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Free-field Frequency Response Synthesis with IMPro Measurement Data

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ABSTRACT

Free-field directional frequency responses for the microphones contained within two smartphone devices were synthesized by combining acoustic measurements and simulations. The hybrid data were produced by combining boundary element simulation data with the measured pressure frequency responses of the devices' integrated microphones using the IMPro measurement method. The hybrid data were compared to measurement results to verify the quality of the generated directional responses. The comparison showed only minimal differences between the hybrid and measured magnitude and phase frequency responses. We conclude that the described synthesis method produces valid directional responses of an integrated microphone device.

1 Introduction

Today, most modern smartphones have multiple microphones supporting advanced media capture applications utilizing spatial audio and improved speech enhancement algorithms, such as noise reduction using deep neural networks. Smartphone acoustics are typically analyzed through lab measurements, but increasing computing power has made numerical simulations a common and time-efficient part of product design. Smartphone devices are favorable for numerical acoustic simulation as the device body is relatively small and can be assumed rigid.

As there are no analytical solutions for such a non-spherical shape, the only option is to apply numerical methods. In this study we show that measurement data acquired according to the previously introduced IMPro method [1] can be combined effectively with numerical acoustic simulations of the waveform scattering around

the device body. This provides an alternative to free-field acoustic measurements in an anechoic chamber. We will show that the IMPro integrated microphone response measurement and the acoustic body scattering problem can be solved separately, which opens new opportunities for the characterization of product microphones and support consumer product design using virtual prototyping techniques.

Accurate directional free-field response measurements require adjustment of the incident angle of the sound source relative to the device under test. Automated systems improve precision and reduce measurement time, but their mechanical components can disturb the anechoic chamber's sound field. For single-plane measurements, a turntable can rotate the device within the chamber to minimize reflections. Full 3D measurements require adjusting the source and device along two axes, but such setups also compromise the chamber's acoustic performance to some extent. Smartphone devices

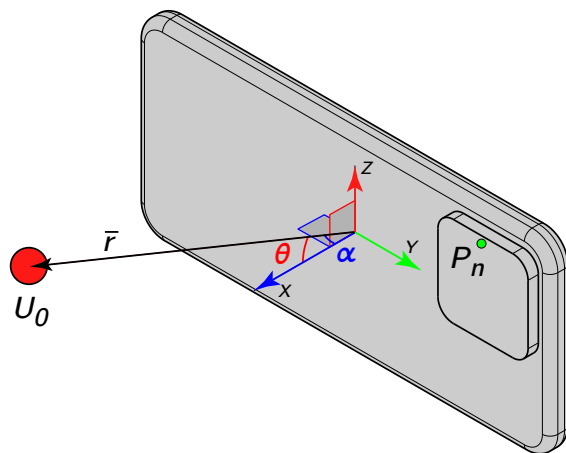


Fig. 1: The coordinate system used, and the relation of azimuth (α) and elevation (θ) angles for the point source location (shown by a red circle), and the location of the field point P_n shown by a green point.

are typically held in the hand or hands, and in different orientations. The presence of hands will change the directional characteristics of the microphones, and the different device orientations (e.g. landscape or portrait) may require additional measurement directions.

Spatial processing algorithms are increasingly used in smartphones and other consumer devices containing multiple integrated microphones. 3D directional responses for each microphone are required for the tuning of these algorithms and increasingly denser measurement grids may improve algorithm performance. Thus measurement time will increase, which may be prohibitive for some laboratories.

In our previous paper [1] the directional frequency response of an integrated microphone in a sphere was successfully synthesized from the measurement of the IMPro pressure response of the integrated microphone (with the use of a probe microphone) and the sound pressure entering the integrated microphone sound inlet which was determined analytically from an expression for the scattered pressure around a sphere from a point source.

In this paper we will use boundary element method (BEM) simulations of the sound field surrounding smartphone devices for point sources of differing sound source incident angles and use the measured IMPro

pressure responses for each microphone in the device to synthesize the hybrid directional free field frequency responses of the devices tested. Two devices are evaluated. Device 1 is a prototype device prepared for 3GPP DaCAS standardization [2] and Device 2 is a real commercial smartphone device.

1.1 Generation of the hybrid directional free-field response

In order to determine the hybrid free-field frequency response for complex shaped devices, the sound pressure at the sound inlet of each microphone under test must be determined using numerical acoustic simulation methods, specifically for this paper using a BEM solver. Once the sound inlet pressure is known for a given point source location, the IMPro pressure response of the microphone in question can be used to determine the output signal expected from the specified point source.

When measuring the free-field frequency response according to IEC 60194:8 [3], the sound pressure p_{ref} from the sound source in an empty field is determined at a unique reference point (the measurement origin) using a measurement reference microphone. This reference pressure is used to equalize the measured frequency response of the test microphone to produce the desired free-field response.

