Tailored Green's function beamforming in numerical data

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Abstract

In order to locate more physical sources, the tailored Green's function is used as a steering vector for beamforming in numerical data. Using the tailored Green's function as a steering vector allowed for the correct localisation and power estimation of sources which were not in a free field environment. Two examples are presented, firstly a simple configuration with an analytical source and an acoustically hard body, to show the capability of this method. The method is then applied to a side mirror of a passenger vehicle in order to locate surface sources, with the acoustic sources being computed with an unsteady computational fluid dynamics (CFD) simulation. The tailored Green's function is calculated numerically with the boundary element method (BEM).

Introduction

Aeroacoustic noise is becoming ever more important in the automotive industry with the increasing expectations of comfort in passenger vehicles, the more prevalent incorporation of electric drive systems in production vehicles, and the desire to reduce costs and vehicle weight. The main noise sources produced by passenger vehicles fall into three main categories, being; powertrain, rolling, and aerodynamic. The aerodynamic noise becomes the dominant source above approximately $30\,\mathrm{m\,s^{-1}}$. Compared to traditional combustion vehicles, electric drive vehicles have a considerably lower powertrain noise level, bringing the aeroacoustic noise further into focus at lower speeds.

The aerodynamic sound field inside the vehicle's cabin that the driver hears above approximately 800 Hz is prominently caused by aeroacoustic sources on the driver's side mirror [1]. These aeroacoustic sources are produced through pressure fluctuations on the mirror's surface, caused by the flow interacting with the mirror. The sources then radiate acoustic pressure waves from the mirror creating a fluctuating pressure loading on the window, leading to a bending wave excitation of the window [1]. The bending waves of the window then generate an acoustic field inside the cabin, which the driver perceives as sound. Even though the hydrodynamic pressure loading on the window has a much higher energy content, when compared to the acoustic, for the case of a typical passenger vehicle the hydrodynamic excitation of the window is of minor importance above circa 500-800 Hz and the interior sound pressure level (SPL) is dominated by the acoustic load [2].

In order to meet the aeroacoustic requirements for future vehicles the acoustic field inside the vehicle cabin needs to be reduced. The most attractive way of achieving this is to prevent the sources being produced in the first place through geometry alterations. However, in order to know where to change the geometry, the critical areas firstly need to be identified. This can be done through numerical beamforming.

Locating the aeroacoustic sources numerically is of great benefit, as it allows the developer to:

- Make informed decisions about geometry choices and changes early in the development process without wind tunnel tests and physical geometries.
- Develop an understanding of what types of geometries are aeroacoustically favourable and what other factors are crucial for a low noise level.

For automotive applications, beamforming is typically carried out in aeroacoustic wind tunnels looking for free field monopole sources, and it has provided valuable and reliable results. However, for side mirror noise, the sources are not of monopole type as there is no injection or extraction of mass into or out of the domain. Volume sources away from the mirror in its turbulent wake are also not expected, due to low Mach numbers of approximately $Ma \approx 0.1$. Surface sources are expected to be the major source type, due to the fluctuating forces exerted by the flow on the mirror, and these will be investigated in this work. In order to correctly locate a source's position and estimate its power using beamforming the assumed source radiation needs to match the physical source radiation. Where for side mirror noise, a free field source assumption is not valid as it is not a free field problem. Thus the tailored Green's function is required in order to determine the physical source radiation, as it contains the influence of any bodies.

Beamforming overview

The conventional beamformer is a straightforward beamforming technique. It is a frequency domain method, in which the powers A of the sources in the scan area $\boldsymbol{\xi}$ are estimated as follows, adapted from [3]. Firstly, the $N \times N$ cross-spectral-matrix (CSM) $C_{mn} = \langle p_m p_n^* \rangle$ of the N microphone pressure signals at $\boldsymbol{x}$ is determined, where m and n are the microphone indices, $*$ is the complex conjugation, and $\langle \cdot \rangle$ denotes the average of the sections. Then the $N \times 1$ steering vector g_m, which describes the pressure signals at the N microphones for an assumed source type at $\boldsymbol{\xi}$ is calculated. The source power can then be obtained through the minimisation of the error between the measured and the assumed signal by minimising

$$F = \sum_{m,n} |C_{mn} - A g_m g_n^*|^2 \ . \tag{1}$$

The solution is

$$\tilde{A}_m = \frac{\sum_{m,n} g_m^* C_{mn} g_n}{\sum_{m,n} |g_m|^2 |g_n|^2} \ , \tag{2}$$

which can be reformulated to

$$\tilde{A}_m = \sum_{m,n} h_m^* C_{mn} h_n \ , \tag{3}$$

where $h_m = \dfrac{g_m}{\sum_m |g_m|^2}$ is the weighted steering vector. In this work, the free field and tailored Green's function will be used as steering vectors.

