A Multiphysics Approach to the Design of Loudspeaker Drivers

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Abstract: Loudspeaker drivers are energy transducers: their main goal is to efficiently convert electrical energy to acoustic energy (sound) through the movement of mechanical parts. As such, they are prime candidates for the application of multiphysics methods and tools.

This paper will outline the growing set of tools that COMSOL puts in the hands of the loudspeaker designer; how they can be put to practical use in everyday work; how they can be applied to different kinds of electroacoustic devices and systems (cone loudspeakers, compression drivers, horns, waveguides) and how the measured performance compares to the simulations.

Keywords: loudspeaker drivers, electroacoustics, transducers.

1. Introduction

A loudspeaker driver is a transducer, a device designed to convert energy across different physical domains. The customary definition of loudspeaker driver is “electroacoustic transducer”, meaning that its role is to transform an electrical signal into an acoustic one. The definition neglects an intermediate step: except for some esoteric types, all loudspeakers convert the electrical signal first to mechanical movement, then to sound pressure.

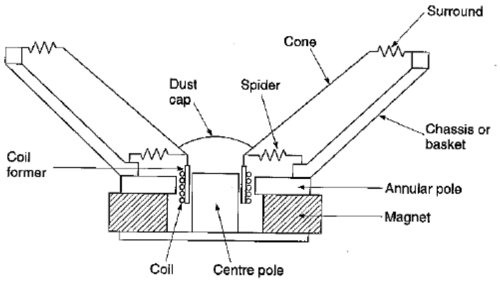

Fig. 1 Structure of a dynamic loudspeaker

Fig. 1 shows the typical structure of an electrodynamic loudspeaker, a device that has been using the same basic principles since its invention in the early 20th century. The electrical audio signal is fed to the voice coil, a conductor wire winding around a cylindrical former. The voice coil is immersed in the air gap, a small cylindrical space where a strong magnetic field is generated by a permanent magnet. There, the electrical current interacts with the B field to generate a Lorentz force acting along the coil axis.

This part of the device is called a “loudspeaker motor” and effects the electromechanical transduction, the first half of the driver's job.

The voice coil is attached to an extended membrane, typically in the form of a paper cone, that moves back and forth by effect of the mechanical force, thus pushing and pulling on the air and generating pressure waves, that can be heard as sound. This is the mechanoacoustic transduction, the second half of the driver's job. The audible result depends on many boundary conditions: whether the loudspeaker cone is in a box, at the throat of a horn, inside a room or outside in free-field, near a wall, a reflecting floor, a corner and so on.

So the loudspeaker driver is a device working across three different physical domains – electromagnetism, mechanics, acoustics – making it a prime candidate for the application of multiphysics simulation techniques.

This paper will explore the set of tools that COMSOL puts in the hands of the loudspeaker designer, by looking at some simulations and results.

2. Electromagnetism

2.1 Magnetic assembly and voice coil

A natural starting point is the loudspeaker motor. Fig. 2 shows a simulation of the whole assembly, including the voice coil. The simulation is based on the AC/DC Module and uses a Small Signal Analysis study. It’s a two-step study, solving first for the fields generated by the permanent magnet, then adding the current flowing in the voice coil as a frequency-domain perturbation. All interactions between magnetic and electric fields are taken into account, therefore not only the Lorentz force is computed, but also the additional magnetic fields generated by the electrical current and the eddy currents induced by the current variations (see 2.2).

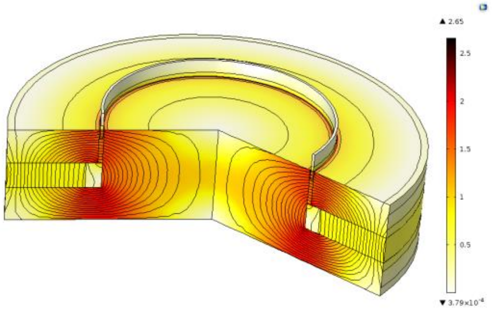

Fig. 2 Simulation of magnetic assembly and voice coil

The magnetostatic simulation helps the loudspeaker designer in sizing correctly the permanent magnet and the polar expansions. Once the voice coil is added, and its displacement changed through a parametric sweep, it is possible to compute the magnitude of the force acting on the moving assembly for any operating condition. The force vs. displacement graph shown in Fig. 3 contains a wealth of information about the excursion capabilities of the loudspeaker motor, its reliability and its nonlinear behavior in the large signal domain.