To be able to compare measured free-field frequency response data against a synthesized hybrid equivalent, the hybrid data must be equalized with the pressure from the simulated point source measured at the measurement origin point. A scaled Green's function [4] is used by the BEM solver to define a point source of strength U_0 , and the resulting pressure at the measurement reference point p_{ref} will be:

$$p_{\text{ref}} = U_0 \frac{e^{-ik\|\mathbf{r}\|}}{4\pi\|\mathbf{r}\|} \quad (1)$$

Here, k is the wavenumber, and $\|\mathbf{r}\|$ is the distance between the measurement reference point and the point source.

The same source strength value for U_0 is used to compute both the pressure at the microphone inlets p_n and at the reference point p_{ref} in the absence of the device. Figure 1 illustrates the simulation setup, where a point source of strength U_0 is placed on vector $\mathbf{r}$, defined by azimuth α and elevation θ in spherical coordinates.

The device under test is centered at the origin, excluding the camera extrusion.

The IMPro reference point p_n for each microphone under test is located at a point offset 1 mm from the device surface directly above the center of the sound inlet in a direction normal to the device surface. By solving the boundary element problem involving the point source and the outer shell surfaces of the device under test, the pressure at the point $p_n(\alpha, \theta)$ due to the radiating point source located at $(\mathbf{r}, \alpha, \theta)$ is determined.

By placing the probe microphone at location p_n , the IMPro method determines the pressure frequency response H_m [units/Pa] for each microphone, *i.e.* the response of the microphone to a constant applied pressure at the IMPro reference point. Thus the directional free-field frequency response $H_f(\alpha, \theta)$ for each microphone tested will be:

$$H_f(\alpha, \theta) = \frac{p_n(\alpha, \theta)}{p_{\text{ref}}} H_m \text{ [units/Pa]}. \quad (2)$$

2 The boundary element method (BEM) simulation model

For this study, a proprietary fast multipole BEM solver (MLFMA) [5] was used to simulate both direct and scattered pressure fields from a point source around solid objects [4]. While commercial and open-source solvers like NumCalc [6], part of Mesh2HRTF [7], are available, the chosen solver offered optimized performance for our needs.

The device under test is represented as a mesh of shell elements, with the element nodal locations defined by 3D cartesian points. The distance between nodes of the same element should be spaced close enough to provide sufficient accuracy of the pressure distribution over the element surface for the highest simulation frequency, but not too close resulting in an overly large total node count. The meshing target is typically about 10 elements per wavelength. Thus for an upper frequency of 24 kHz, the element length should be about 1.5 mm. Rigid Neuman ($\delta p / \delta n = 0$) boundary conditions are applied to all surfaces of the meshed device, since the materials used in the tested devices are hard, non-porous, and assumed to be mechanically rigid.

The model setup should represent closely the equivalent free-field measurement setup. Thus a point source

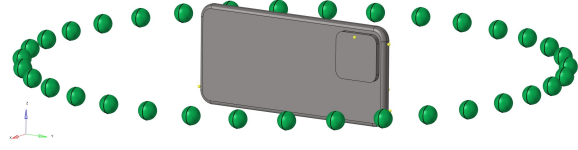


Fig. 2: Figure shows the locations of the point sources about the device (point source circle radius not to scale)

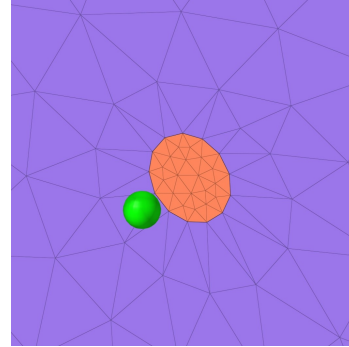


Fig. 3: Mesh detail of a device microphone sound inlet (orange) and the 1 mm offset field point P_n , corresponding to the IMPro reference point, in green.

is placed at the location of the equivalent loudspeaker source's acoustic center for the required incidence angle. A pressure measurement field point node is located at the equivalent point p_n for each microphone tested. The pressure solution must be determined for each frequency point. Thus for N frequency points, M microphones, and P point source locations, $N \cdot P$ solutions will need to be solved. For a large number of source directions, the simulation time grows very quickly. However, since we are using simple point sources, the principle of reciprocity can be applied [8], and the roles of the point sources and measurement field points in the BEM can be exchanged, and the number of solutions reduces to $N \cdot M$.

Figure 2 shows the source point cloud representing the equivalent 36 loudspeakers required to measure the directional response for azimuth angles 0° to 350° in 10° steps. Note that in the figure the source to origin distance is scaled for visual purposes, whereas the true radius was 1.2 m.

Figures 4 and 5 show the meshes for devices 1 and 2. All surfaces are modeled as rigid. Purple indicates the

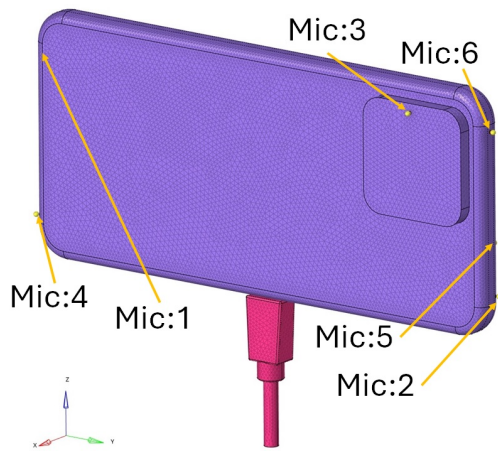


Fig. 4: Device 1 shell mesh

device body and pink the jigs holding the device during measurement, which were included to replicate the anechoic chamber setup. Microphone field points P_n are shown as yellow spheres. Microphone field points P_n are marked with yellow spheres. Device 1 has six microphones: four on the edges, one near the camera, and one at the earpiece. Device 2 has three: two on the edges and one on the camera extrusion.

