Synthesis of a moving virtual sound source applying the spectral division method

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Introduction

Sound field reproduction (SFR) is a state-of-the-art technique, aiming to physically reproduce an arbitrary sound field, most often the sound field, generated by a virtual sound source or a plane wave. To achieve this, a densely spaced loudspeaker array, termed as *secondary source distribution* is driven by a *driving function* derived either in spatial or spectral domain.

The sound field reproduction of the field of a stationary sound source is a well-developed research topic, having an extensive literature. Wave field synthesis (WFS) [1] and spectral division method (SDM) [2] are the two most prominent techniques when using a linear secondary source distribution. Besides the reproduction of stationary sources the synthesis of moving sound sources has gained an increasing interest, having a straightforward application in virtual reality systems or in cinemas. For moving sources the proper reconstruction of the Doppler effect is of primary importance. Early implementations simulated the source motion as a sequence of stationary positions, which approach ends up in a Doppler-like effect with several undesired artifacts [3, 4]. In recent studies efforts were made to give analytically correct driving functions by incorporating the dynamics of a uniformly moving point source [2]. However, for linear secondary source distribution a mathematically inconsistent solution is presented by applying frequency-domain approximations in the time-domain.

In the present contribution analytically correct driving functions are given for both WFS and SDM to synthesize the sound field of a point source, traveling uniformly parallel to the secondary source distribution, based on the spectral description of a moving source.

Synthesis of a moving point source

The arrangement, used during the research can be seen in figure 1. The secondary source distribution is a continuous distribution of acoustic point sources along an infinite line at $[x\,0\,0]^{\mathrm{T}}$. The virtual sound source is a point source, traveling with a uniform velocity v parallel to the secondary sources, located at $[x_s\,y_s\,0]^{\mathrm{T}}$ at the time origin, oscillating at ω_0.

The spatial solution to derive the driving function for the secondary sources is given by wave field synthesis, which relies on the 2.5-dimensional formulation of the Rayleigh-integral [5]. The Rayleigh-integral states that by driving a planar source distribution with the normal derivative of the desired sound field taken on the secondary source plane would ensure a perfect reconstruction in front of the plane. The integration can be carried out along the

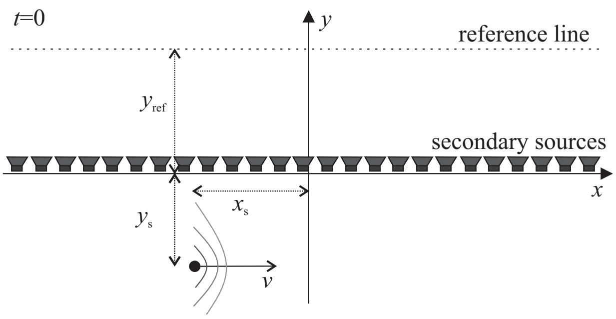

Figure 1: Arrangement used to synthesize the field of a moving point source

vertical dimension by employing the stationary phase approximation leading to a line integral, that explicitly contains the linear driving function. A further application of the stationary phase method is needed to ensure perfect synthesis on a line (instead of a point), parallel to the secondary source distribution, termed as the *reference line*.

The spectral solution utilizes the fact, that the radiated field of the secondary source distribution can be written as a convolution of the driving function and the field of an individual secondary source element on the reference line. The spectrum of the driving function can be therefore obtained as the ratio of the spectra of the desired sound field and the sound field of one secondary source element taken on the reference line. In both cases the secondary source elements are modeled as monopoles, described by the free-field Green's function.

For both techniques the starting point of the derivation is the spectral description of a moving sound source, which is well-known in the field of ground-bourne vibrations. For WFS after carrying out the procedure described above, as a final result one will obtain

$$Q_{\mathrm{WFS}}(x,\omega) = \frac{1}{v}\sqrt{\frac{y_{\mathrm{ref}}}{y_s + y_{\mathrm{ref}}}}\,\mathrm{e}^{-\hat{k}_t y_s - \mathrm{j}\hat{k}(x-x_s)}, \qquad (1)$$

with $k = \frac{\omega}{c}$, $\hat{k} = \frac{\omega-\omega_0}{v}$ and $\hat{k}_t = \sqrt{\hat{k}^2 - k^2}$.