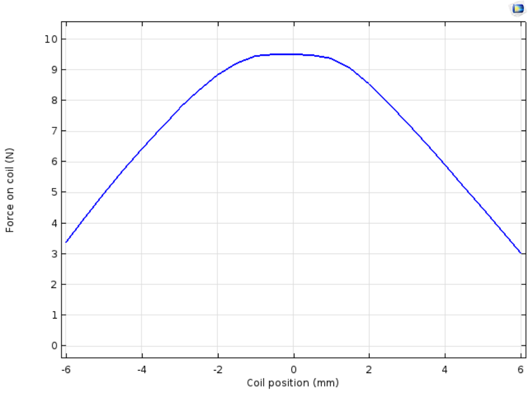

Fig. 3 Force on the voice coil vs. coil displacement, for a fixed current of 1 A

2.2 Eddy currents

The variation of current flowing in the voice coil induces eddy currents in the metal parts of the motor structure. The magnitude and spatial distribution of eddy currents at any frequency can also be investigated through simulation.

In the example shown in Fig. 4, the voice coil, not pictured, is centered in the gap and fed with a sinusoidal signal at different frequencies. The eddy currents induced in the steel structure of the loudspeaker motor vary in density and depth depending on the frequency of the signal and the distance between the voice coil and the metal parts, as shown by the images on the left.

A common method for counteracting the eddy currents is to put a ring of conductive material, aluminium in this case, inside the structure. The simulation helps assess the effectiveness of that short-circuiting ring. Looking at the right side of Fig. 4, the ring appears to do a good job in shielding from eddy currents the bottom part of the structure, especially at low frequency, but is much less effective at high frequencies and in the air gap area.

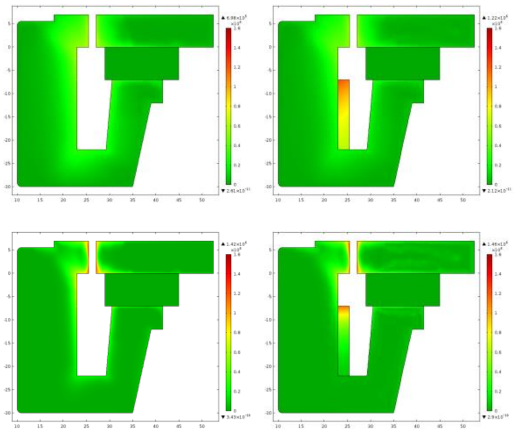

Fig. 4 Density of eddy currents induced by the voice coil in the loudspeaker motor at 50 Hz (upper row) and 500 Hz (lower row), with (left) and without (right) short-circuiting aluminium ring.

3. Mechanics

3.1 Structure of a compression driver

In order to illustrate mechanical simulations, it’s better to analyze a close relative of the cone loudspeaker: the compression driver. In professional audio, the compression driver is by far the most commonly used high frequency device. The typical range of compression drivers is from around 1 kHz to the upper limits of human hearing, around 20 kHz.

The motor structure is the same as the cone loudspeaker, while the membrane shape is typically a dome, whose outer edge is flattened and clamped to the structure and acts as a suspension. The voice coil is attached between the dome base and the suspension.

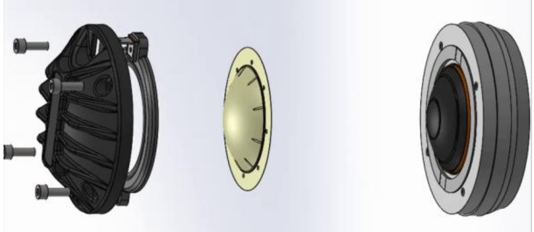

Fig. 5 Internal structure of a compression driver

Unlike the cone loudspeaker, though, the compression driver membrane does not radiate sound directly in open air, but through a system of thin channels called a phase plug (black in the figure, inside the motor on the right), whose role is to bring the sound radiated from different parts of the dome in the correct phase relationship and to enhance the acoustic load, and therefore the transduction efficiency. A loudspeaker horn is customarily connected at the phase plug outlet.

