Audio Engineering Society

Convention Express Paper 38

Presented at the 153rd Convention
2022 October

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The effect of user's hands on mobile device frequency response, Part 2

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ABSTRACT

Earlier work has shown that the user's hands have a significant effect on the frequency responses and polar patterns of portable devices such as smartphones and tablets, relevant for both sound playback and sound capture. Measurements using actual users, which led to these results, are valuable for basic research, but practical device design requires both a measurement device that resembles acoustically the user's hand and a simulation model that can be used for numerical design. This paper discusses the development of a prototype measurement system and related simulation models for design and device testing. Also the effects of user's hand on conventional telephony usage, especially the effect on handset uplink response, are discussed.

1 Introduction

The practical importance of hand effects for audio devices has been known for a long time, but qualitative results have been published only recently, first for performer microphones [1] [2] and then for loudspeakers in handheld devices with the form factor of smartphones or game consoles [3]. The work done so far has concentrated on measurements done using actual users, which is extremely important for gaining a good understanding of the acoustical phenomena, and indicated that the acoustical interaction between a device and the hand is surprisingly complex. This prompted initiating study on the possibility of developing a test system and a related simulation model based on the actual dimensions of a human hand.

As shown in this work, this approach is successful, but what is also shown is that simple one-point frequency response measurements are insufficient to describe the acoustical behavior of the system, and industry practices for this evaluation need to be developed.

2 Earlier experimental results

The earlier hands-free loudspeaker study [3] was conducted on 16 subjects holding a device, where a miniature microphone was mounted on a boom at 350mm distance from the front surface, which corresponds to the typical listening distance in hands-free use. The reflections from user and the environment gated out so that only the hand effects should be visible in the measurements. The results indicated both strong coloration of the frequency responses and very high individual variability of the responses, including highly variable channel balance in stereo use and limited test repeatability even under optimal conditions, especially at high frequencies.

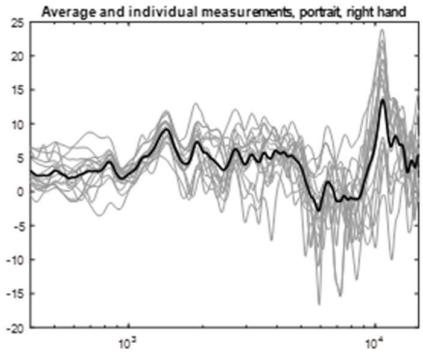


Figure 1. Individual variation of hands-free loudspeaker responses for 16 users holding the device in nominally the same position (right hand, portrait orientation) [3].

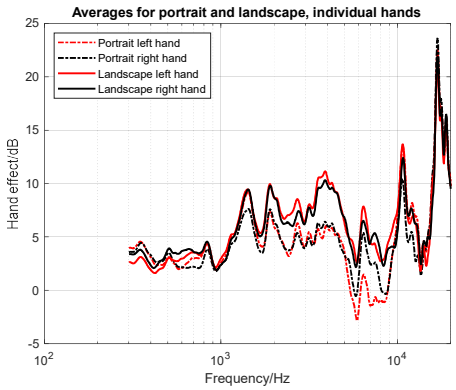


Figure 2. Average frequency responses (difference to a free-field response) measured for a phone hands-free mockup [3].

3 Simulation model and results

The simulations and physical test hand prototypes were based on a 3D scan of a hand holding a transparent phone-sized plastic piece, which was erased from the scan in the post-processing of the data. This created a 3D model that has the fingers in positions corresponding to actual phone use and the palm shape, critical for reflections, corresponds also to actual use. The wrist was edited to end in a round shape so that the diffraction from the wrist would be minimal in both simulations and in a physical prototype. The calculations presented here were done using COMSOL Multiphysics acoustics module. All the simulated frequency responses are far-field ($r \to \infty$) approximations of the exterior field.



Figure 3. Hand scan used in the simulations and for building the physical test hand prototype.

The simulations were used in this study to determine how much the variation of the device position relative to the hand affects the frequency response, both individual directions in free-field and the total radiated power. These results will be used to determine the recommended measurement and averaging methods, briefly discussed in Section 4, and the necessary device positioning accuracy.

