ACOUSTIC HOLOGRAPHY FOR MOVING OBJECTS

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ABSTRACT

A method for the detection of noise sources on moving objects using the acoustic holography method is presented. The object is moving parallel to the microphone array with constant speed. The velocity of the object has to be known. The distance perpendicular to the axis of movement of the object with respect to the microphone array is given. The acoustic holography is used to transform the measured sound pressures to the frequency wavenumber domain. The movement of the object leads to a shift of the frequencies in dependency of the wavenumber in the direction of the movement and the speed of the object. The projection of the sound pressure field to the surface of the object parallel to the microphone array is done calculating the wavenumber perpendicular to the plane of the array and the distance of the surface with respect to the array. This algorithm will be used to evaluate railway test runs recorded near Vienna with a 64-channel microphone array. Recorded were test runs with a Railjet with speeds from 100 km/h up to 230 km/h and an ICE with speeds up to 320 km/h.

1 INTRODUCTION

The aim of the project is the detection of noise sources at moving trains. Especially high speed trains lead to a hearable Doppler effects that have to be compensated for a correct detection of the noise sources. Several approaches exist in the time and frequency domain. Here, an approach in the time wavenumber domain will be examined.

The acoustic holography is mainly used in the near field (NAH - near field acoustic holography). Here a distance of 10.4 m is given between the surface of the train and the microphone array. Therefore, evanescent waves that dominate the near field are neglected. The advantage of the acoustic holography is that the movement of the source can be incorporated in the wavenumber frequency domain [1].

Two trains are investigated in the project. One is a full length Railjet with speeds from 100 km/h to 230 km/h and the other is the ICE-S with two traction vehicles and one measurement wagon with speeds from 100 km/h up to 320 km/h. The test terrain was the new railway line from St. Pölten to Vienna at Tullnerfeld. In the majority of the tests, trains drove from Vienna to St. Pölten using the opposite track 9 in the greater distance from the microphone array.

2 ACOUSTIC HOLOGRAPHY

The acoustic holography is based on the Fourier integral transformation. However, in reality a numerical approach e.g. the discrete Fourier transformation is used, because the extension of the array is limited and a sampling about the microphone positions is needed.

The theoretical approach is given by

$$\hat{p}\left(k_x, y, k_z, \omega\right) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p\left(x, y, z, t\right) e^{-j\left(k_x x + k_z z + \omega t\right)} dx\, dz\, dt \,. \tag{1}$$

The wavenumbers k_x, k_y and k_z belong to the orthogonal coordinates x, y, z and the angular frequency ω is related to the time t. The wavenumber k is split up to the components k_x, k_y and k_z. Due to the Helmholtz equation, the wavenumber is also coupled to the angular frequency ω and the wavespeed c:

$$k^2 = k_x^2 + k_y^2 + k_z^2 = \frac{\omega^2}{c^2} \,. \tag{2}$$

A reordering of the equation allows determining the unknown wavenumber k_y:

$$k_y = \pm\sqrt{\frac{\omega^2}{c^2} - k_x^2 - k_z^2} \,. \tag{3}$$

The sign can be determined from the direction from which the wave propagate to the microphone array. If the waves propagate from the positive half-space to the negative half-space and ω is larger than zero the positive sign has to be used. The knowledge of the wavenumber k_y can be sued to project the sound field from the known distribution at the plane of the microphone array ($y = 0$) into the depth:

$$\hat{p}\left(k_x, y, k_z, \omega\right) = \hat{p}\left(k_x, y = 0, k_z, \omega\right) e^{+jk_y y} \,. \tag{4}$$

From the pressure distribution, it is possible to derive the velocity distribution:

$$\begin{aligned}
\hat{u}_x\left(k_x, y, k_z, \omega\right) &= \frac{jk_x}{\rho\omega^2}\,\hat{p}\left(k_x, y, k_z, \omega\right) \\
\hat{u}_y\left(k_x, y, k_z, \omega\right) &= \frac{j\sqrt{\omega^2/c^2 - \left(k_x^2 + k_z^2\right)}}{\rho\omega^2}\,\hat{p}\left(k_x, y, k_z, \omega\right) . \\
\hat{u}_z\left(k_x, y, k_z, \omega\right) &= \frac{jk_z}{\rho\omega^2}\,\hat{p}\left(k_x, y, k_z, \omega\right)
\end{aligned} \tag{5}$$

The knowledge of the pressure and velocity allows to derive the sound intensity.