3.2 Eigenfrequency analysis

Since the compression driver acts on high frequencies, where the wavelengths are smaller and the displacements are in the sub-millimeter range, the simulation must be much more detailed than in the cone loudspeaker. Fig. 6 portrays an example of the eigenfrequency analysis of a compression driver moving assembly, used to optimize the materials, thickness, weights and shapes of all the parts.

The simulation uses both the Solid Mechanics and Shell physics settings from the Structural Mechanics Module.

The eigenmode shown in the pictures is the first one usually found after the fundamental, pistonic mode and is called a “rocking mode”. In this case, the simulation is aimed at designing the small ribs in the suspension (seen in the bottom part of the figure), in order to heighten the eigenfrequency and reduce the amplitude of the rocking motion.

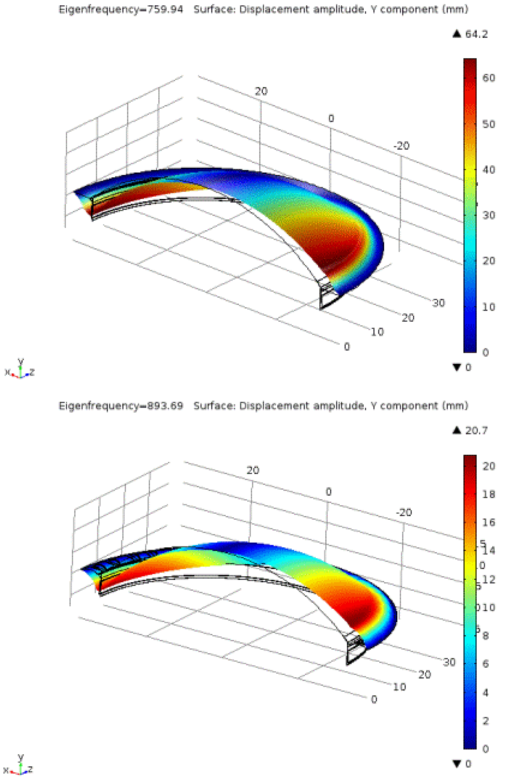

Fig. 6 Rocking mode of a compression driver membrane, with flat suspension (above) and suspension ribs (below)

4. Acoustics

4.1 Phase plug design

The phase plug is a device put between the driver dome and the driver outlet. It is composed of thin, concentric channels and its goal is to yield a simple plane wavefront at the throat of the horn at all frequencies.

The simulation can show the resonant frequencies and mode shapes of the compression chamber, through an Eigenfrequency study, as well as help the designer refine the path and expansion of the channels, to maximize the efficiency and minimize internal resonances, through Frequency Response and Optimization studies.

Fig. 7 shows the results of such an optimization, in the case of a phase plug with straight channels. Notice how the resonances in the compression chamber (the dome-shaped cavity at the top of simulation domain) have no effect on the plane-wave propagation at the driver outlet.

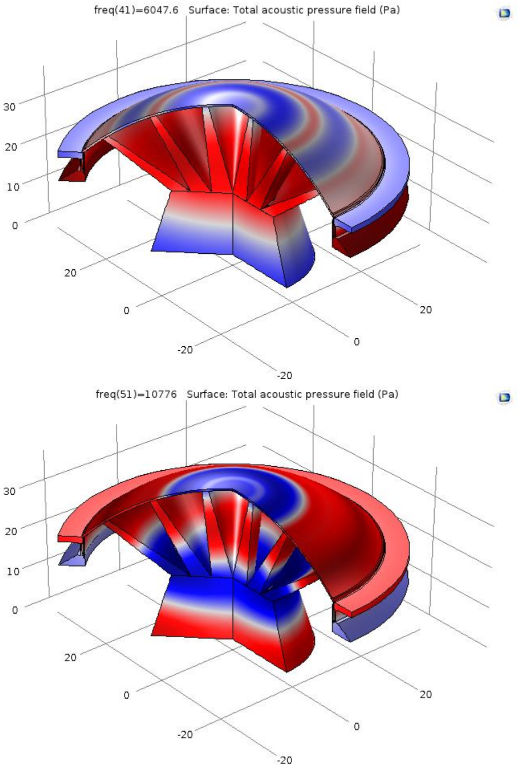

Fig. 7 Sound pressure propagation through a compression driver phase plug

4.2 Loudspeaker horn design

An especially effective application of FEA is in the design of loudspeaker horns. Fig. 8 represents the sound pressure field propagation inside a loudspeaker horn, from the circular throat where the driver is connected up to the sound radiating end, in this case an elliptical mouth.

