Simulation of the head-related transfer functions using cloud computing

Tomi Huttunen*, Kimmo Tuppurainen, Antti Vanne, Pasi Ylä-Oijala, Seppo Järvenpää, Asta Kärkkäinen and Leo Kärkkäinen

*Corresponding author's address: Kuava Ltd., Kuopio, 70211, FI, Finland, tomi.huttunen@kuava.fi

Due to the complexity of measurements for obtaining individual head-related transfer functions (HRTFs), numerical simulations offer an attractive alternative for generating large HRTF data bases. In this study, HRTFs are simulated using a fast multipole boundary element method (BEM). The BEM is well suited for the HRTF simulations. Namely, only the surface of the model geometry is discretized which simplifies the pre-processing compared to other full-wave simulation methods (such as finite element and finite difference methods). The BEM is formulated in frequency domain and the model is solved separately for each frequency. Since a large number of frequencies is needed in wide-band HRTF simulations, the BEM simulation greatly benefits from distributed (or parallel) computing. That is, a single computing unit takes care of a single frequency. In this study, a distributed BEM using cloud computing is introduced. Simulations are computed in a public cloud (Amazon EC2) using a realistic head and torso geometry (3D laser scanned geometry of Bruel & Kjaer HATS 4128 mannequin). The frequency range of the simulations is from 20 to 20000 Hz. The feasibility of cloud computing for simulating HRTFs is examined and first analysis results for the simulated HRTFs are shown.

Published by the Acoustical Society of America through the American Institute of Physics
INTRODUCTION

The term cloud computing refers to a distributed computation architecture in which computational task are run on remote servers (opposed to computations on local desktops). The motivation to the cloud computing is the more flexible and efficient use of computational resources which results in savings in the needed computational capacity and in the maintenance costs of the computation facilities. Software-as-a-service (SaaS) is a cloud based delivery model for software. In SaaS, users typically access to software using a web browser and data is stored in the cloud.

In this paper, a SaaS model for acoustic simulations is introduced. In the core of the simulation model lies a fast boundary element (BE) method [1] which solves the acoustic wave equation in the frequency domain (i.e. the Helmholtz equation). As a model problem, the simulation of the head-related transfer function (HRTF) is examined.

The HRTF characterizes the effect of external ear, head and torso on the sound in the ear-canal. Several studies have focused on the numerical simulation of the HRTF, e.g. [2], [3], [4]. Improvements in numerical methods and computational capacity have made it possible to simulate the HRTF over the entire audible frequency range using realistic head and torso models [5]. In listening tests, simulated HRTFs have been shown to perform even better than those obtained via measurements [6]. Recently, the use of fast multipole BE methods has lead to a significant speed-up in the HRTF simulations [7],[8]. The goal of this study is to couple a fast BE technique to the cloud computing in order to maximize the efficiency of the HRTF simulations.

CLOUD COMPUTING

The cloud architecture consists of a front-end that is visible to the end-user and of the back-end that is hidden to the user. The user access to the cloud computing can be done, for example, using a web browser. Hence, the technical details of computation server, the location of the data or the server are not essential information to the end-user. The back-end gathers the computational data provided by the user, allocates the sufficient computational resources and distributes the simulation tasks to the cloud.

The cloud servers can be located in organization’s own premises (private cloud), they can be external servers (public cloud) or a combination of these two (hybrid cloud). Public cloud resources allow the flexible allocation of computational capacity based on the size of simulation tasks at hand. The simulation model reported in this paper has been run on Amazon’s EC2 [9] cloud.

Compared to conventional simulations on local desktop, the cloud computing offers several attractive features. In an ideal case, only a web browser is needed as an user interface for running the simulations. Hence, the local installation of a software is not necessary. Other positive features of the cloud computing include:

- Flexible allocation of computational resources.
- The data in the cloud is easy to share.
- Access to data and software needs only a web browser.
- In the case of a public cloud, costs are based on the use of service, no maintenance costs.

While the cloud computing offers several positive features, certain challenges still remain. These include:

- Simplicity of the user interface. The bandwidth of the current networks limit capabilities of GUIs.
- Limitations in the data volumes that can be transferred to/from the cloud in a tolerable time. Some simulation methods can generate tens of gigabytes of data.

- Data security. The data is stored in external servers which may concern some users.