The last step is the inverse Fourier integral transformation of the desired quantities f. In normal cases, the spectrum is wanted. Therefore, the inverse transformation with respect to time is not needed:

$$\hat{f}\left(x,y,z,\omega\right)=\frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\hat{f}\left(k_x,y,k_z,\omega\right)e^{j\left(k_x x+k_z z\right)}dz\,dx\,. \tag{6}$$

3 MOVING SOURCE

The acoustic holography can be extended to a moving source that is moving in direction x with velocity v. The movement of the point source is given by a delta Dirac distribution $\delta(\ )$. The angular frequency of the moving source is Ω and the complex amplitude is A:

$$f\left(x,t\right)=A\,\delta\left(x-vt\right)e^{j\Omega t}\,. \tag{7}$$

The Fourier transformation in time and space gives:

$$\begin{aligned}
\tilde{f}\left(k_x,\omega\right)&=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}f\left(x,t\right)e^{-j\left(k_x x+\omega t\right)}dx\,dt\\
\tilde{f}\left(k_x,\omega\right)&=A\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\delta\left(x-vt\right)e^{-jk_x x}dx\,e^{-j\left(\omega-\Omega\right)t}dt\\
\tilde{f}\left(k_x,\omega\right)&=A\int_{-\infty}^{\infty}e^{-jk_x vt}\ e^{-j\left(\omega-\Omega\right)t}dt\\
\tilde{f}\left(k_x,\omega\right)&=A\int_{-\infty}^{\infty}e^{-j\left(\omega-\Omega+k_x v\right)t}dt\\
\tilde{f}\left(k_x,\omega\right)&=A\int_{-\infty}^{\infty}e^{-j\varsigma t}dt\ \ ,\quad \zeta=\omega-\Omega+k_x v\\
\tilde{f}\left(k_x,\omega\right)&=2\pi A\delta\left(\zeta\right)=2\pi A\delta\left(\omega-\Omega+k_x v\right)
\end{aligned}\ . \tag{8}$$

The movement of the source leads to a shift in the wavenumber frequency domain.

$$\omega=\Omega-k_x v\,. \tag{9}$$

This linear transformation can be inverted. For the source localisation, the frequencies ω in the fixed system are measured and have to be converted to the moving system Ω:

$$\Omega=\omega+k_x v\,. \tag{10}$$

This conversion has to be applied before the inverse Fourier integral transformation with respect to the coordinate x is processed.

4 APPROXIMATIONS OF THE FOURIER INTEGRAL TRANSFORMATIONS

The Fourier integral transformation has to be approximated in three coordinates: t, x, z.
The used microphone array has a spacing of 0.1 m in both directions. 64 microphones lead to a grid of 8 x 8 microphones. Therefore, the total length is 0.7 m. A linear interpolation in the

wavenumber domain is used to virtually enlarge the size of the microphone array. The interpolation of the array is done by a factor of 10. The virtual size is in this way extended from -3.5 to 3.5 m in both directions x and z.

An alternative approach is the usage of the Filon method. In this approach, the modulation caused by the Fourier kernel is handled analytically and only the amplitudes are interpolated linear. This approach becomes instable for low modulations. In this region, a Simpson integration has to be used. The Filon method allows for arbitrary wavenumbers. Therefore, no interpolation in the spectrum is needed, just the grid is 10 times denser than in the discrete Fourier approach.

The transformation with respect to time is always the first step. A window length is chosen that allows the moving source to propagate from -4 to 4 m. A Hanning window is used to reduce leakage. In the time domain, the discrete Fourier transformation is always applied. The windows overlap by a factor of 4.