Other critical aspects of horn performance can be evaluated through simulation. The graphs in Fig. 9 show the radiation pattern of the horn, i.e. the size and shape of the area covered by the sound emission on the horizontal and vertical plane of the horn, and how it changes with frequency.

In this example, the graphs show that the horizontal coverage of this horn is generally broader and smoother that the vertical one, that has many sidelobes and tends to decay faster at high angles from the axis.

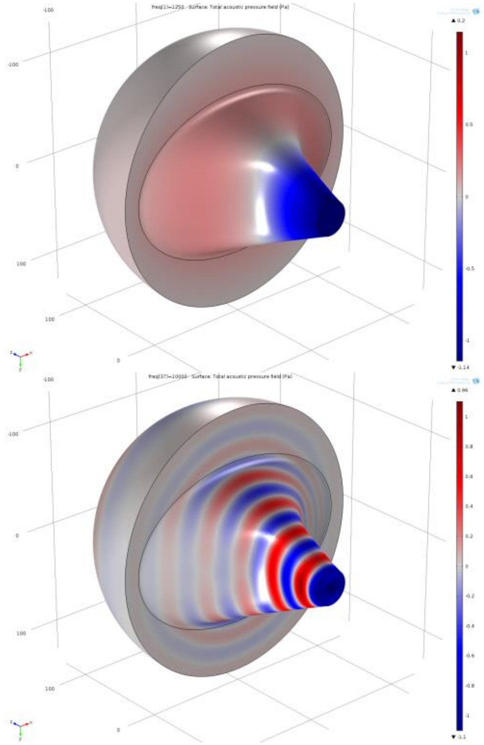

Fig. 8 Acoustic pressure in a loudspeaker horn, at 1.25 and 10 kHz

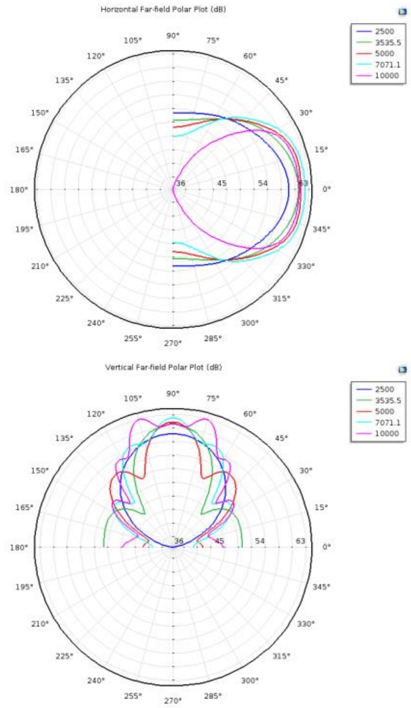

Fig. 9 Horizontal and vertical polar plots for the horn in Fig. 8

Another important evaluation criterion is the acoustic load, or acoustic impedance at the throat, that affects the overall efficiency of the horn-driver system by interacting with the mechanical impedance of the moving assembly.

The acoustic impedance in fig. 10 has a good, uniform acoustic resistance from 3 kHz up, and the reactive part is never larger than the resistance, despite some irregularities in the lowest range.

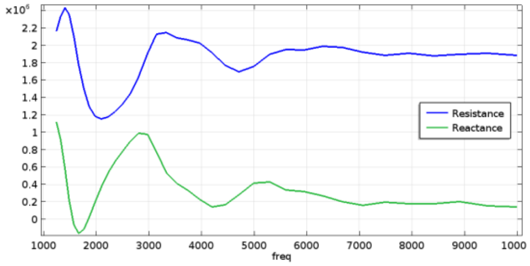

Fig. 10 Acoustic impedance at the throat of the horn in Fig. 8

4.3 Line array acoustical waveguide

A different example of sound propagation analysis comes from the design of a high-frequency waveguide for line-array professional sound systems, presented at the 2009 COMSOL Conference in Milan [1]. The project goal was to modify a waveguide so that the outgoing wavefronts were as flat as possible in the vertical plane. In other words, the shape of the outgoing waves had to be cylindrical, diverging in the horizontal plane, but staying straight in the vertical plane up to the highest audio frequencies.

