysics® (coupling Magnetic Fields (*mf*) – Pressure Acoustics, Frequency Domain (*acpr*) – Solid Mechanics (*solid*) – Thermoviscous Acoustics, Frequency Domain (*ta*)) together with the LiveLink™ for SOLIDWORKS® are used as a unique environment platform for designing and simulating a digital twin of a typical ring radiator tweeter for automotive applications, analyzing some limits and improving them adding a new phase plug, radiating sound directly toward the listener area. Then a physical prototype has been developed and its measurements have been compared with simulations of the digital twin model.

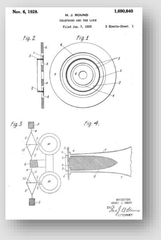




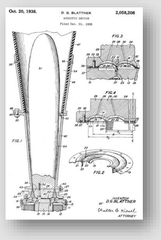
- Annular membranes origins
- Ring Radiator
  - *Digital twin* 3D model
  - Moving parts *Eigenfrequencies* 2D and 3D: straight ⩛-shape vs curved ⩛-shape
  - Acoustic simulations
- Ring Radiator + Phase Plug
  - State of the art & patent pending
  - *Digital twin* 3D model
  - Acoustic simulations
  - Acoustic measurements of physical prototypes
  - Digital twins in *Plane Wave Tube*: searching for a *plane wave*
- Conclusion and outlook

Annular membranes origins

US1690840
RCA Corp.
1924

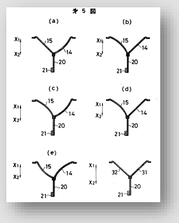


US2058208
BELL TELEPHONE LABOR Inc.
1935

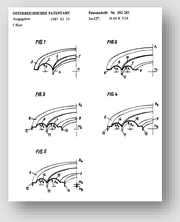


GB619882
THE BRITISH THOMSON-HOUSTON Co. Ltd
1946

JP57053198
TOSHIBA Corp.
1980



AT382281
AKG
1984



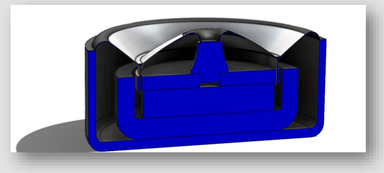
US1690840 annular diaphragm with flat section (fig. 2) and double ⩛-shape section (fig. 3)

US2058208 annular diaphragm with ⋒-shape section

GB619882 and then **JP57053198** disclose different diaphragms ⩛-shape section configurations. *Straight* and *curved* sides, with different radius and convexity.

AT382281 discloses about different configurations of the ⋒-shape section diaphragms

Ring Radiator digital twin 3D model



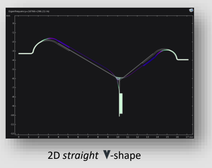
Ring Radiator geometry used for simulations

The ⩛-shape section is selected for the aluminum diaphragm

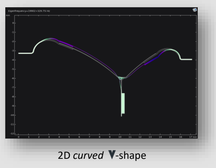
…but straight or curved sides?

Ring Radiator digital twin acoustic simulations

straight ⩛-shape *vs curved* ⩛-shape



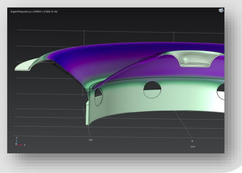
2D *straight* ⩛-shape



2D *curved* ⩛-shape

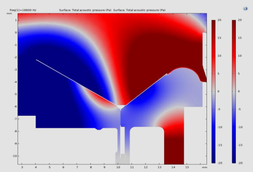
The *straight* ⩛-shape shows a break-up mode @18.8 kHz
The *curved* ⩛-shape shows a break-up mode @19.9 kHz

The *curved* ⩛-shape is selected and a detailed 3D model/analysis is done for validating 2D results

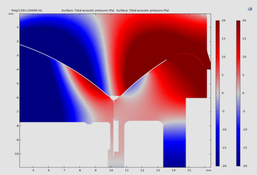


Ring Radiator digital twin acoustic simulations

straight ⩛-shape *vs curved* ⩛-shape



2D *straight* ⩛-shape



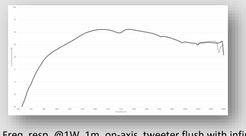
2D *curved* ⩛-shape

At the corresponding break-up frequencies both ⩛-shapes show a **side anti-phase behavior** of the acoustic pressure, causing a SPL dip

NOTE: a limited amount of materials damping is set to better visualize points where anti-phase is localized

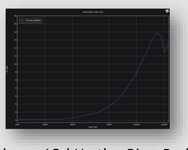
Ring Radiator digital twin acoustic simulations

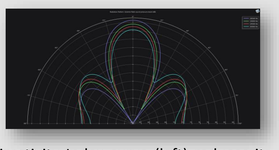
straight ⩛-shape *vs curved* ⩛-shape



The *curved* ⩛-shape membrane is selected. The break-up frequency is shifted although the dip is more pronounced: as expected for curved shapes, the released energy is bigger.

