Doctoral School on Engineering Sciences
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Extended summary

Acoustic Beamforming: innovative methods to overcome current limitations

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Abstract. Since its introduction acoustic beamforming has imposed itself as the principal technique for the mapping of acoustic sources in the far field. Even if some decades have passed since it was firstly used, important limitations still remain at the state of the art. In particular, the main shortcomings are relative to three aspects. The first one is the beamformer resolution capability, that strictly depends on the structure of the array, i.e. on the hardware available for the measurement. The second is the relative phase assessment amongst sources, that can not be achievable by the known state of the art techniques. The third is that the measurement background noise can be high and cover the phenomenon of interest, in particular in some applications as the aeroacoustic ones.

The aim of the present research is to introduce new methods to overcome the limits above. At first the technique called VAMOS (Virtualized Array for MOving Sources) is introduced and treated. It can be used in all those cases when the object under investigation is moving, such as pass–by or fly–over measurements. Once the measurement is performed, VAMOS exploits the object motion to virtually extend the array used for the acquisition: in this way the array aperture, i.e. its resolution, is increased in the direction of motion. Numerical validations, performances and uncertainty analysis are treated in the dissertation.

Secondly, the problem of relative phase assessment is treated. Two new techniques are described. The first one is the Phase Mapping by Monopole Substitution (PMMS). It constitutes a post–processing step to be performed after beamforming calculations to complete the obtained sound power beam- forming map with that of phase. The technique is presented with a complete uncertainty analysis and both numerical and experimental results. The second technique introduced is an inverse technique directly proceeding by Suzuki's L1 Generalized Inverse Beamforming. The map of sources relative phase is obtained by modeling the sound field with a orthonormal base of monopoles.

Finally, multi–sensor data integration is exploited to highlight and understand aeroacoustic noise generation mechanisms. In particular, the acoustic field due to a wind turbine will be analyzed by means of Coherent Beamforming: aeroacoustic contributions are separated by means of a reference signal sensitive to the other disturbing sources, such as mechanical ones. At the end, the acoustic field of a laminar separation bubble will be studied by means of beamforming and causality correlation approach.

Keywords. Aeroacoustics, Beamforming; microphone array; moving source; phase mapping.

1 Introduction

Sounds, be they natural or man–made, are used by animals and humans for different purposes; as instance to detect an incoming danger, to establish relationships or to relax and share emotions. However, in some cases sounds can be annoying, painful or polluting. They can even cause health problems such as hearing impairment, sleep perturbations, cardiovascular and mental health disturbances [1].
In these cases sound even changes its name to become noise. In this perspective, it is easy to understand why the attention to noise pollution is increasing more and more. In fact, noise emission characterizes almost every machinery built by men and used in every–day life. It is sufficient to think about transportation: from tyres and cars, to airplanes and trains, they all emits sounds perceived as disturbs.
The complete knowledge of the sound generation mechanisms, i.e. the complete characterization and localization of the acoustic sources is, thus, the first element needed to control and avoid the noise emission. In the last decades beamforming has imposed itself as the principal technique for the sound sources localization and identification. The work described in this thesis aims to over-come its main limitations, still present at the state of the art, by proposing innovative methods.

Practically the main limitations of acoustic beamforming can be resumed in the following points:

1. resolution, i.e. the capability of resolving two separate but close sources;
2. detection of relative phase amongst different sources, useful to obtain as instance information about the structural behaviour of the studied object;
3. separation of aeroacoustic contributes from the other noise generation mechanisms.

In this Thesis these aspects are treated and innovative methods to improve beamforming performances are introduced. The purpose of this dissertation is to improve the state of the art techniques to better and exhaustively reconstruct the sound field. This is achieved by following the Thesis rationale illustrated in Figure 1.

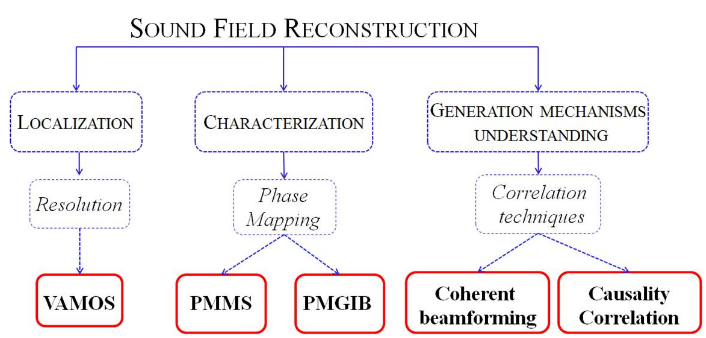


Figure 1. Thesis rationale.