The sound ports of the integrated microphones are excluded from the mesh, leaving holes in the device surface. To ensure a closed BEM mesh without free edges, these holes are sealed with filler surfaces. Figure 3 shows a close-up with the orange filler surface behind the pressure field point corresponding to the IMPro reference point P_n , marked by a green sphere. A denser mesh on the filler surface was applied for improved pressure accuracy.

3 Device data acquisition

The free-field response measurements and the IMPro measurements required the recording of sound files containing the signals generated by the device microphones due to the loudspeaker measurement stimulus. For the prototype, device 1, the digital pulse-density modulation (PDM) signals of the MEMS microphones were captured with a USB device. For the commercial product, device 2, the signals from the microphones were recorded on to the device directly, and the recorded sound files downloaded later for analysis.

The locations of the sound inlets of the device microphones were determined primarily by visual inspection.

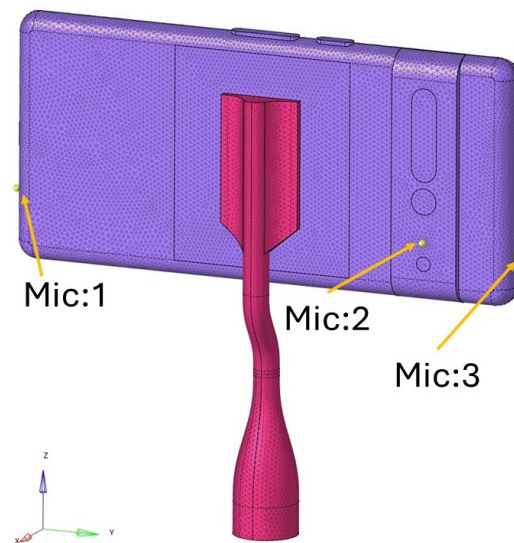


Fig. 5: Device 2 shell mesh

For a device with less obvious microphone sound inlets, a sound recording where air is gently blown over the device surfaces sequentially can determine the faces of the device where microphones are located, and detailed locations determined using an air-jet source such as a dust blower used to clean digital camera sensors and lenses.

It is critical that the hardware and software chain involved in the recording of the microphone signals in the device do not modify the response of the microphones. For this reason special software was installed on device 2, to enable the recording of the unprocessed (raw) signals generated by the microphones.

The measurement of the directional responses results in recordings containing multiple sine sweeps [9]. Irregular pauses between measurement sweeps are present in the recordings, coinciding with the times where the device is automatically repositioned. In order to obtain a consistent group delay, the impulse responses obtained from the sine sweeps were time aligned by aligning the impulse response envelope signal.

The IMPro measurement data presented in this paper was acquired under anechoic conditions. However, IMPro measurement data can be acquired also in a normal room environment [1].

