Acoustic Holography in-Solids for Computer-Human Interaction

W. Rolshofena, M. Yangb, Z. Wangb

a Institute for Mechanical Engineering (IMW), Technical University of Clausthal, Robert-Koch-Str.32, 38678 Clausthal-Zellerfeld, Germany

b Manufacturing Engineering Centre, Cardiff University, Newport Road, Cardiff CF24 3AA, Wales, UK

Abstract

Computer-Human Interfaces can be generally categorised into two groups, tangible and intangible. The most commonly used computer input devices such as keyboards, touch-pads or touch-screens are tangible. In this paper a new approach to the development of tangible acoustic interfaces based on acoustic holography is described. The principle of acoustic holography in solid is described and the achieved theoretical results are shown in this paper. A prototype of such a tangible acoustic interface has been developed and will be further optimised.

1. Introduction

Following the use of visualisation and speech recognition for man-machine interaction interfaces, the next challenge for the future is haptic or contact technology which is based on acoustic source localisation and tracking. In this paper the acoustic source localisation method which is based on the acoustic holography is described. This method is under development and will be implemented for various computer applications in the EU-project “Tangible Acoustic Interfaces for Computer-Human Interaction (TAI-CHI)” [1,2].

2. Acoustic source localisation methods

Principally, there are two kinds of stimulation of physical objects: passive and active modes. In the passive mode any change in the acoustic properties of an object, due to its vibration as a consequence of interaction (knocking, tapping etc.), is detected and then used to estimate the location of the interaction. With regard to the active mode, the absorption of acoustic energy at the contact point of an object surface must be ascertained. Different types of impact can be identified like knocking, beating, scratching, rubbing, touching, as well as continuous motions.

Currently there are three passive methods under investigation for tangible acoustic interfaces: time delay of arrival (TDOA), time reversal and acoustic holography. This paper focuses on the acoustic holography in solids

3. Introduction of Holography principle

The idea of optical holography was formulated for the first time by Gabor [3] in 1948. There were many related inventions (e.g. laser) before the principle was proved experimentally. A holographic picture is created by recording a hologram and then reconstructing the recorded hologram in three-dimensional space. If a wavefront propagates through
an object point, a new spherical wave is built according to the Huygens-Fresnel’s principle. This is called the object wave contrary to the first existing reference wave. The superposition of the amplitudes and the phase distribution can be recorded on a photosensitive plate (see Fig. 1).

The main advantage of holography is that it can produce the vast information contents of holograms. This is because a three-dimensional wave field can be reconstructed from two dimensional photosensitive surfaces using the saved phase information [5].

4. Theoretical description of Acoustic Holography

In acoustic holography, a two-dimensional sound pressure field is stored and used to determine the three-dimensional sound pressure field, which can be the field of the particle velocity, the field of acoustic intensity vector, the field of surface velocity and the field of the intensity of a vibrating sonic source [6].

In general, the acoustic holography is a measurement of a sonic wave field on a suitable surface and uses the measured two-dimensional acoustic wave field to reconstruct a three dimensional acoustic intensity distribution. A holographic reconstruction is just the convolution (deconvolution) of the measured values with the values of the measured Green’s function [6].

The main approximation, that the sonic source creates a wave field \( \Psi(r,t) \), can be described with the following wave equation:

\[
\nabla^2 \Psi(r,t) - \frac{1}{c^2} \frac{\partial^2 \Psi(r,t)}{\partial t^2} = 0
\]

Where \( \nabla^2 \) is the Laplace-Operator and “\( c \)” is a constant propagation velocity. In order to process the equation (1) more approximations are needed, such as the assumption of the existence of an infinitely dimensional surface surrounding the target area.

Also, the following Helmholtz equation with the wave number \( k=\omega/c \) must be fulfilled. Results in the complex wave field \( \tilde{\Psi}(r,\omega) \) can be obtained by applying the Fourier transformation to the above equation (1). The value of the amplitude and phase in the new equation depends on the distance between the position of a measurement to the source “\( r' \)”. For the spatial analysis a constant frequency value \( \omega \) is normally adopted in order to make a wave field satisfy the requirements of the Helmholtz equation.

\[
\nabla^2 \tilde{\Psi}(r,\omega) + k^2 \tilde{\Psi}(r,\omega) = 0
\]

5. Rayleigh-Sommerfeld Algorithm

With the increment of the distance between the source and the recording plane, further approximations become necessary. Concerning the tangible acoustic interfaces, the Rayleigh-Sommerfeld approximation is promoted which is referred to Rayleigh’s integrals and Sommerfeld’s radiation condition. It is the most general and valid formula which can be applied through out in the entire space.

A mathematical model of Huygens-Fresnel principle can be deduced from the Rayleigh-Sommerfeld diffraction formula, because this corresponds to the convolution integral. With regard to convolution theorem, convolution is just a multiplication in the Fourier space. From the analytical computation of the transfer-function (Green’s Function), the wave propagation between hologram level and picture level can be calculated with the following formula (Rayleigh-Sommerfeld Algorithm) and displayed [7].