For a source moving parallel to the secondary source distribution both the Fourier-transform of the desired sound field, and the inverse transform of the spectral ratio may be carried out analytically. The resulting driving function is given by

$$Q_{\mathrm{SDM}}(x,\omega) = \frac{1}{v}\frac{H_0^{(2)}\left(-\mathrm{j}\hat{k}_t(y_s + y_{\mathrm{ref}})\right)}{H_0^{(2)}\left(-\mathrm{j}\hat{k}_t y_{\mathrm{ref}}\right)}\mathrm{e}^{-\mathrm{j}\hat{k}(x-x_s)}. \qquad (2)$$

As the derivation for SDM employs no approximation this solution will ensure perfect synthesis on the reference line. Note, that by using the large argument exponential approximation for the Hankel-function the result would equal to the WFS solution, indicating that WFS is the far-field approximation of SDM.

Results

To validate the pertinence of the derived driving functions the synthesized field was compared with the field, generated by a moving point source, as it is described by the related literature [6]. In the present example a virtual point source is moving 2.5 m behind the secondary source distribution with a uniform velocity of 200 $\frac{\text{m}}{\text{s}}$, oscillating at $f_0 = 100$ Hz, while the reference line is set to 6 m. The calculation was evaluated at the time origin.

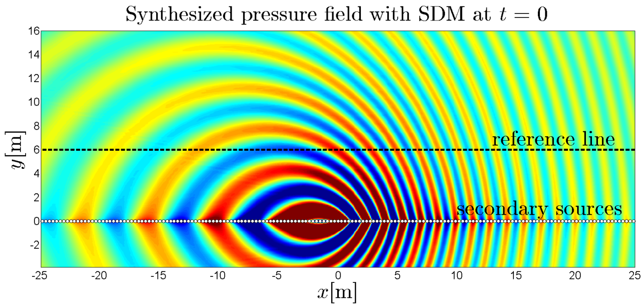

Figure 2: Synthesis of a moving source with SDM

Figure 2 shows the synthesized pressure field by employing the SDM driving function, while figure 3 shows a comparison on the result for WFS and the pressure field of a real moving source measured along the reference line. It can be seen, that not only SDM, but WFS also ensures perfect synthesis on the reference line, meaning that sufficiently far from the secondary source distribution the large argument approximation applied to the SDM solution will not have any significant effect and the result of the two methods can be considered to be equal. Naturally, in other parts of the synthesis plane amplitude errors will be present.

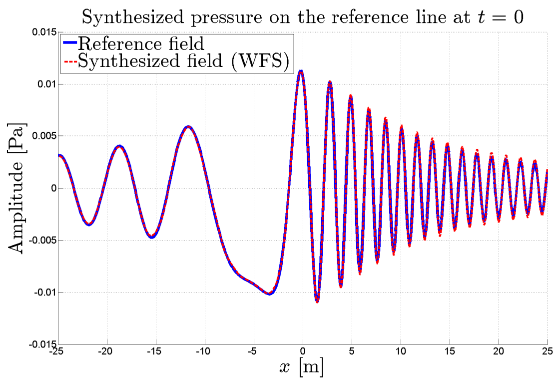

Figure 3: Synthesis of a moving source with SDM

For transient source signals no general formulation was found. In order to calculate the spectrum of the driving function for such a source, the spectrum of the driving function has to be calculated for each ω_0 frequency bin, weighted by the corresponding spectral coefficient of the input signal and summed. In figure 4 snapshots of the transient sound field of a traveling source is shown, emitting a Gaussian-pulse at the time origin.

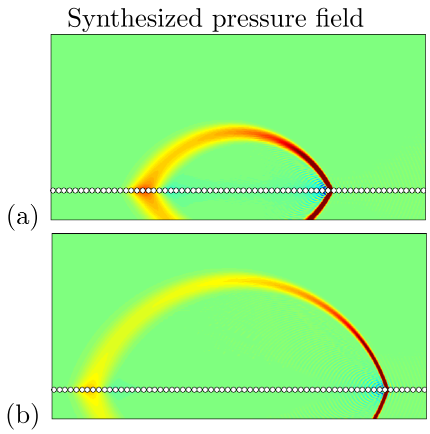

Figure 4: Synthesizing moving source with a Gaussian-pulse excitation at (a) $t = 680\mu$s and (b) $t = 1$ms

Conclusion

In the present paper we presented a novel approach to synthesize uniformly moving sources based on the spectral description of moving sources overcoming the limitations of the previous solutions. Here only sources moving parallel to the secondary source distribution were considered, however both WFS and SDM can be extended to synthesize sources moving at arbitrary direction. So far only ideal, continuous infinite secondary source distribution was assumed. However both discretization and truncation may have serious artifacts on the radiated sound field. The investigation of these effects compared with the case of synthesizing stationary sources is a topic of future research. Also for sources with arbitrary time-domain excitation the presented method is yet computationally expensive, thus the feasibility of efficient implementation is also up to be investigated.

References

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