5 MEASUREMENTS AT TULLNERFELD

During the opening phase of the new railway from Vienna to St. Pölten measurements with a Railjet and ICE-S were processed. The speed range was from 100 km/h up to 230 km/h for the Railjet and up to 320 km/h for the ICE-S. Figure 1 shows the ground plan and Figure 2 the cross section of the measurement location. Most traffic was on the track 9 (Gleis 9) from right to left direction. The coordinate system is x-direction from right to left, z-direction to the ground and y-direction from the microphone array to the tracks.

The tests of the new procedure are taken from a pass-by of the ICE-S with 98 km/h on track 9 in the positive x-direction.

The microphone array consist of 8x8 Microphones numbered in the positive x-direction and the positive z-direction.

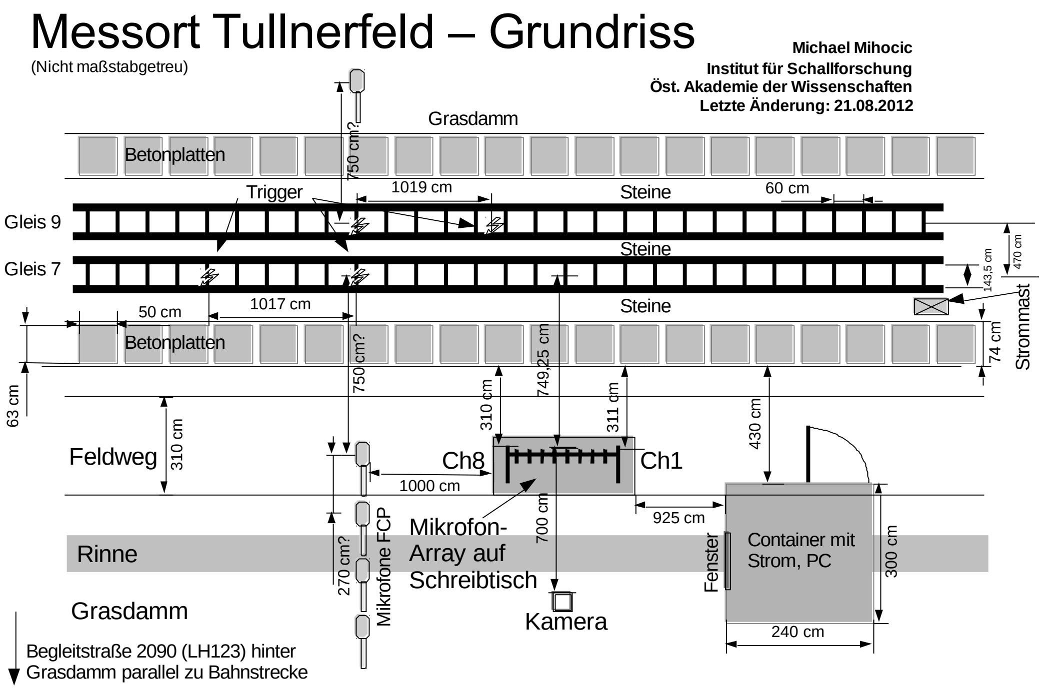

Fig. 1. Ground plan of the microphone array at Tullnerfeld.