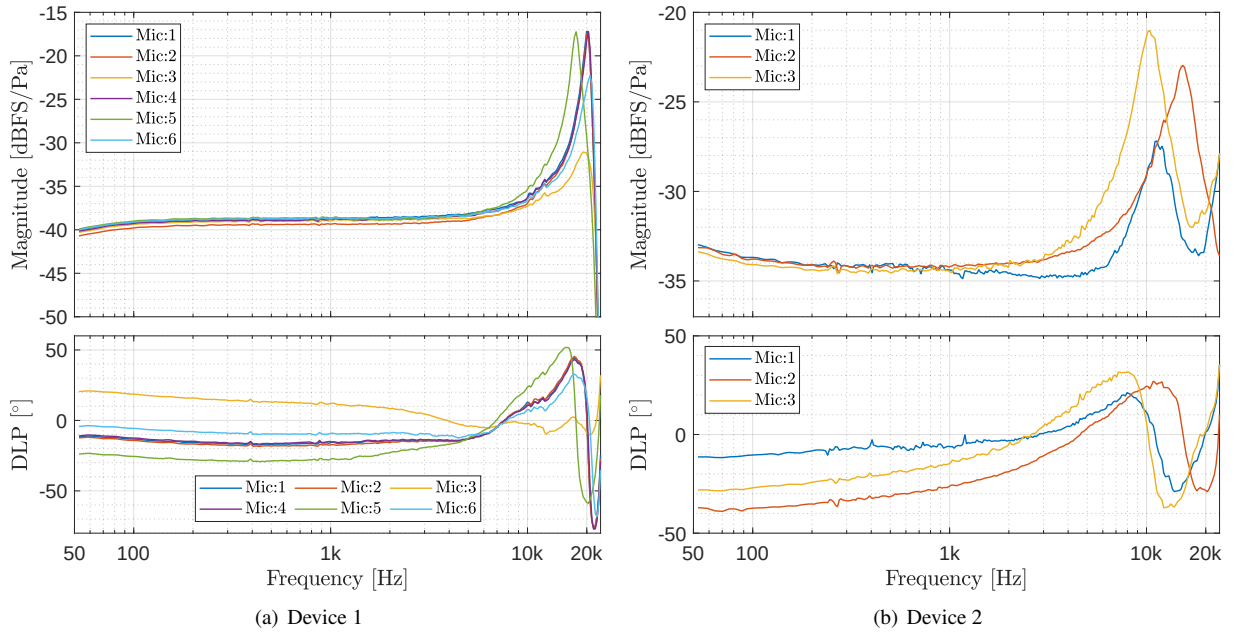


Fig. 6: IMPro pressure frequency responses for devices 1 and 2, showing the source angle independent logarithmic magnitude and deviation from linear phase responses

4 Results

The measured IMPro method pressure frequency responses for the microphones in devices 1 and 2 are shown in Figure 6. The IMPro pressure responses for device 1, Figure 6(a), show resonance frequencies in the range 16 kHz to 19 kHz, and with differing damping values. The pressure response shows clearly the slight differences in the dimensions of the sound ports for the different microphones. The offset in the deviation from linear phase response for microphone number 3 may be caused by inaccurate fitting of the unwrapped phase response for the deviation from linear phase (DLP) visualization. The IMPro pressure responses for device 2, Figure 6(b), show microphones with a slightly higher sensitivity, and sound port resonant frequencies in the range 10 kHz to 15 kHz. In addition the high frequency responses for microphones 1 and 3 show the leading tails of the microphone's secondary resonances.

Figure 7 shows the measured and hybrid free-field frequency responses for the microphones in device 1 for the azimuth angle of 0° . The hybrid magnitude responses are very similar to the measured data, with general error levels of ± 1 dB, except at low frequencies, where noise is present in the measured data, and

at the resonant frequencies, where measurement errors are magnified. The hybrid DLP responses are also matching the measured responses, with errors of about $\pm 10^\circ$. Figure 11 shows the same data for device 2, and demonstrates the same level of matching between the hybrid and measured data. Errors are a little higher for this device compared to device 1, due to the presence of a higher noise level in the measured free-field data.

Figures 8 and 9 show spectrograms of the magnitude and deviation from linear phase responses for each of the incident angles measured for the device 1 microphones. The difference between the hybrid and measured response data is shown in the right hand column spectrograms using the ΔH function, which is defined as follows

$$\Delta H = H_f^{(h)} / H_f^{(m)}, \quad (3)$$

where $H_f^{(h)}$ is the hybrid free-field frequency response, and $H_f^{(m)}$ the measured response.

The magnitude error spectrogram visualization values are saturated to ± 2 dB range to best show the details in the error spectrograms, rather than focus on the resonance location errors. Visually there is virtually no

difference between the hybrid and measured magnitude responses. Higher errors appear to be located at frequencies/rotations where dips in the response occur partly due to lower noise floor in simulated data. The deviation from linear phase results for device 1, in Figure 9, are similar in quality to the magnitude data, except for the results of microphone number 5. For this microphone, which is located in the earpiece area of the device, the DLP response changes quickly for rotations between source azimuth angles 300° and 320° . Both the hybrid and measured data show this feature, but the measured response range is far higher, and this is shown clearly in the error spectrogram for this microphone. Since these discrepancies are limited to a few angles, the large errors likely stem from a mismatch between the simulated and measured sound pressures at the microphone inlet, rather than from the IMPro measurement data.

The spectrogram plots for magnitude and deviation from linear phase for device 2 are shown in Figure 10. As with device 1, the match between the hybrid and measured data is very good, especially in the magnitude responses. Microphone number 2, located on the camera surface, shows high errors in the deviation from linear phase response for angles between 180° and 250° . This issue is similar to the DLP errors seen in microphone 5 of device 1. For some of the angles in this directional error range, issues in the linear phase prediction processing part of the DLP calculation may be present as well as large changes in the DLP response between the rotational steps.

5 Conclusions

The results presented show that the synthesized hybrid free-field directional frequency responses closely match real measured responses for the two devices tested, and we conclude that this hybrid technique can be applied to any commercial device containing integrated microphones, provided that there is the ability to record the device's microphone signals and that the IMPro method is appropriate for the device and its microphone integration.

The accuracy of the hybrid data is comparable to direct measurement in both magnitude and phase. This leaves a free choice as to which method to use to obtain the free-field directional frequency response. The IMPro measurement method does not require an anechoic chamber. This means that free-field directional

responses can be readily generated without the need for an anechoic chamber.

High density directional data are easily generated, removing the need to acquire automation systems for positioning the device under test relative to the source loudspeaker, saving on measurement time. In fact, for applications that require very high spatial direction densities, the hybrid method is the most practical choice. It can also be expected that simulations that are feasible today for computing clusters will be also possible with desktop computers in the not so distant future.