**SIMULATION MODEL**

The goal of this study is to use cloud computing for the simulation of the HRTF. The simulation geometry is built by laser scanning the surface of Brüel & Kjaer head and torso simulator (HATS). Simulations are computed for closed ear-canals. Using the principle of reciprocity, a monopole point source is located at the entrance of the ear-canal (1 mm outside from center of the entrance) and the sound field is recorded in measurement points that surround the HATS (a simulation geometry and a set of observation points is shown in Fig. 3).

Two simulation cases are investigated. First, the effect of the head rotation on the HRTF is simulated. Second, a comparison between near-field and far-field HRTFs is made.

In the first case, the head of HATS is rotated from -52 to 52 degrees in four degrees intervals, and the HRTF is recorded in the far-field. All far-field observations of this study are made in the horizontal plane in the 2.6 m distance from the origin of the head-related coordinate system [10]. The far-field HRTF is recorded in the horizontal angels from 1 to 360 degrees in one degree intervals. Each rotation of the head necessitates a new simulation geometry, so this part of the study consisted 27 HATS geometries. For each geometry, 62 frequency steps were simulated in the frequency range from 100 to 20000Hz. The simulation geometry with 0 degree rotation angle is shown in Fig. 1 and the HATS for -52 degrees head rotation is shown in Fig. 2.

In the second case, the near-field HRTF is studied in 12240 observation points in the horizontal plane at distances from 13 to 80 cm from the origin. The radial spacing of the points is 1 cm and the angular spacing is two degrees (see Fig. 3). One of the aims of the near-field simulations is to obtain a good spectral accuracy. Hence, this model is simulated using 25 Hz frequency steps over the range of 100-20000Hz (797 frequencies).

The acoustic pressure field \( p \) surrounding HATS at the frequency \( f \) is modeled using the Helmholtz equation

\[
\nabla^2 p + k^2 p = 0, \tag{1}
\]

where \( k = \omega/c \) is the wave number with the speed of sound \( c \) and angular frequency \( \omega = 2\pi f \). All surfaces of the HATS are assumed to be rigid so that

\[
\frac{\partial p}{\partial n} = 0, \tag{2}
\]

where \( n \) is the unit normal of the surface.

The BE method is well suited for solving the equations (1) and (2). Namely, the method gives a full-wave solution for the acoustic field so that all complex phenomena (including diffraction and multiple reflections) are take into account. In addition, only a surface mesh of the structure is needed in the BE model which simplifies the pre-processing compared to other full-wave simulation methods (such as FE and finite difference methods). Consequently, BE methods are commonly used for the HRTF simulations.

The conventional BE method results in fully populated system matrices which makes the solution extremely time and memory consuming if the model geometry consists of a large number of surface elements. The fast BE methods, such as used here [1], expedite the computation of the matrix-vector product during an iterative solution of the matrix equation and greatly reduce the needed computational capacity.

Since the BE method is formulated in frequency domain, the acoustic simulation has to be computed separately for each frequency. Due to the large number of frequencies needed in a
wide-band HRTF simulation, the BE simulation greatly benefits from distributed computing. That is, a single processor takes care of a single frequency.

Recalling the pros and cons of the cloud computing from previous section, the two main reasons that make acoustic BE models good candidates for cloud computing are

1. **Trivial parallelization.** Each server takes care of a single frequency at a time, so the simulation greatly benefits from the flexible allocation of computational resources.

2. **Relative small input data.** The BE model requires surface meshes only (opposed to volumetric data of FE models) which speeds-up the data transfer to the cloud.

**RESULTS**

The results shown here summarize the computational requirements of the HRTF simulations and include a short overview on the simulation results. The detailed analysis and the perceptual evaluation of the simulated HRTFs are among the topics of ongoing and coming work.

For the BE model, the surface of HATS was discretized using 89060 vertices and 178116 triangular elements. The maximum edge length of the triangles was 4.9 mm which corresponds to 3.5 elements per wavelength at the frequency of 20000 Hz. In the case of the head rotation, the geometry was changed so that the number of elements remained unchanged.

**TABLE 1:** A summary of the boundary element mesh and computational requirements.

<table>
<thead>
<tr>
<th>#vertices</th>
<th># elements</th>
<th>Mesh file (MB)</th>
<th>Simulation time / frequency (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>89060</td>
<td>178116</td>
<td>10.1</td>
<td>150-300</td>
</tr>
</tbody>
</table>

Simulations were computed on Amazon EC2 High-CPU Extra Large Instance. This 64-bit platform provides 7 GiB of memory, 8 virtual cores and 1690 GB of instance storage. From 6 to 20 parallel instances were used in this study. In the case of the head rotation study, a typical simulation time was 150-300 s per frequency. Due to the larger number of observation points, the corresponding simulation time for the near-field HRTF model increased approximately by factor 1.5. The largest data file to be uploaded to the cloud was the mesh file. The time needed to upload the simulation input files and download the result files to/from the cloud were only a small fraction of the overall simulation time.