- Free field Green's function g_0.

$$g_0 = \frac{1}{4\pi r} e^{-ikr} \tag{4}$$

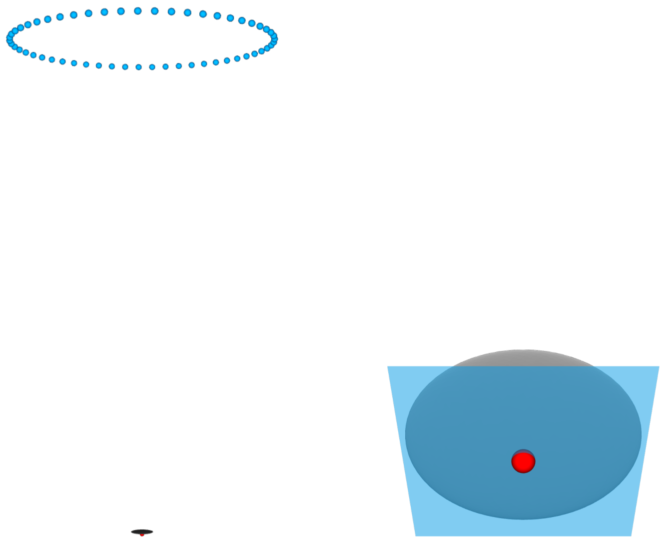
- Tailored Green's function g, determined with the boundary element method (BEM).

Results

Monopole shielded by an acoustically hard body

This example was chosen to highlight the errors that can result when using a free field steering vector for a non-free field problem. A monopole source is placed behind an acoustically hard scattering disc, shielding the source from the ring array's view, see Figure 1. The monopole has a given strength of 100 dB at the reference distance and the problem has a Helmholtz number of $He \approx 3$.

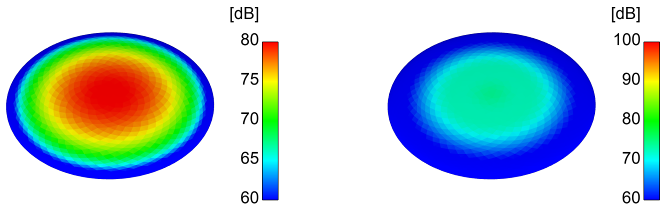
Beamforming was carried out with the free field and the tailored Green's function as steering vectors. Figure 2 shows the estimated source power maps on the top of the scattering object and on the scan plane intersecting the monopole's location for free field g_0 and tailored g Green's function steering vectors. It is seen that the free field Green's function underestimates the source power by approximately 20 dB at the source's location on the scan plane, and finds a source with approximately the same power on top of the scattering disc. However, when using the tailored Green's function the source power is estimated correctly at the source's position and no source is found on the top of the disc. Here the estimated source power is approximately 28 dB below the found source's level. This shows how beneficial it can be to use the



(a) Overview: A ring array above the scattering disc. The monopole is positioned below and close to the disc, 'out of sight' from the array.

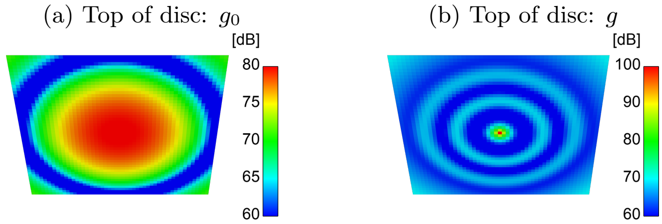
(b) Detail of underside: The scattering disc is shown with the monopole positioned below. A square scan plane is pictured intersecting the monopole, which is parallel to both the array and disc.

Figure 1: A monopole point source is placed below an acoustically hard disc, shielding the source from the ring array's view.



(a) Top of disc: g_0

(b) Top of disc: g



(c) Scan plane: g_0

(d) Scan plane: g

Figure 2: Source power maps on the top of the scattering disc and on the scan plane intersecting the monopole's location for free field Green's function g_0 and tailored Green's function g steering vectors.

tailored Green's function for non-free field problems, as large error's can arise when a free field assumption is made. Even through the available dynamic with the tailored Green's function steering vector is greater than for the free field steering vector, the point spread function (PSF) of the array still plays a role in the produced source map. Seen in the side lobe rings surrounding the source position in Figure 2(d).