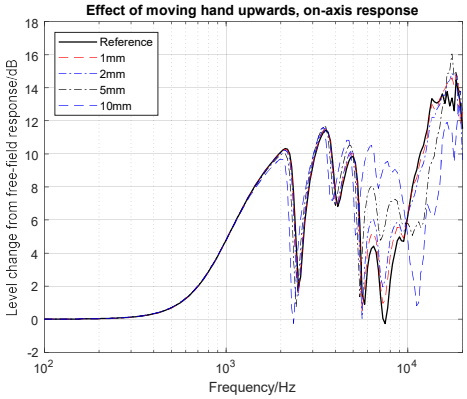


Figure 4. Effect of moving hand upwards behind the phone.

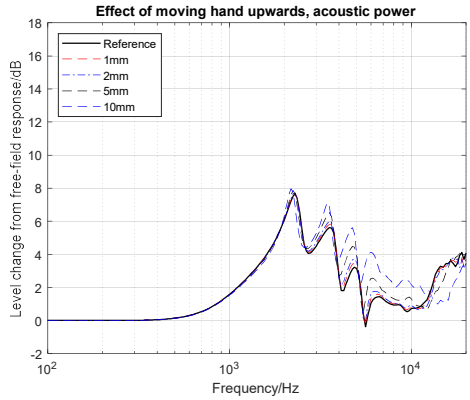


Figure 5. Effect of moving hand upwards on the acoustic power.

Another test was on the effect of the distance between the hand and the phone. This has great practical significance, since the distance varies a great deal between users. A small survey with 6 male subjects, 3 phones of different widths (73.2, 76.5, and 85.5mm), using both hands, gave for the distance between the back of the phone and the part of the user's hand directly under the bottom side of the phone a minimum value of 0.58mm, maximum value of 17.95mm, mean of 9.31mm and a standard deviation of 5.27mm, and a larger test sample would have increased the variation range that needs to be taken into account in designs.

The results from backwards movement computation (Figure 6) suggest that the first two dips around 2.5 and 4 kHz are due to a reflection from the palm, since they move downwards in frequency when the distance increases. Similar conclusions cannot be, however, easily drawn for higher frequency response features.

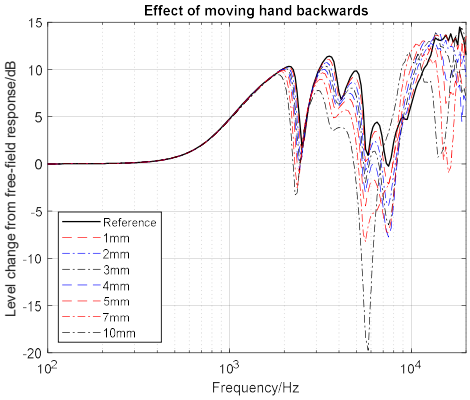


Figure 6. Effect of moving hand backwards behind the phone.

If the phone and hand are kept stationary, but the observation point is changed then the high-frequency response exhibits a very irregular behavior (Figure 7 and 8),

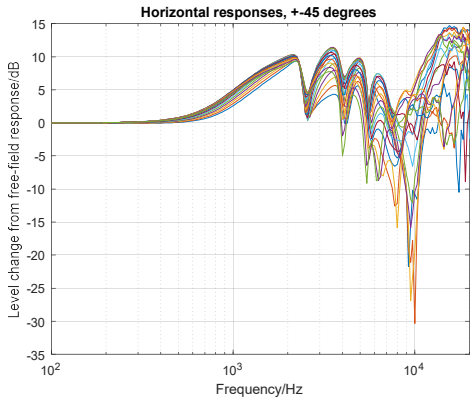


Figure 7. Frequency responses over a ±45° horizontal sector at 5° intervals.