One bottle-neck in the described hybrid method is in the generation of the simulation mesh. The approach taken for this study was to generate as accurate a mesh as possible, and a considerable portion of the time required to generate the hybrid data was spent in obtaining the mesh. Further studies into the optimal accuracy requirements of the mesh are needed; the results of which will help to determine possible shortcuts that could be made to reduce the time required for the mesh generation task.

The holder jig placing the devices in the measurement position may affect the measured responses. With a reliable method to determine the change to the scattered field caused by the holder, investigations can now be made to quantify the effect that the holder has on directional responses.

The phase errors seen in the DLP spectrogram responses in a few of the directions for microphone 5 of device 1, and microphone 2 of device 2, require further investigation to determine the cause of such large changes in the phase response in both the measurement and simulation data within a small range of rotations.

For this study, the simulated measurement setup was rather simple consisting only a device in a free field environment. We predict that more complex acoustic scatterers, such as HATS, could be included in the model without loss of accuracy. In addition, the proposed hybrid method could be applied also in non-anechoic environments such as in car interiors [10] and would assist in the design and integration of car audio systems.

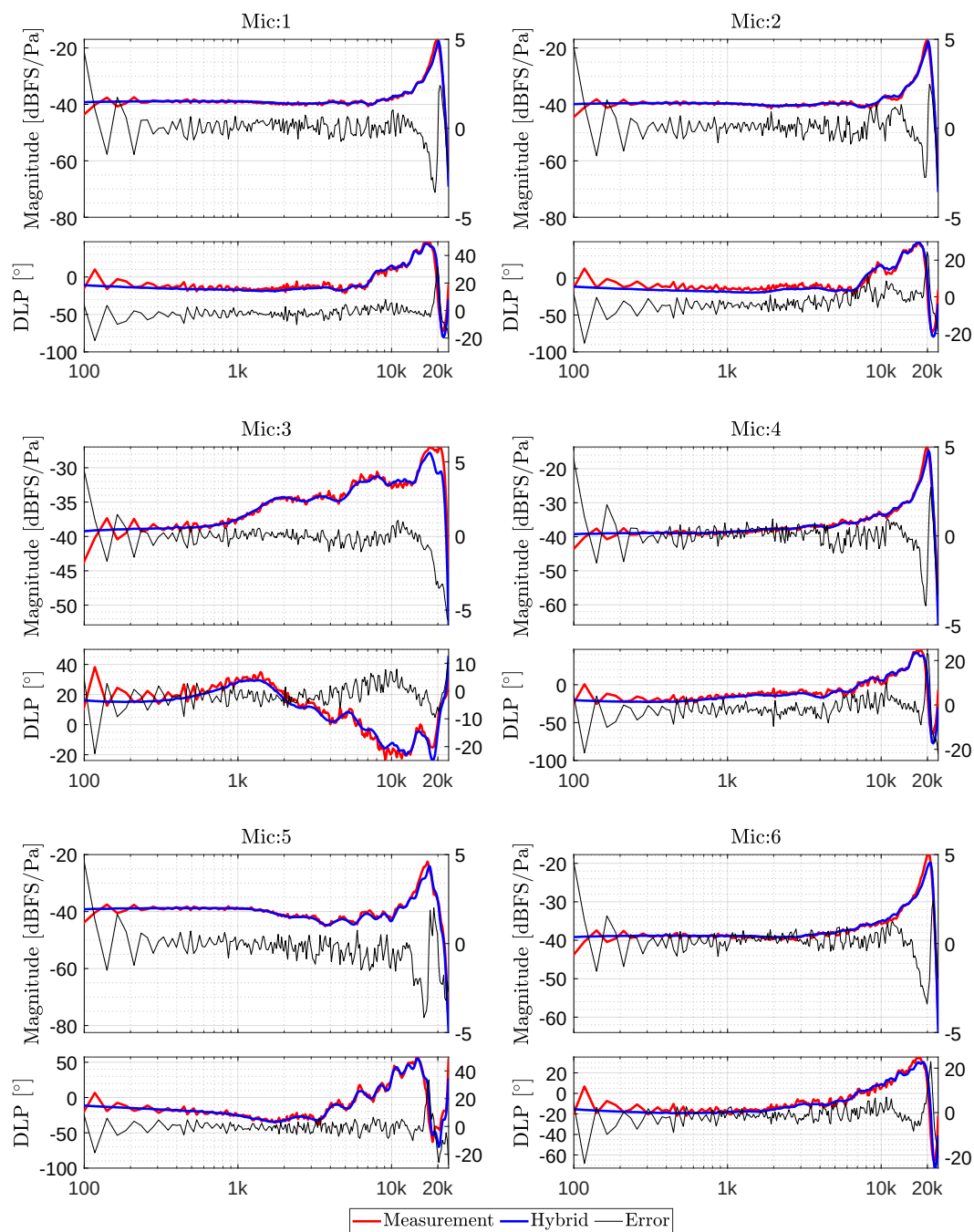


Fig. 7: Free-field responses $H_f(0^\circ, 0^\circ)$ of each microphone in device 1 for measured and hybrid data, showing the magnitude and deviation from linear phase, and the difference between the measured and hybrid responses on the right-hand axis.