The solution we found was to create an acoustic lens inside the waveguide, by adding the rigid obstacles seen in the bottom part of Fig. 11, in a triangular shape. It’s easy to appreciate the effect of the lens in flattening the curved wavefronts to a straight segment.

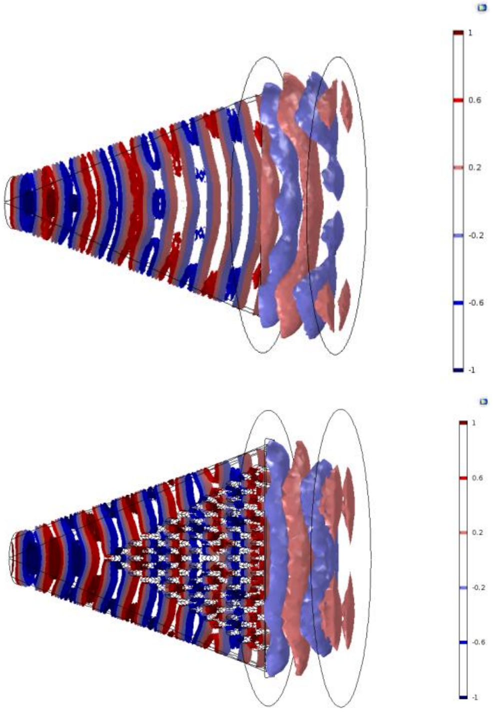

Fig. 11 Design of an acoustical waveguide for line array systems. The comparison shows the effect of the acoustic lens in flattening the wavefronts at the outlet.

5. Thermodynamics

To make a good professional loudspeaker driver, there's more than electromagnetism, mechanics and acoustics. At the very least, one has to consider thermodynamics, that plays a vital role in the reliability and durability of the device. Thermal failure, in the form of voice coil burnout, is the most common cause of failure in demanding applications.

The images in Fig. 12 are taken from a study commissioned by B&C Speakers to the University of Firenze in 2010 [2] with the goal of analyzing the thermodynamics and heat paths inside the motor of a large low-frequency loudspeaker driver. The issue is especially important when the material of the permanent magnet is neodymium-iron-boron, that is known to demagnetize easily under excessive heat.

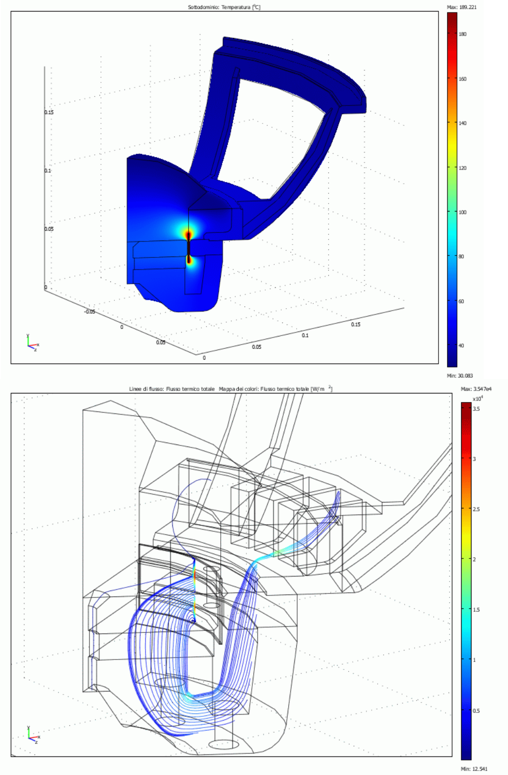

Fig. 12 Temperature map (above) and heat flux (below) of a loudspeaker structure in operating conditions.

The top image is a map of the temperature distribution in working conditions, and shows that the tips of the voice coil are hotter that the rest, because they are away from the heat dissipating effect of the steel structure around the air gap. The bottom image shows the heat flow out of the coil, through the steel and the permanent magnet and eventually to the basket.

This kind of simulation is very useful to assess the effect of heat-dissipating features, like the fins located between the basket spokes.