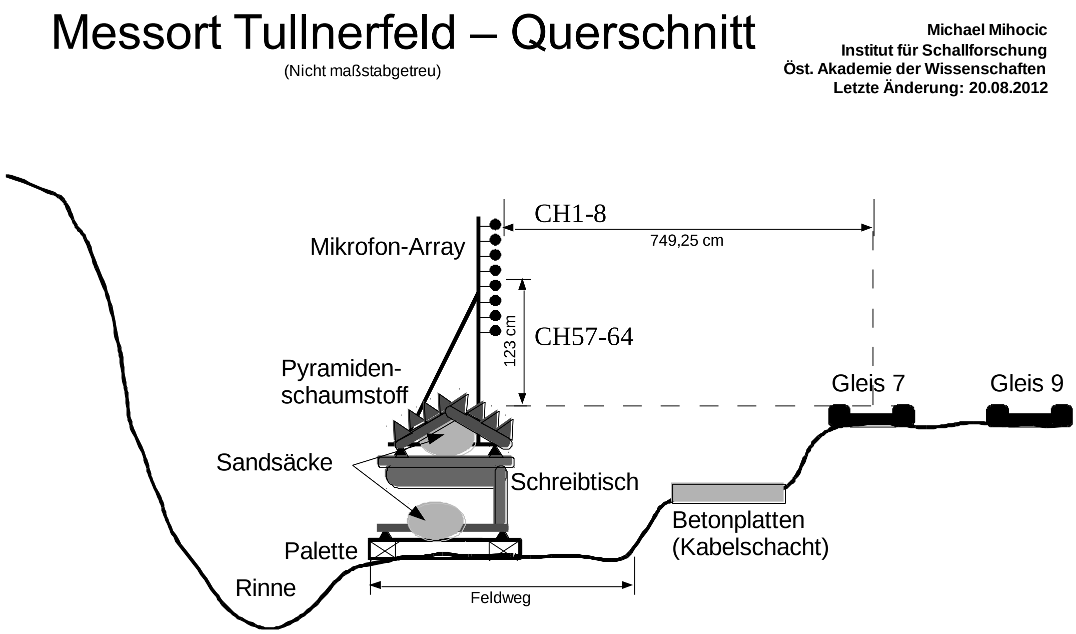

Fig. 2. Cross section of the microphone array at Tullnerfeld.

6 EVALUATION WITH THE ACOUSTIC HOLOGRAPHY

For the test of the procedure, one recording is selected with an ICE-S moving with 98 km/h.

Two methods are tested the first approach is based on the Fast Fourier Transformation (FFTPACK) and the second is based on the Filon method. Presented are in the Figures 3-10 the magnitudes in dB for a band pass filter from 500 Hz to 2000 Hz.

6.1 Results from the calculation using FFTPACK

The first approach was the application of FFT as an approximation of the Fourier integral transformation for the axes x and z. The calculation of the total sound file lasts one hour.

It becomes visible from Figure 3-6 that the main source is the rail wheel contact ($z=+1.2$ m). Also at higher values of z large amplitudes occur. This is the effect of the ground reflections. To take ground reflections into account a change from the acoustic holography method to the inverse 2.5D boundary element method is needed [2,3,4]. Additionally, a wraparound effect at a very low interpolated wavenumber becomes visible.