Side mirror

Applying the beamformer to a passenger vehicle's side mirror allows for new knowledge about the corresponding aeroacoustic sources to be gained. For this, a highly spatially and temporally resolved unsteady incompressible CFD simulation of a generic test vehicle based on the SAE Type 4 body was carried out, see Figure 3. The sound was radiated from the mirror's surface through the convolution of the tailored Green's function G with the source term Q_p over the source region V (5), where the source region was taken as a small volume layer directly above the mirror's surface. As these volume sources are located just above the surface, their physical radiation corresponds to surface sources with a dipole type of radiation characteristic, due to their proximity and interaction with the surface.

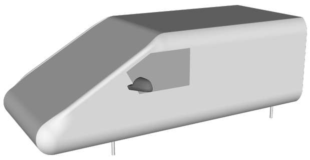


Figure 3: SAE body.

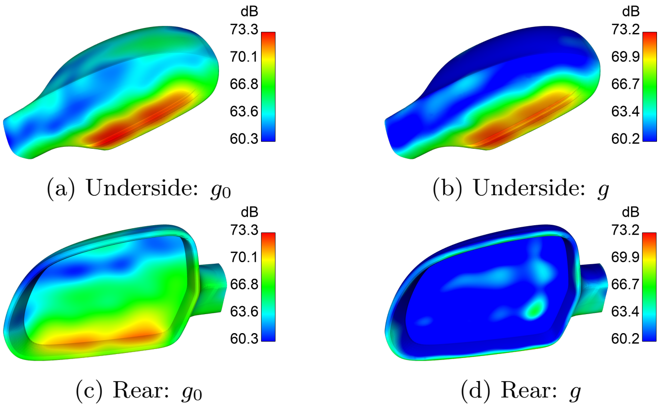
$$p(\boldsymbol{x},\omega) = \int_V G(\boldsymbol{x},\boldsymbol{\xi},\omega)\, Q_p(\boldsymbol{\xi},\omega)\, dV(\boldsymbol{\xi}) \tag{5}$$

The acoustic source term used was

$$Q_p = \frac{-1}{a_0^2}\frac{\partial^2 p_{inc}}{\partial t^2}\ , \tag{6}$$

where p_{inc} is the fluctuating incompressible pressure. This source term can be obtained from Lighthill's inhomogeneous wave equation [4] for pressure when neglecting changes in entropy and viscous friction stresses for an incompressible flow. The resulting source term $\frac{\partial^2 \rho v_i v_j}{\partial x_i \partial x_j}$ can then be substituted with $-\Delta p_{inc}$. Then decomposing the fluctuating pressure into incompressible and acoustic parts $p' = p_{inc} + p_a$ and applying elementary algebraic manipulation results in a wave equation for p_a with the source term (6) [5].

Beamforming was carried out with the free field and the tailored Green's function as steering vectors with Figure 4 showing the estimated source power for approximately 4300 Hz. Both beamforming steering vectors identified the forward facing step on the underside of the mirror as an acoustic source, with the free field Green's function correlating well with the tailored Green's function with a difference of approximately 0.1 dB. On the rear of the mirror the tailored Green's function did not find any noticeable sources, with the areas on the mirror's glass below approximately 65 dB thought to be a result of the array's PSF. The free field Green's function however found a powerful source region on the inside bottom edge of the mirror, which is thought to be unphysical, as there are only weak hydrodynamic pressure fluctuations in this region. It is most likely this region was falsely identified as a source because the beamformer can also place a source at this location, representing the physical source on the underside of the mirror, as the free field Green's function does not contain any information about the geometry.



(a) Underside: g_0 (b) Underside: g

(c) Rear: g_0 (d) Rear: g

Figure 4: Source power maps of the underside and rear of the mirror for free field Green's function g_0 and tailored Green's function g steering vectors.

Conclusion

The application of the tailored Green's function as a steering vector for beamforming in numerical data has been presented in order to find more physical acoustic sources. These results were compared to the free field Green's function steering vector. It was shown that the free field Green's function for non-free field problems can lead to large errors in the found source positions and power estimations, where the use of the tailored Green's function delivered the correct source positions and power estimations. Applying the method to a generic vehicle's side mirror, where the source terms were calculated with an unsteady CFD simulation, showed that the both steering vectors found the forward facing step on the underside of the mirror as an acoustic source. The free field steering vector however, estimated an unphysical source region on the rear of the mirror, which the tailored Green's function did not identify.

This work could be extended for the localisation of surface sources by comparing the tailored Green's function steering vector with a free field point force steering vector orientated in the surface normal direction, as a possible alternative approximation for the tailored Green's function.

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