2 High resolution technique for moving sources (VAMOS)

One of the most critical aspect of beamforming [**Errore. L'origine riferimento non è stata trovata.**, **Errore. L'origine riferimento non è stata trovata.**, **Errore. L'origine riferimento non è stata trovata.**] is the spatial resolution obtainable for results. It depends not only on the source wavelength, but also on the array geometry: it should be as larger as possible, but still maintaining a number of sensor high enough to assure good SNR levels. In addition, since its introduction, beamforming established itself as the leader technique for acoustic measurements on moving sources [**Errore. L'origine riferimento non è stata trovata.**, **Errore. L'origine riferimento non è stata trovata.**, **Errore. L'origine riferimento non è stata trovata.**], above all because of the measurement quickness.
The technique proposed in this Thesis is called VAMOS (Virtualized Array for Moving Sources) and has been developed to exploit the source movement so to virtually extend the array aperture, thus increasing the beamformer resolution.
The VAMOS technique is intended as a pre–processing step to be performed after beamforming measurements. By exploiting the de–dopplerization procedure and the Green's propagation, virtual time histories corresponding to virtual microphones along the source trajectory can be obtained and used in the beamforming calculation, with the rationale shown in Figure 2.

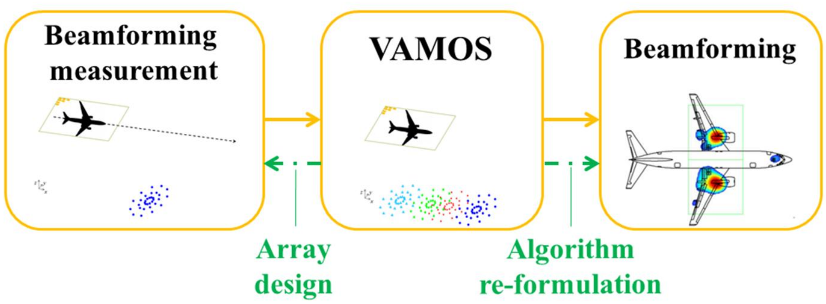


Figure 2. VAMOS as a pre-processing step in standard beamforming measurements.

The technique will be analyzed and validated by numerical simulations; performance analysis will be treated all along the dissertation. By the comparison with the standard state of the art techniques, VAMOS potentiality will be demonstrated, as its results are much more resolved and with higher SNR, as shown in Figure 3. This is confirmed also by the Type B standard uncertainty analysis performed: the technique uncertainty is quite low. On the whole, VAMOS is a powerful technique that actually helps when high resolution is needed.

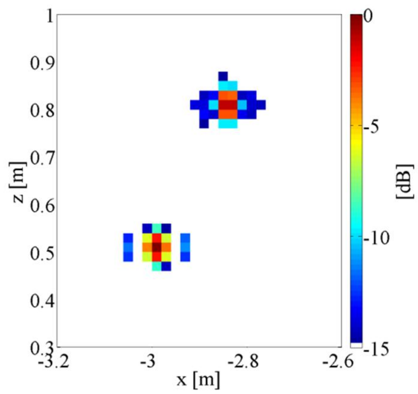


Figure 3. Conventional beamforming map obtained after VAMOS application: the array consisted only of 50 microphones aligned in the z direction.

3 Phase mapping techniques

The information of relative phase amongst the sound sources constituting the sound field is not achievable by state of the art beamforming methods. However, this information can be useful in several applications, such as sound behaviour understanding, echoes recognition or sound synthesis. In this Thesis two innovative methods to estimate the relative phases of sources are introduced.

3.1 Phase Mapping by Monopole Substitution (PMMS)

This method is based on the hypothesis, common to the most used formulation of beamforming, that the sound field can be represented by a set of individual monopoles: this does not restrict its applicability because its generalization to multipoles is straightforward.
The technique allows the obtainment not only of the strength of the principal sound sources, but also, and above all, of the phase delay amongst them.
This technique is intended as a post processing step to be applied after a beamforming calculation; Figure 4 shows the flow chart of PMMS method. It is based on a beamforming measurement, i.e. on a measurement performed by a microphone array. The principal, i.e. the most powerful, sound sources acting in the sound filed are at first localized by a beamforming algorithm. The source locations, together with power ratios, are the inputs of the technique, that then find the relative phase by iteratively solving an inverse problem. As final step, the relative phases of sources are plotted together with the beamforming map, to give a complete characterization of the sound field.