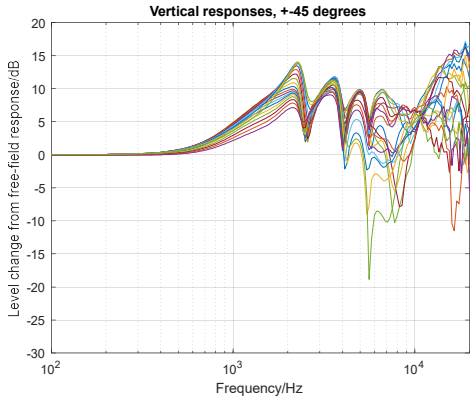


Figure 8. Frequency responses over a ±45° vertical sector at 5° intervals.

The behavior of the frequency response at high frequencies can, according to these results, be quite well called chaotic, i.e. sensitive to small changes in the test setup in a manner that is hard to predict statistically.

4 Free-field spatial averaging and power response estimation

Experimental results from earlier studies and the simulation results above indicate the single point on-axis responses are highly sensitive to measurement parameter variations and thus repeating a measurement would need much care. The overall radiated power is less sensitive to the precise device placement, but as

the devices are often used in the near field the power response is less important than for far field home loudspeakers, but the power response can give some guidance to target response definition and equalizer design.

The example used for evaluating the usability of spatial averaging methods is the response change when the hand is moved 5mm upwards from the reference position. Practical experience indicates that the difference in the frequency response is not significant with music or speech, although clearly audible with broadband noise. This implies that it is necessary to find a measurement method that indicates the change but does not exaggerate it. The following methods were used: on-axis response, power average of 5 points at ±15° around the on-axis point, and a multi-point average over ±15° horizontal and and vertical sectors, 5° between the points. Total acoustic power was calculated as a reference.

The results indicate that the on-axis response is, as in previous results, very sensitive to the change, while averaged results do yield a less sensitive and thus more credible result.

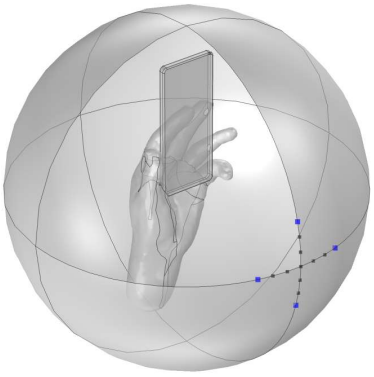


Figure 9. Directions used in computing the average responses.

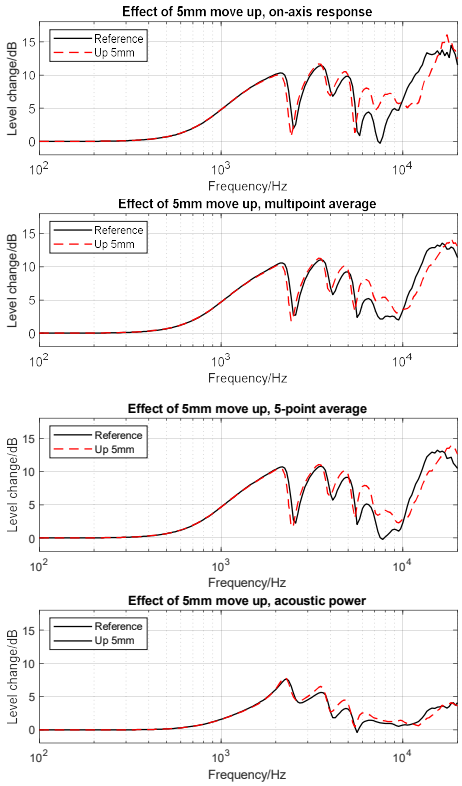


Figure 10. Comparison of the result of different averaging methods for a small movement of user's hand.

If the averaging is done over narrower sectors then the smoothing effect decreases accordingly. Also, increasing the number of measurement points makes the response smoothing more effective (Figure 11).

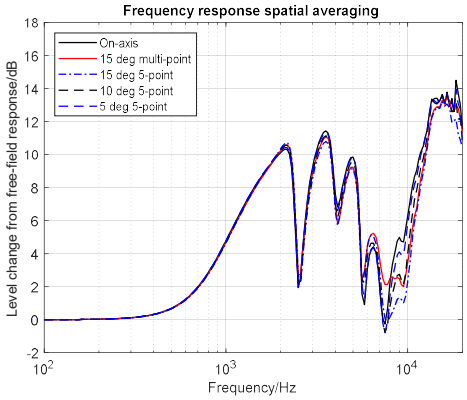


Figure 11. Comparison of free-field averaging methods.