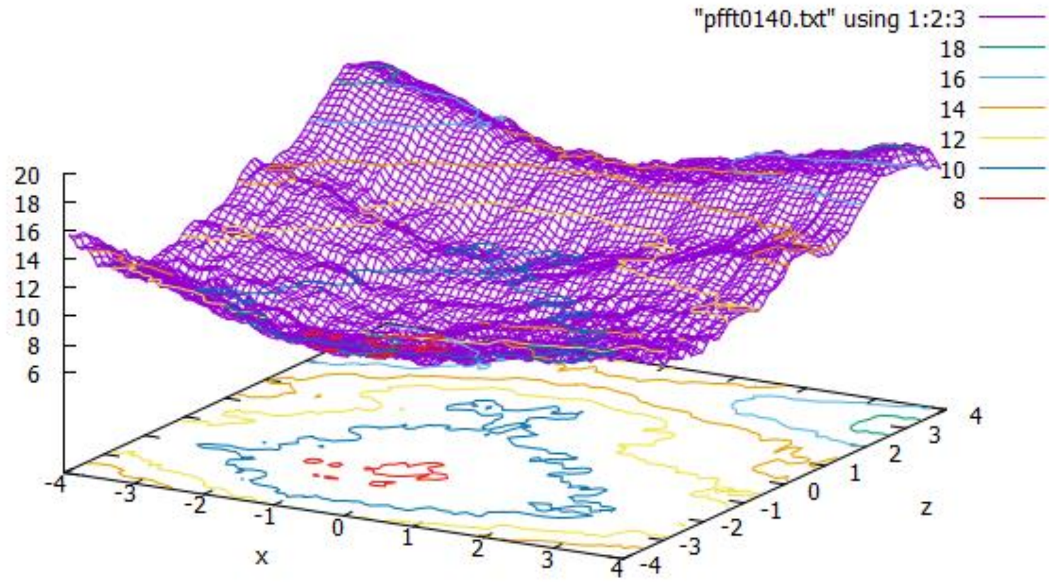

Fig. 3. Results of the holographic approach based on FFTPACK for the frame 140.

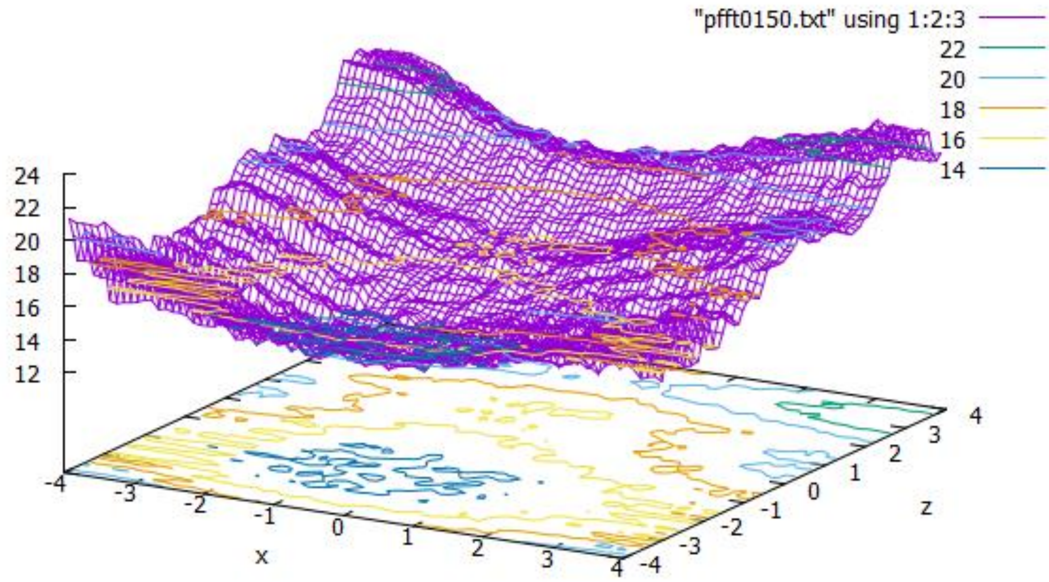

Fig. 4. Results of the holographic approach based on FFTPACK for the frame 150.