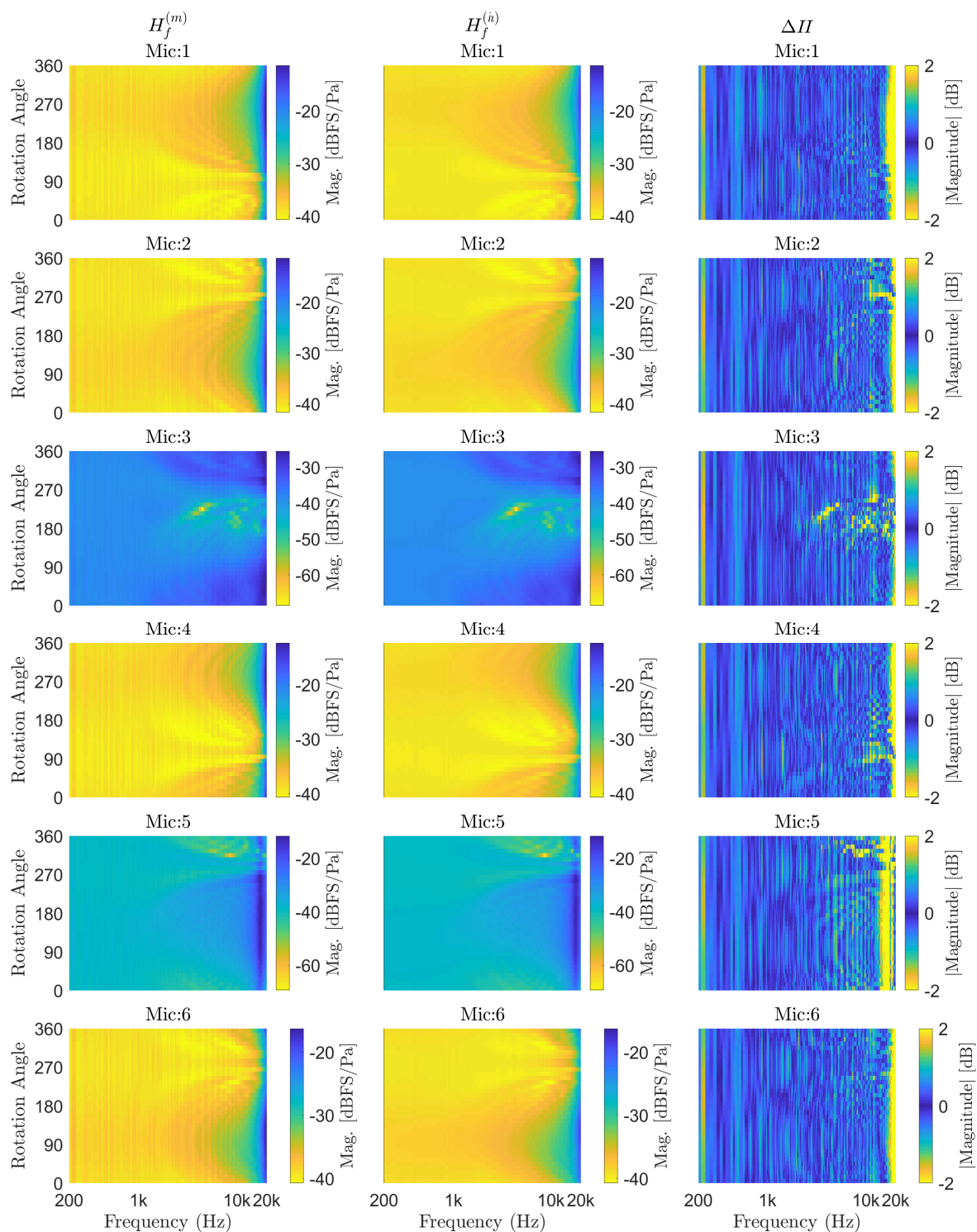


Fig. 8: Free-field responses of each microphone in device 1 for measured and hybrid data, showing for all rotations the magnitude response, and the magnitude of the error function response ΔH .