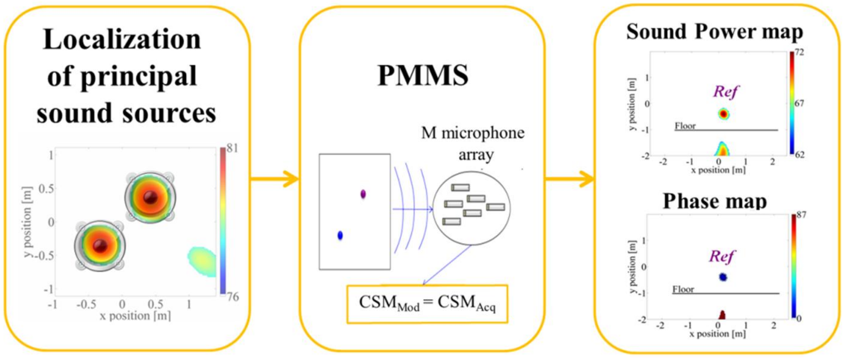


Figure 4. PMMS structure.

Both numerical and experimental validations will be treated in the Thesis. Simulations were performed by considering both un-disturbed and noisy conditions, always obtaining good results and low uncertainty. Experimental tests were also conducted, always obtaining good results. In particular, the case of mirror sources due to the presence of reflective surfaces, was considered as shown in Figure 5. As shown in Figure 6, the technique correctly estimates the relative phase between the actual source and its mirror, just equal to the phase shift due to the difference between direct and reflected propagation paths.

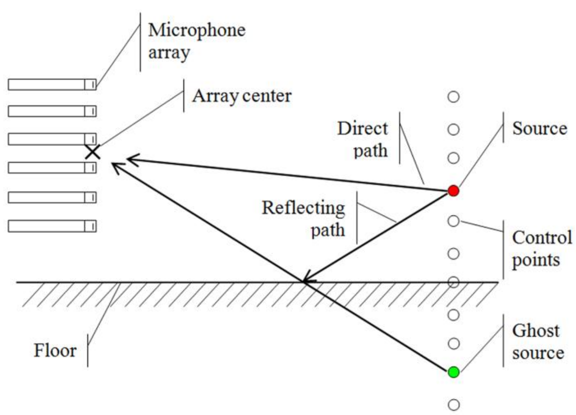
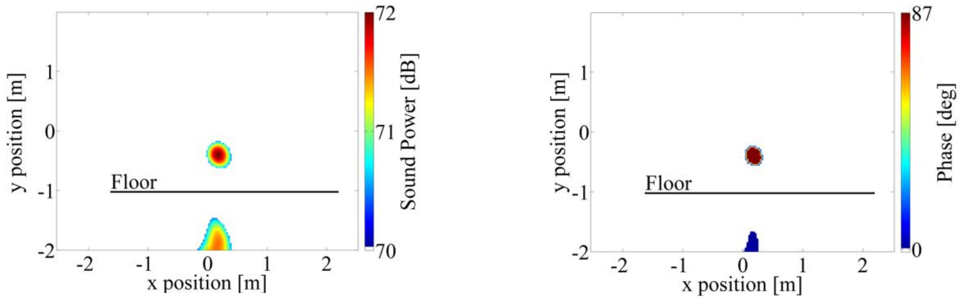


Figure 5. scheme of acoustic mirror experiment.



(a) (b)

Figure 6. Amplitude (a) and phase (b) maps relative to the mirror experiment.

A Type B approach was used to assess the uncertainty of the technique. A series of Monte Carlo simulations were performed to evaluate the sensitivity of PMMS to the most influencing parameters. In the worst case, uncertainty on the relative phase is of about 10°.

3.2 Phase Mapping through L1 Generalized Inverse Beamforming (PMGIB)

In 2011 Suzuki introduced the L1 Generalized Inverse Beamforming (GIB) algorithm [**Errore. L'origine riferimento non è stata trovata.**], able to successfully localize multipole sources regardless of the pole orientation and coherency. The method proposed and called Phase Mapping through L1 Generalized Inverse Beamforming (PMGIB), specializes GIB in order to obtain relative phases amongst sources. This is done by describing each point of the target domain (i.e. the sound field) through a couple of monopoles with orthogonal phases. By properly combining results obtained from PMGIB solution, also the sources relative phase information can be assessed. Both simulated and experimental results are reported in the thesis with good results.