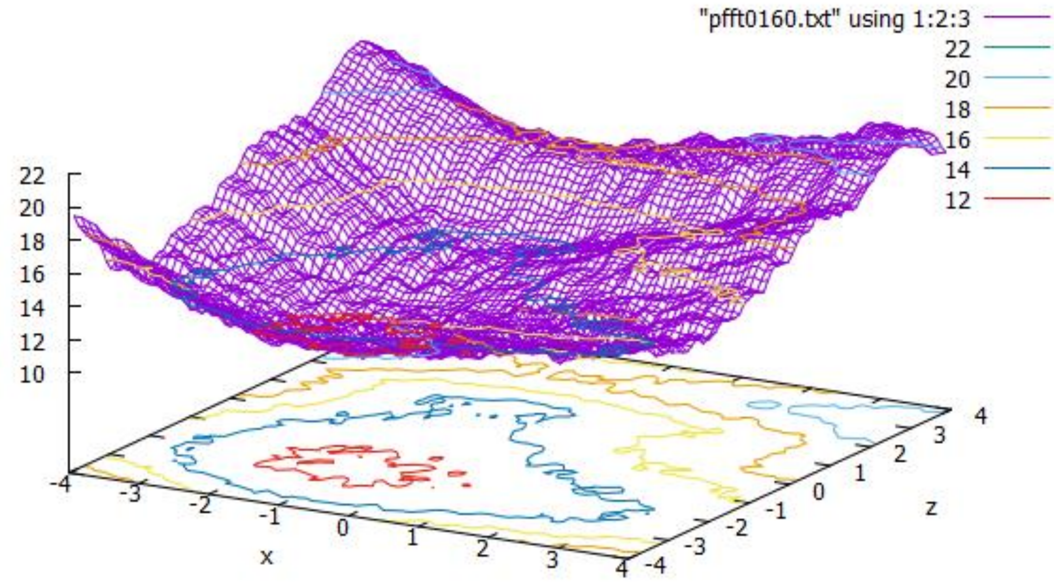

Fig. 5. Results of the holographic approach based on FFTPACK for the frame 160.

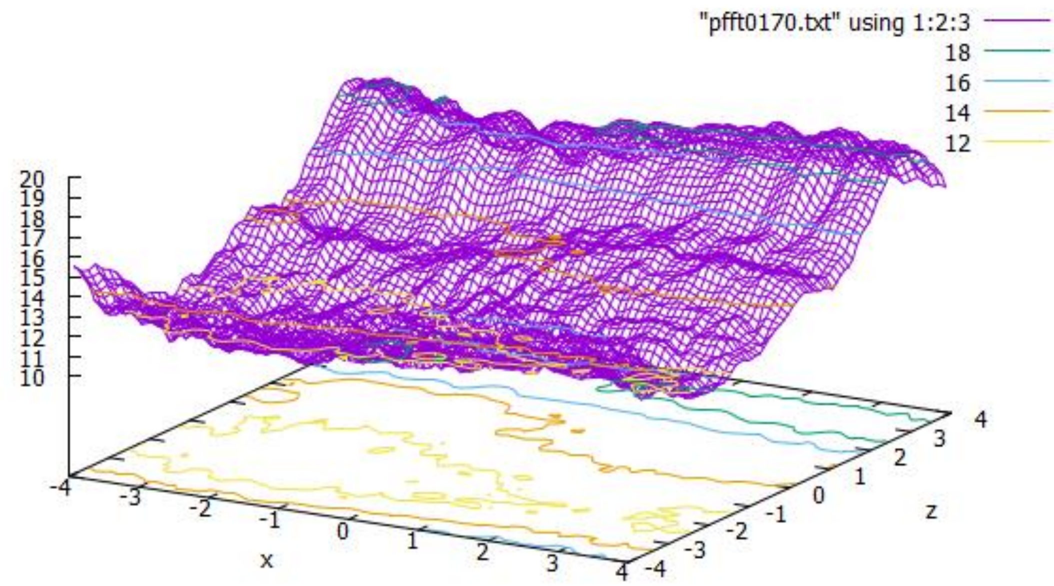

Fig. 6. Results of the holographic approach based on FFTPACK for the frame 170.

6.2 Results from a calculation based on the Filon method

The second approach was the usage of the Filon method as an approximation of the Fourier integral transformation for the axes x and z. The acoustic holography based on the Filon method needs two days of calculation time.

The results from the Filon method are difficult to interpret. The jumps near $x = 0$ are probably caused by the Filon method that leads to numerical problems around $x = 0$ and $k_x = 0$. The switching to the Simpson method for values less than *0.1* might be to late.