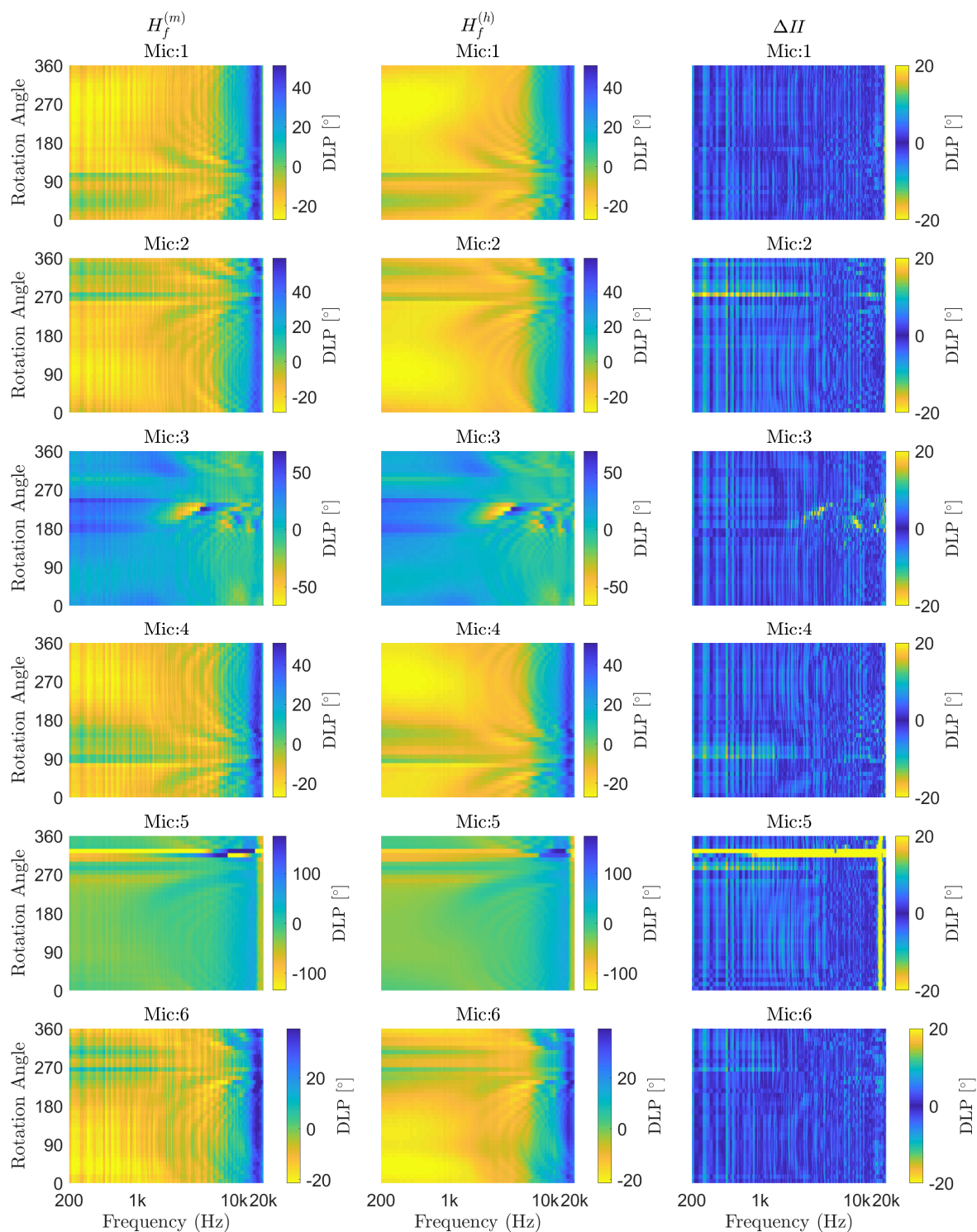


Fig. 9: Free-field responses of each microphone in device 1 for measured and hybrid data, showing for all rotations the deviation from linear phase response (DLP), and the DLP of the error function response ΔH .