The total acoustic power (power response) can be easily computed during modelling by integrating the magnitude of the intensity over a boundary surrounding the source. Although the intensity might have a small tangential component, and so the magnitude and the normal component are not precisely equal in the near field, calculation examples show that in this case the acoustical powers calculated using intensity magnitude, integrated squared far-field sound pressure, and normal component of the intensity at a finite distance differ from each other by less than 0.15 dB up to 10 kHz, and the integrated intensity magnitude is at least one order of magnitude faster to compute than the theoretically more precise power estimates.

The experimental determination of the acoustic power requires some care. Gerzon [4] already pointed out in his discussion of calculating the directivity from limited polar information that area-weighted power averages are numerically less than optimal way of determining the overall radiated power, as they correspond to the trapezoidal rule of numerical integration, which is known to have a low accuracy. However, the methods suggested by Gerzon (and for more recent discussion on numerical integration over an unit sphere, see e.g. An & Chen [5]) rely on having a smooth enough function so that spherical polynomial expansions have only small higher-order components, which usually holds well for conventional loudspeakers, but unfortunately is not valid for the highly irregular high frequency polar patterns of hand-device systems. This implies that only simple averaging (or trapezoidal integration) methods can be applied.

The amount of measurement points needed for a good power response estimate was tested using 6 points (unweighted average, front/back, left/right, up/down), and an area weighted 18-point measurement at 45° intervals (Figure 12), and comparing it against the integrated intensity. The results (Figure 13) indicate that the 6-point average is too inaccurate for any practical use, but the 18-point weighted average yields usable results up to approximately 15 kHz.

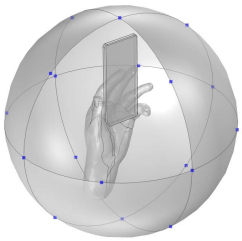


Figure 12. Directions used in computing the 18-point average response.

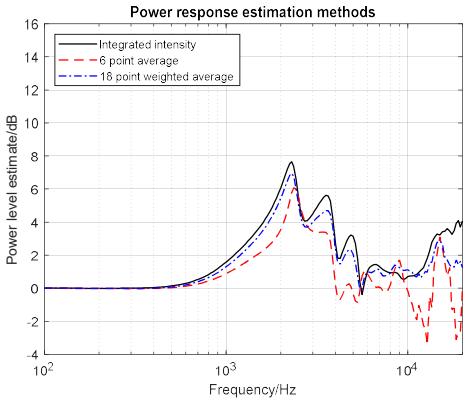


Figure 13. Comparison of different power response estimation methods.

5 The effect of sound source distribution

Most of the simulations presented in this work were done using a point source at the center of the bottom side of the phone. This kind of source placement is well defined and thus good for simulation models, but practically all actual device designs use hands-free loudspeaker ports that are distributed on a wide area.

The effect distributing the sound radiation to multiple ports was studied using a simple example where the radiation from a central port, two ports placed 40mm apart, and an array of 11 ports at 4mm distances, resulting in a total source width of 40 mm, was compared (Figure 14), both for on-axis response and for the total acoustic power. It is very difficult to claim any "improvement" with the increased source directivity from the on-axis responses, but the overall radiated power indicates less high-frequency variation when the source is distributed over a wider area.

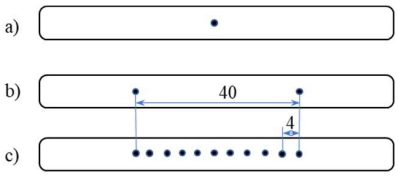


Figure 14. Port locations used in the simulations.

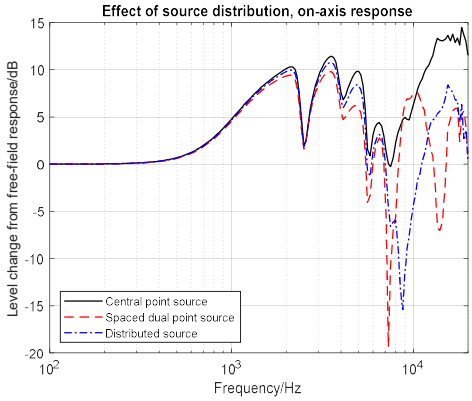


Figure 15. On-axis response change for different source distributions.