The number of the frequency domain HRTF models solved during this study was $27 \times 62 = 1674$ simulations for the head rotation model and 797 simulations for the near-field HRTFs.

The simulated HRTF in the far-field for the reference head position is shown in Fig. 1. The effect of the head rotation is shown in Fig. 2. The plot on the right shows the effect of the rotation as compared to the reference position. The comparison was made by computing the relative sound pressure level (SPL) as follows

$$\text{SPL(dB)} = 20 \log \left( \frac{R|p|}{R_0|p_0|} \right),$$

where $p$ is the simulated pressure for the rotated head and $p_0$ for the reference position. In this case, the distance from the origin to observation points was the same in both cases, i.e. $R = R_0 = 2.6$ m.

An example of near-field HRTFs is shown in Fig. 3. In this case, the relative SPL was computed using $R_0 = 2.6$ m for the reference measurement in the far-field and $R = 0.2$ m for the near-field observation.
FIGURE 1: Simulated HRTF amplitude in the far-field.

The near-field HRTFs, and the effect of the head rotation are compared more detailed in Fig. 4. Two extreme rotation angles -52 and 52 degrees are included in the comparison. To simplify the comparison, results were scaled by the distance of sound source $R$ so that

$$\text{SPL}(\text{dB}) = 20 \log \left( \frac{R}{|p|}/p_0 \right).$$

Here, $p_0 = 2e - 5$ Pa is the reference amplitude.

CONCLUSIONS

In this paper, the cloud computing and a fast BE method is used for simulating the HRTF. Results suggest that relatively large HRTF data sets can be simulated in a reasonable time and computational capacity. As an illustrative example, the effect of head rotation on the HRTF was simulated using 27 different head-and-torso geometries. In addition, the near-field HRTF model that consisted of 12240 sound directions was investigated.

Using the principle of reciprocity, the solution of the HRTF is done in two steps. First, the BE problem is solved to obtain the sound pressure on the surface of the model geometry. Second, the sound field is evaluated at the observation points surrounding the surface. As shown by the simulations, the increase from 360 to 12240 observation points increased the simulation time approximately by factor 1.5. Hence, the simulation time is dominated by the first step. Consequently, adding new observation points to existing HRTF results can be considered as a simple post-processing routine. The result in a new point is as accurate as the existing results (opposed to interpolation that is commonly done in adding new directions to existing measurement values).
FIGURE 2: Simulated HRTF amplitude in the far-field when the head is rotated 52 degrees. The figure on the right shows difference to the reference position of Fig.1. The relative SPL is computed using the equation 3.

Here, the head-and-torso model had perfectly rigid surfaces and the ear-canals of the dummy head were closed. Both features were made to simplify the model but can be easily replaced by a more realistic model. The fast BEM is not limited to rigid surfaces. BE simulations using the same algorithm for open ear-canals and with an impedance on the ear-drum have already been reported in [7].

The cloud computing is a viable tool for running large acoustic BE simulations. The flexible allocation of computing instances is ideal for running large number of trivially parallel simulations tasks. On the other hand, the BE model needs only surface mesh of the geometry which leads to a relatively small input data that needs to uploaded to the cloud. Recent improvements in web technology (such as HTML5 and WebGL) have made it possible to visualize the simulation results in the cloud (using a web browser only). This will reduce the need for downloading all output data back to a local desktop for post-processing.

Only the first analysis results were reported here. Next steps of the study focus on the more detailed analysis of the simulated HRTFs data and perceptual evaluation of HRTF filters that are generated from the simulated data. One of main challenges in coming studies is the simulation of personalized HRTFs in the cloud. For this, an efficient method for generating personalized model geometries is needed.

ACKNOWLEDGMENTS

Author wish to acknowledge the support from the Finnish Funding Agency for Technology and Innovation (Tekes). Cloud computing resources were provided by Amazon via the Uber-Cloud Experiment.
FIGURE 3: Simulated HRTF amplitude in the near-field. Near-field results are computed in the points shown in the left. The HRTF corresponding to the $R = 20$ cm source distance (red dots on the right figure) is shown in the middle. The figure in the right shows the HRTF amplitude relative to the far-field HRTF (that is computed using the equation (3)).

REFERENCES


Figure 4: Simulated HRTF amplitudes for different sound directions.