This is the holographic reconstruction of the complex wave field \( \tilde{\Psi}(x_{\phi},z_{\phi}) \) with the hologram data \( \tilde{\Psi}(x_{\mu},z_{\mu}) \), where \( F \) symbolise the Fourier and \( F^{-1} \) the inverse Fourier transform. Besides, the spatial co-ordinates are given with \( x \) and \( z \), as well as the wave number \( k \).
In equation (3), the indices $B$ and $H$ indicate the source plane and the hologram plane respectively, $\lambda$ is the wavelength, and $\gamma$ and $\delta$ describe the associated local frequencies [7].

According to the measured signals at the sensors’ positions shown in Fig. 2, the amplitude and phase distributions of the recorded signal is back-projected onto a digital image plane from each sensor’s position to find the source position which corresponds to a maxima in the image reconstruction plane. The maximum in the signal distribution corresponds to the contact point.

The theory and the developed algorithm of acoustic holography were applied to various tests. Different materials were selected for the experiments, which included metal plates, wood boards and a glass-ceramic hob. In the experiments an impulse stimulus was repeatedly created by a hammer on the tested objects to simulate human finger taps for generating the required acoustic signal. The generated acoustic signal was recorded at each sensor’s position and then processed for back projection, which was performed on a pixel-based mesh with each sensor’s position as the back projection centre. In consequence, a local maximum at the source position can be observed (see Fig. 2). The sensors used for the experiments were accelerometers and the measured signal was recorded with a signal analyser. Finally, the Rayleigh-Sommerfeld algorithm was used to process the recorded data and compute the localisation. For this a cross-correlation algorithm was used for the received signals to extract the reflected and reference wave for reconstructing holographic images.

6. Material and applications

The approximation of homogeneity and isotropy was used for the analysis of behaviours of acoustic wave propagation in a physical object. However, based on this assumption, the developed theoretic model has some degree of difficulty to characterize acoustic wave behaviours in real object. Therefore different materials, have been tested to investigate the effects of the approximations on the experimental results.

A test rig has been established to carry out the acoustic holography experiments (seen in Fig. 3). A detailed view of the installation of accelerometers and strain gauges is presented in the Fig. 4. Another example for the transducer arrangement and the kind of sensors used is shown in Fig. 5, where the sensors were mounted in the middle of the plate instead of along the edges.

Position determinations were performed with the Rayleigh-Sommerfeld algorithm which was programmed with in Matlab code. The results were 3-D images of acoustic holograms of amplitude and phase distributions.

An impulse hammer was used to generate the required precise acoustic signals. Then the acoustic signals were measured with a linear array of sensors which were connected with a data acquisition system.
8. Experimental and simulation results

Basically, an acoustic holographic image is the reconstruction of acoustic wavefronts by their amplitude and phase distribution, because a phase shift in the wave propagation within a plate can be detected by the sensors installed at different locations. The first experimental setup and a reconstruction of an acoustic wave image are shown in Fig. 2. In the reconstructed digital holographic image, there are existing several local maxima, however only one of them is associated to the acoustic source. The others formed at the edges of the image were caused presumably by boundary effects.

In the experiments with a metal plate, three measurements have been carried out at a same position (co-ordinates x=15, z=30) on the tested object’s surface. The results were presented in the Figures 6, 7 and 8. Two of them lack of the ability to recognise the source position. Reason for that could be a fault in the algorithm because of boundary effects. Therefore, wave propagation was researched.

So the in-solid wave propagation, like the used metal plate, was simulated with the Finite Element Method (FEM). According to the elastic parameters of the plate as well as the size, the simulated displacements after a knock on the object surface have been obtained and shown in the Figures 9 to 11.

A certain amount of tapping force was simulated and applied to tap on the plate. The originating acoustic wave propagation due to the tap was retraced. In accordance with the idealised model of the theory, no captivation was used to the boundary and the displacement of each grid point was calculated. The investigation indicated that strong wave reflections may occur at the edges of the tested object and as a result of this, it can be concluded, that the acoustic wave propagates faster in certain areas of the object (Fig. 11). A future step will be to set the plate in constraint condition during the simulation to clarify what kind of movements of the plate are resulted from the acoustic wave propagation at the sensors positions.
Fig. 7 Holographic result at source position \((x=15, z=30)\), where the second of repeated measurements were done.

Fig. 8 Holographic result at source position \((x=15, z=30)\), where the third of repeated measurements were done.

Fig. 9 First time step in FEM simulation. A certain force like a tap on the plate is simulated and the displacement of the material is approximated.

Fig. 10 Second time step in FEM simulation.

Fig. 11 Third time step in FEM simulation. Due to boundary reflection, acoustic wave propagation along the borders of the object is faster than inside the plate.

7. Conclusion

Laboratory experiments and mathematical simulations of Acoustic Holography in-solids have been conducted. The Rayleigh-Sommerfeld algorithm was developed for reconstruction of acoustic holographic images. At the moment, methods to improve the reliability of acoustic source localisation with acoustic holography are still under investigation. In future the development of NAH will involve in the development of new algorithms, the use of new types of transducers and searching for the best geometrical arrangement. Also the active method will be studied, where the media is dived by a continuous acoustic energy source. Moreover, numerical simulations for the wave propagation in-solids will be further strengthened.
Acknowledgements

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References

[2] Reference to the TAI-CHI homepage. URL: http://www.taichi.cf.ac.uk/