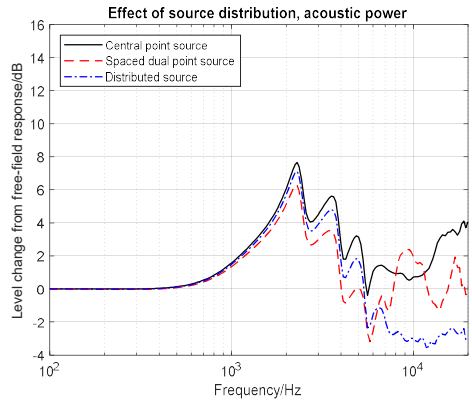


Figure 16. Total radiated power change for different source distributions.

6 Test hand design and results

The practical measurement of frequency responses using real hands, as was done in the first part of the study, is important for assessing the importance of the hand effects, but an impractical approach for practical design work. This is due to the need of test subjects, limited repeatability, and frequency resolution limitations due to the necessary gating of the measurement signal. To make the hand measurements practical an artificial test hand was constructed based on the same 3D scan as the simulation model. Two different types of hand were constructed: two (mirror images to enable two-hand testing) made as a hard, hollow 3D print from PLA (polylactide) plastic, and one with a PLA core and a silicone coating resembling the elastic properties of human tissue.



Figure 17. Test hands used in the comparison.

The hands were compared against a measurement made using the actual user's hand, made so that the test subject could see a real time measurement of the frequency response and adjust his hand accordingly to obtain a response that was as close to test hand measurements as possible. To obtain a good bandwidth and signal-to-noise ratio the measurement was made as a reciprocal measurement using a ¼" laboratory microphone inserted in a phone mockup made of MDF board, and with a small two-way loudspeaker at about 70 cm distance.

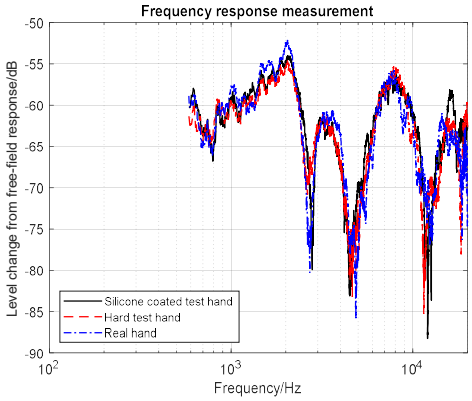


Figure 18. Frequency responses measured using a silicone coated test hand, a hard test hand, and a human hand.

The shapes of the responses appear very similar, and this is confirmed by looking at the differences between

the human hand and the test hands, and the individual test hands. As it is apparent from simulation data, the exact location of the frequency response dips is highly dependent on the precise locations, and so the minor differences observed here are apparently due to the small differences in the placement and the small shape differences. The material of the test hand appears not to be relevant to the results (this was suggested already by earlier simulations), and so a hard hand, possibly with some elastic coating on the mechanical contact points, would appear appropriate for the construction of the test hand.

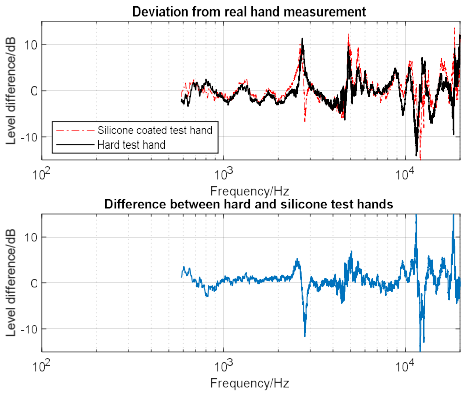


Figure 19. The difference between the test hands and a real hand (upper graph) and the difference between hard and silicone coated test hands.