6. Multiphysics

6.1 Full model of a compression driver

Putting all of the tools together in a single simulation yield results like the one in Fig. 13. The products used include the Structural Mechanics Module, the Thermoacoustics Study from the Acoustics Module and the AC/DC Module for the electric equivalent circuit of the loudspeaker motor.

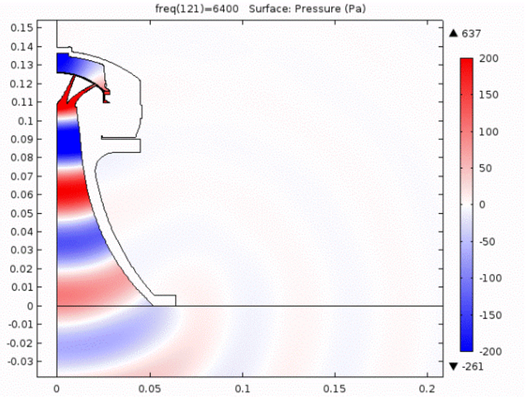

Fig. 13 Complete simulation of a compression driver and horn.

7. Results

The complete simulation also allows a comparison of predicted and measured results on the same device.

The graph in Fig. 14 compares the simulated and measured electrical impedance of a compression driver on a horn. Since the loudspeaker is a transducer where the different physical domains are strictly tied to each other, the electrical impedance contains a wealth of information not only on the electromagnetic characteristics of the device, but also on the mechanical and acoustical features. The simulation tracks surprisingly well not only the main features of the impedance curve, but also many of the finer ones.

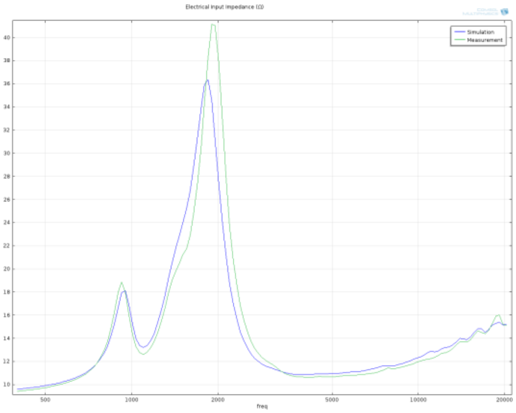

Fig. 14 Electrical impedance of a compression driver on a horn, simulation vs. measurements.

The final test of performance for a good loudspeaker is the transfer function between input signal and sound output, that is, the frequency response. Fig. 15 compares the simulated and measured frequency response of the same compression driver. The fit between the two curves and the amount of features successfully replicated are excellent.

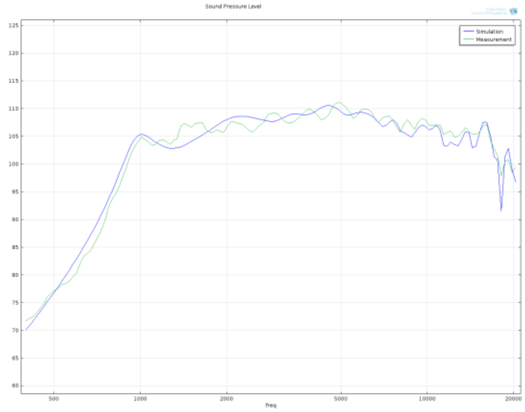

Fig. 15 Frequency response of a compression driver on a horn, simulation vs. measurements.

8. Conclusions

The loudspeaker driver is a multiphysics device, where the physical phenomena in each domain are strictly interwoven with each other. The examples shown in this paper prove that any attempt to model the behavior of the driver needs a multiphysics approach to be successful.

COMSOL features a rich set of tools that help the loudspeaker driver designer in applying such an approach, and is constantly striving to overcome the limitations of Finite Element Analysis. For example, the combination of Perfectly Matched Layers and Far-Field Calculation make COMSOL a good solution for open boundary acoustic problems. The integration of lumped parameter modeling through the use of equivalent electrical circuits is also a handy tool for loudspeaker modelling [3].

Furthermore, the number of different tools in the Acoustics module is constantly increasing. The addition of the thermoviscous losses in small passages has been instrumental in improving the simulations of compression drivers. Some of the new Physics interfaces, like Ray Tracing and Acoustic Diffusion, further extend the range of problems that COMSOL can tackle.

9. References

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