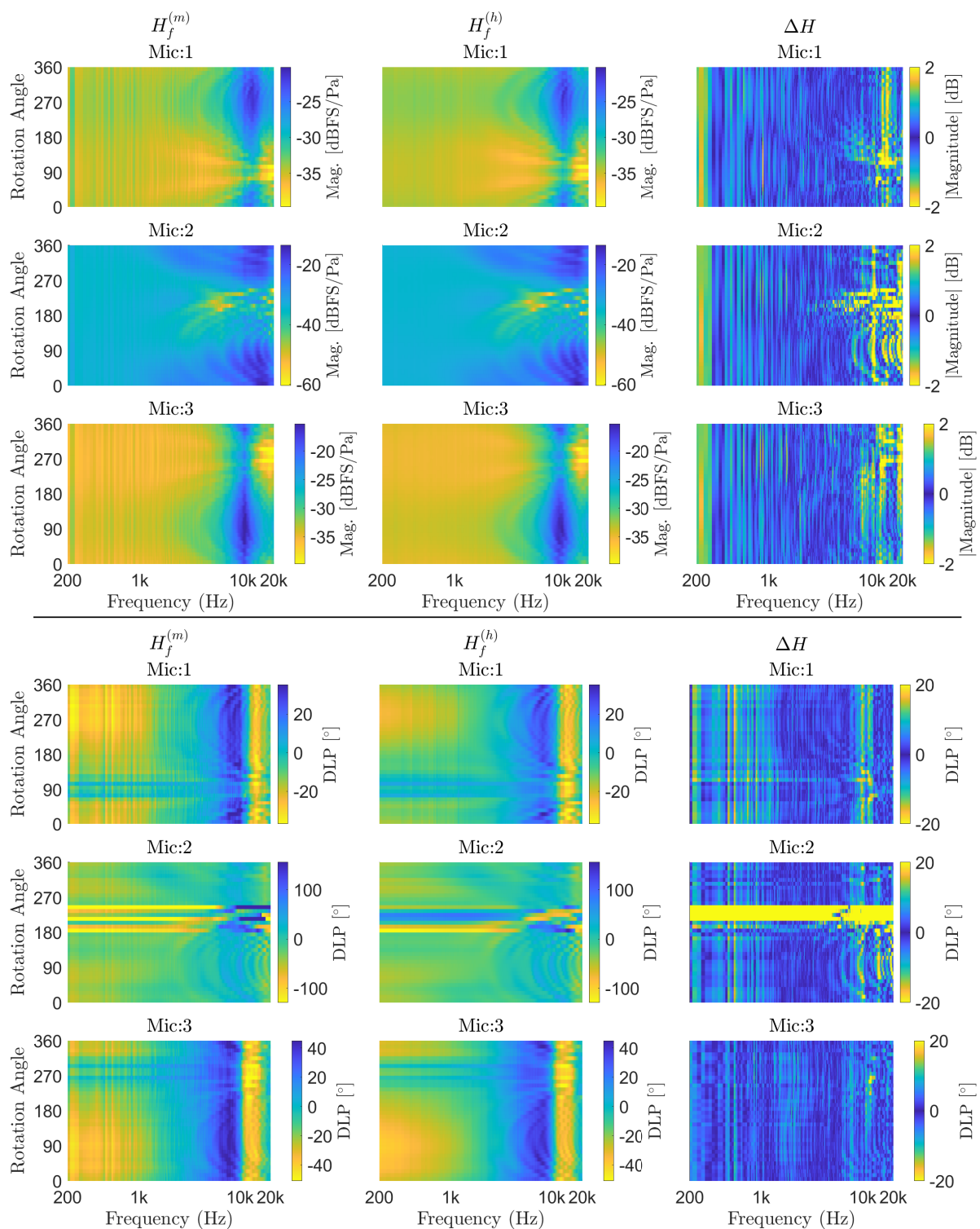


Fig. 10: Free-field responses for the microphones in device 2, showing the magnitude response (top), the deviation from linear phase response (bottom) for the measured and hybrid data for all rotations and the error function responses ΔH for each response form.

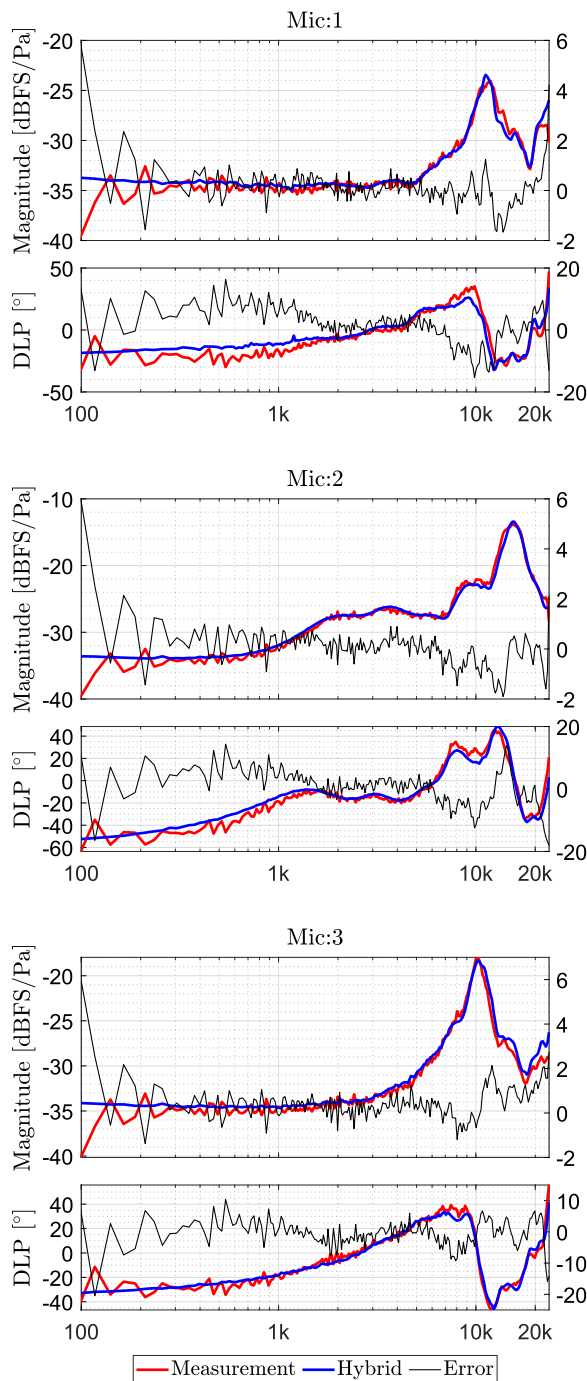


Fig. 11: Free-field responses $H_f(0^\circ, 0^\circ)$ for the microphones in device 2, showing the measured and hybrid data in magnitude and deviation from linear phase forms. The difference between the measured and hybrid responses use the right-hand axis.

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