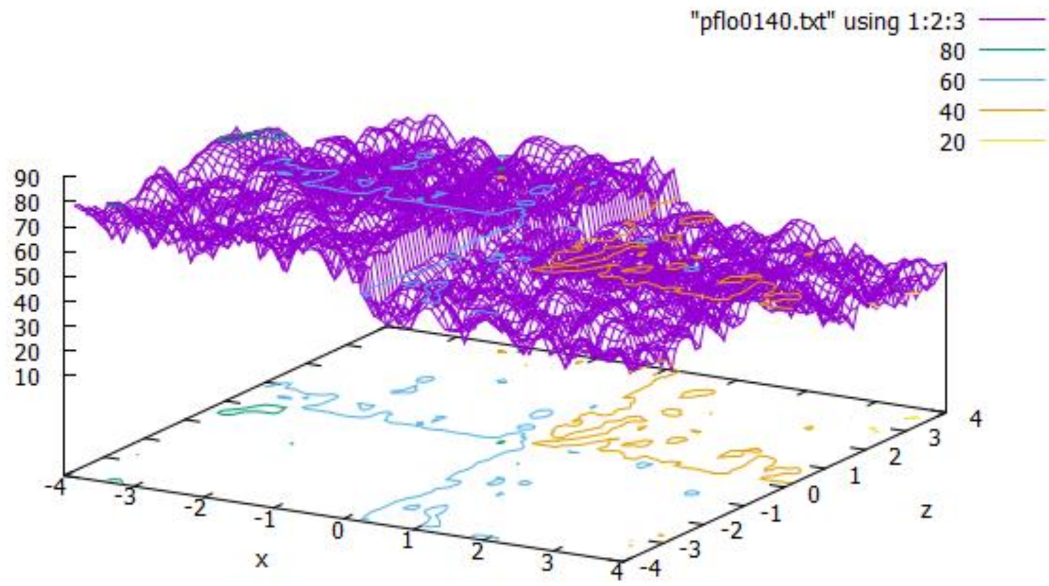

Fig. 7. Results of the holographic approach based on Filon Method for the frame 140.

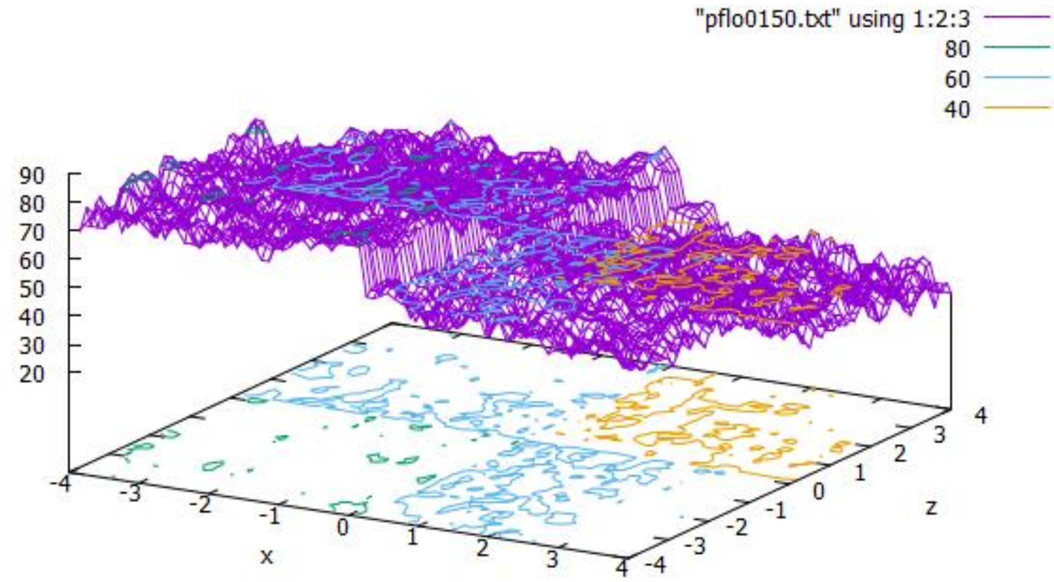

Fig. 8. Results of the holographic approach based on Filon Method for the frame 150.