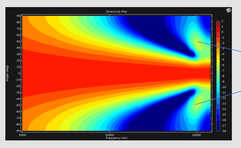
Freq. resp. @1W, 1m, on-axis, tweeter flush with infinite panel for curved (solid) and straight (dashed) annular ⩛-shape



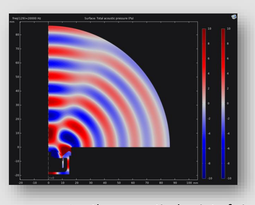


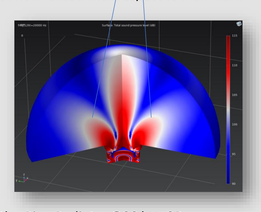
Above 18 kHz the Ring Radiator Directivity Index curve (left) reduces its rise, at first sight presenting a better behavior. But this is due to the presence of two off-axis side lobes showed in Radiation Pattern (right), their entity is not negligible if compared to on-axis sound pressure.

Ring Radiator digital twin acoustic simulations



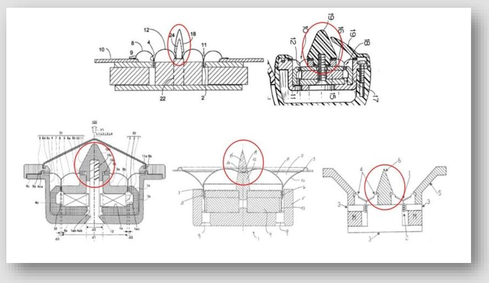
The two side lobes displayed in Directivity Plot normalized with respect to maximum





Another acoustical point of view of the *Ring Radiator* @20 kHz 2D Acoustic Pressure (left) and 3D SPL (Right)

State of the art phase-plugs in annular membrane direct radiating tweeters

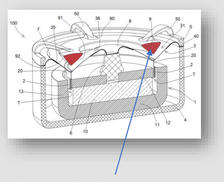


Existing patents having a Phase-Plug as central element (inside the red circle)

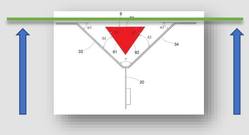
Ring Radiator + Phase Plug patent

A phase plug is added to the ring radiator tweeter, optimized for the smallest volume occupation, required in automotive applications.

Key target: the new device doesn't modify the original product size



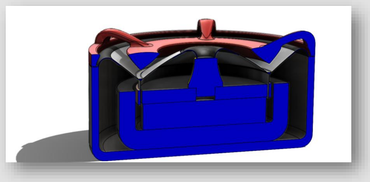
New device in red color



Same size of the original product

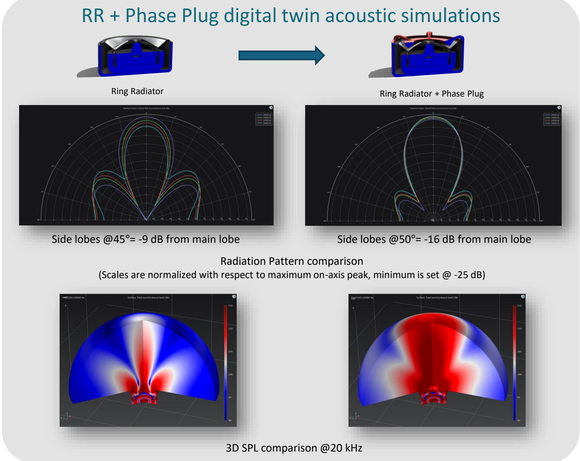
NOTE: International Application No. PCT/IB2024/054233