7 Other test hand applications

The test hand applications discussed in detail in this paper are confined to hands-free loudspeaker measurements. experiments and simulations suggest that test hands could be applied to a broader range of portable device testing applications, such as phone handset testing and wind noise testing [6]. Testing hand-held microphones, as encouraged by the results of Brixen and Schneider, would also be interesting, but it requires a test hand design different from the one needed for portable device testing.

The first test on the additional applications was done by measuring the effect of user's hands (3 test subjects, 4 trials each) to a phone microphone tested on a head and torso simulator (HATS). An important observation is that the hand effects would bring the uplink response of a phone handset well outside the tolerance windows of any response requirement [7], even narrowband requirements would be occasionally exceeded.

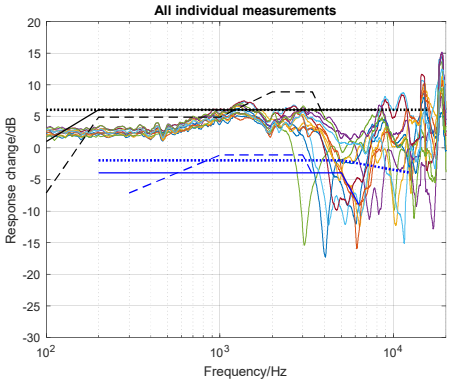


Figure 20. Hand effect from individual users (3 users, 4 trials each) compared against 3GPP narrow-band (dashed), wideband (solid), and super wide band (dotted) handset uplink response windows [6].

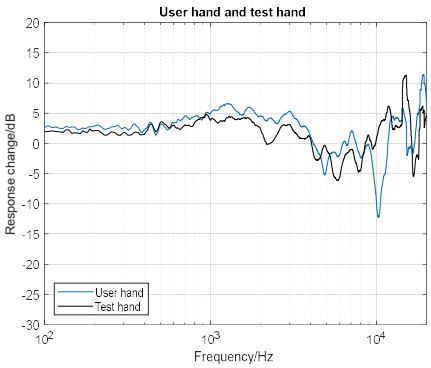


Figure 21. Comparison of HATS uplink response changes when the test is made using a real user's hand and a plastic test hand [6].

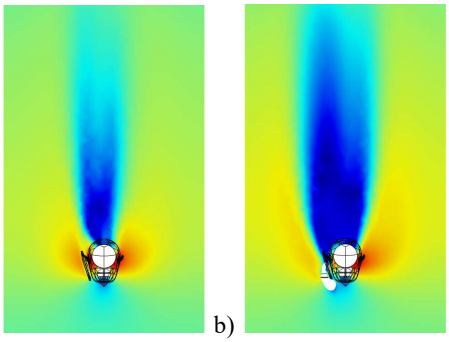


Figure 22. Flow velocity around a telephone handset and a HATS a) without hand, b) with hand [6], showing the effect of the hand on flow distribution.

The flow noise spectrum, obtained through time domain CFD analysis shows that the presence of the hand increases the noise level significantly (inlet flow velocity 10 m/s).

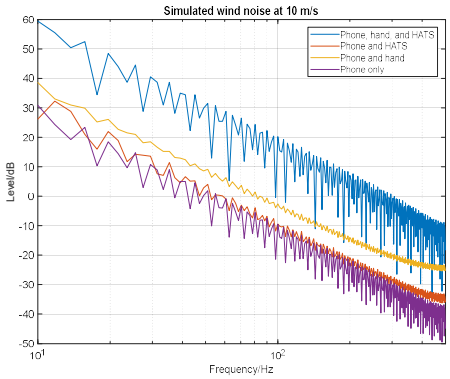


Figure 23. Simulated wind noise spectra when the realism of the simulated system is increased from a phone-sized device only (bottom) to a system with a device, head model (HATS geometry) and a hand [6].

8 Conclusions

The results presented in this paper strongly suggest that taking the acoustical interaction between the user's hand and the device is highly recommended in the development of portable devices and it is possible to obtain realistic measurement results under laboratory conditions using a test adapter modeled on a human hand. However, the measurements appear to be highly sensitive to parameter variations, so together with the test device development it is necessary to develop procedures for averaging and evaluating the test and measurement data.

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