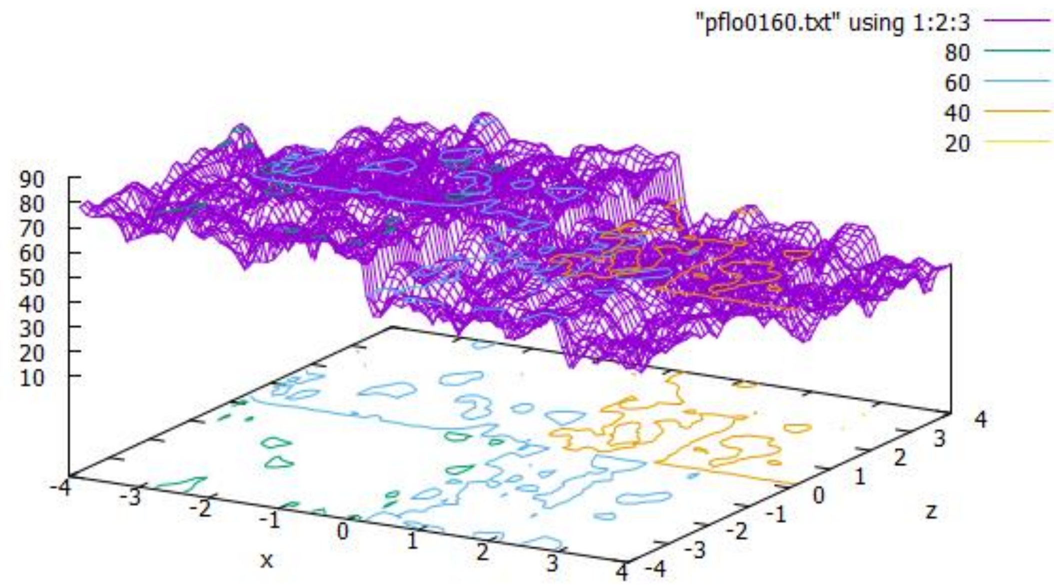

Fig. 9. Results of the holographic approach based on Filon Method for the frame 160.

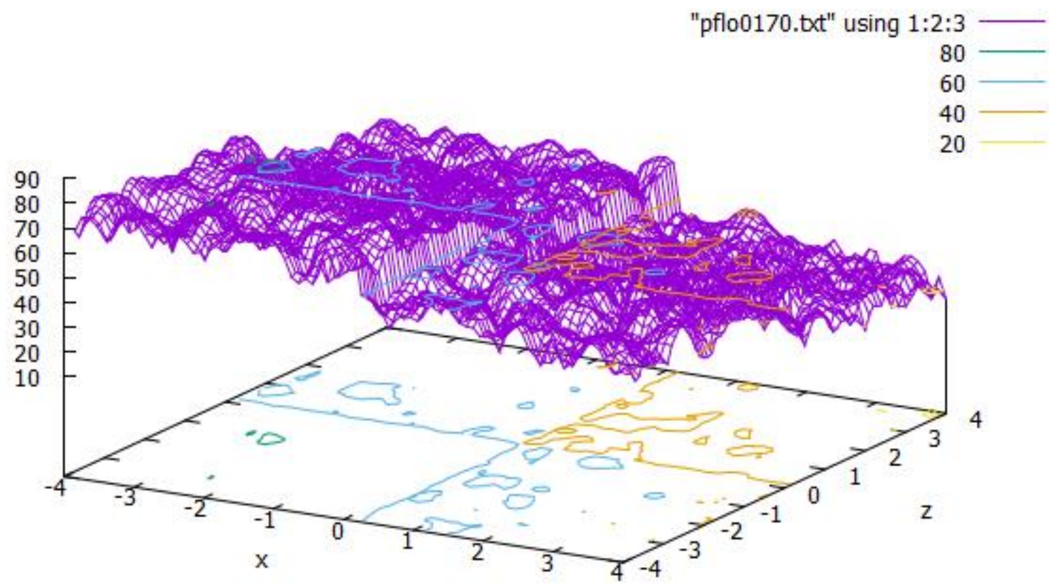

Fig. 10. Results of the holographic approach based on Filon Method for the frame 170.

7 CONCLUSIONS AND OUTLOOK

The advantage of the presented approach is the possibility to include the movement of the source into the proposed method by simple measures. However, reflections from the ground cannot be taken into account. This would be possible, if the holographic approach in the vertical direction is substituted by the 2.5D BEM with a moving source.

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