RR + Phase Plug digital twin 3D model

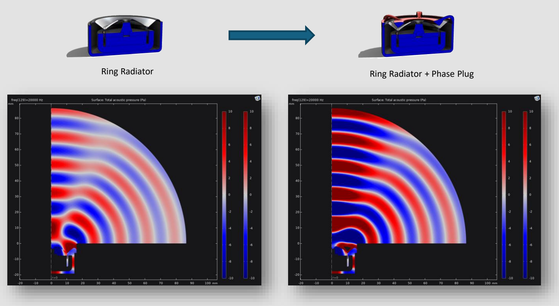


Ring Radiator + Phase Plug geometry used for simulations

RR + Phase Plug digital twin acoustic simulations

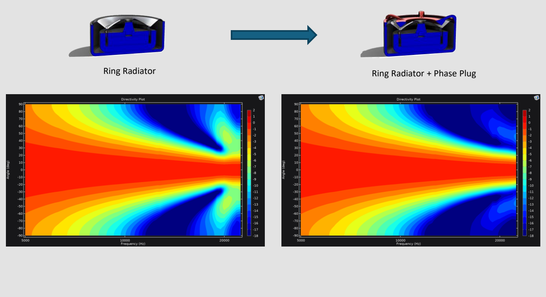


RR + Phase Plug digital twin acoustic simulations



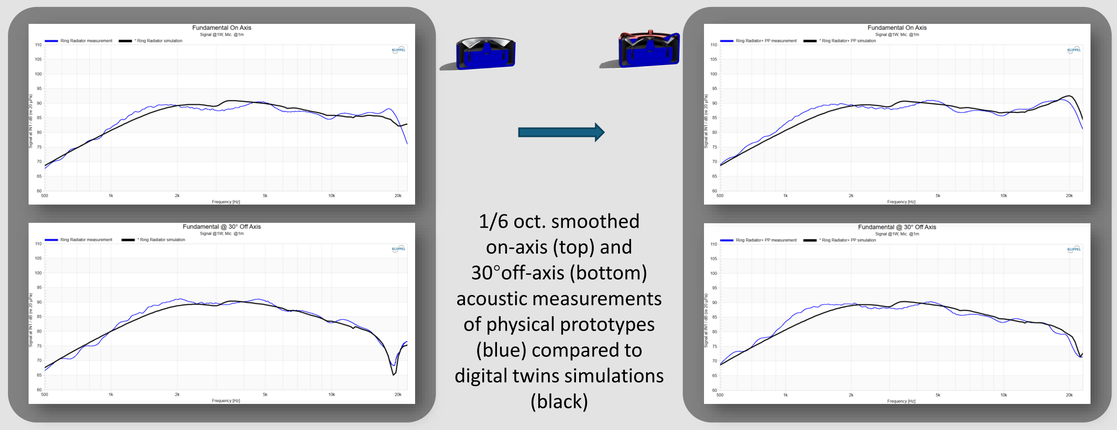
Acoustic Pressure comparison @20 kHz

RR + Phase Plug digital twin acoustic simulations



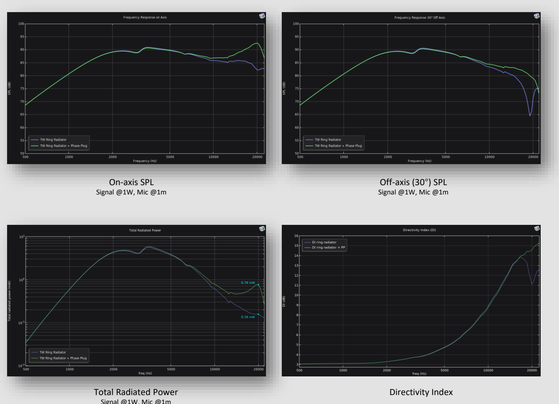
Directivity Plot comparison

Acoustic measurements of physical prototypes

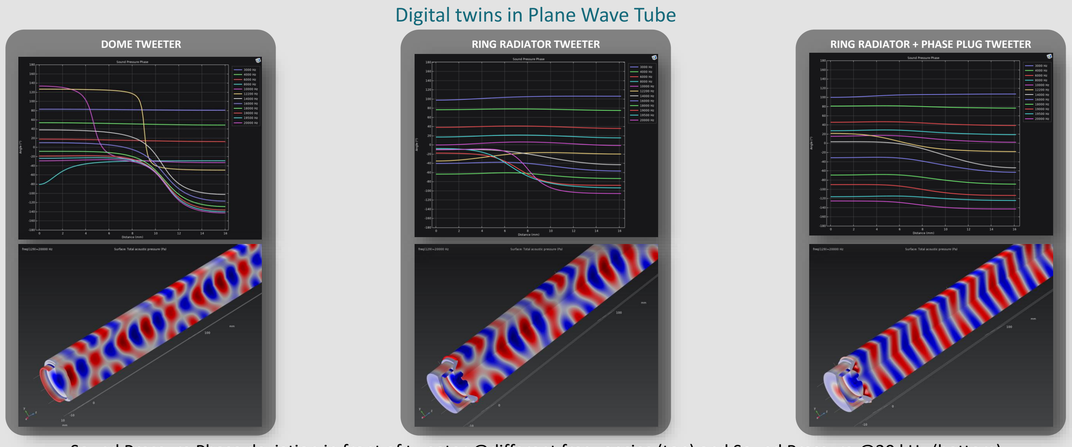


1/6 oct. smoothed on-axis (top) and 30°off-axis (bottom) acoustic measurements of physical prototypes (blue) compared to digital twins simulations (black)

RR + Phase Plug digital twin acoustic simulations



Digital twins in Plane Wave Tube



Sound Pressure Phase deviation in front of tweeter @different frequencies (top) and Sound Pressure @20 kHz (bottom)

Conclusion and outlook

- An annular membrane with a curved ⩛-shape is selected (higher break-up frequency) for the ring radiator model
- A patent pending phase plug is added to the ring radiator tweeter
- Smallest volume occupation: the new device doesn't modify the original product size
- Simulations of the digital twins and then acoustic measurements of the physical prototypes demonstrate how the ring radiator with phase plug gains:
  - SPL increase in the upper frequency band on-axis
  - SPL increase in the upper frequency band off-axis
  - Reduction of directivity side lobes
  - Increase of total radiated power above 7 kHz
- PWT test shows how the Phase Plug turns the Ring Radiator tweeter into a Direct Radiating Plane Wave Emitter. It is well suitable also for loading Waveguides or Lenses

- Future improvements: extend max frequency response to 40 kHz

Excerpt from the Proceedings of the COMSOL Conference 2025 Amsterdam