4 .Multi-sensor data integration for aeroacoustic sources

In the last part of the Thesis the problem of better understanding aeroacoustic sound generation mechanisms is treated by means of multi-sensor data integration.

4.1 Coherent Beamforming

In particular, a technique called *Coherent beamforming* is at first presented and applied to filter out mechanical sources contribution from the wind turbine rotor noise emission. The measurement of hub vibration through a LDV used as reference signal in Coherent Beamforming allowed the identification of trailing edge sources on the blade as shown in Figure 7.

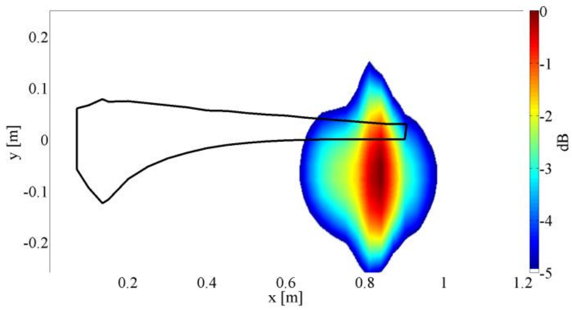


Figure 7. Coherent beamforming result in frequency range [9700–10000] Hz.

4.2 Aeroacoustic investigation of a laminar detachment on an airfoil

In the second part, both beamforming and causality correlation are described in their application for the detection of the noise emission due to a laminar separation bubble on a 2D HQ–41 airfoil.

Measurements have been performed in the wind tunnel facility of GroWiKa at the Technical University of Berlin. Several sensors were used to sample the fluid-dynamic and acoustic field. Practically:

- a 144 channel beamforming array (FFA) was employed to sample the acoustic far field;
- a 7 channel microphone array (NFA) was used to measure the acoustic near field downstream the airfoil;
- 22 MEMS surface hot wires array was mounted on the airfoil pressure side to measure the wall shear stress, so to identify and characterize the separation bubble.

Tests were repeated in several flow conditions. The acoustic signature of the LSB was obtained (Figure 8) and, by causality correlation, it has been possible to link the actual source position upstream of the LSB, as shown in Figure 9. Spatio-temporal evolution of correlation coefficients between the pressure signal of a microphone in the near field and the SHWs in the laminar detachment area. The blue line has a slope of −0.6 U_{∞}.Figure 9.

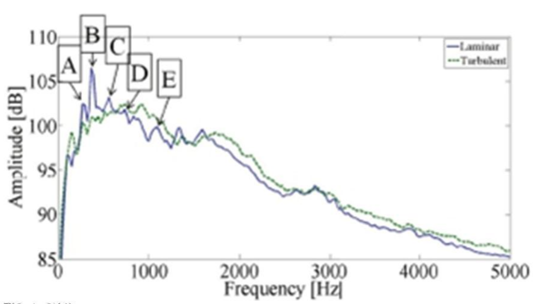


Figure 8. Spectra acquired in the laminar detachment (solid line) and turbulent detachment (dashed line) measurements.

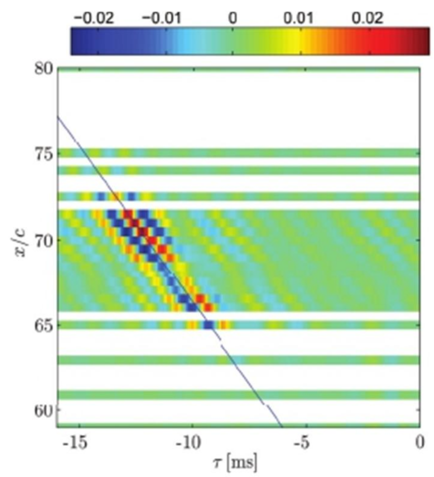


Figure 9. Spatio-temporal evolution of correlation coefficients between the pressure signal of a microphone in the near field and the SHWs in the laminar detachment area. The blue line has a slope of $-0.6\ U_{\infty}$.

5 Conclusions

In this Thesis new approaches to beamforming to overcome the state of the art limitations are presented.

Firstly, VAMOS technique is introduced as a pre–processing step. By exploiting the object motion, the aperture in the direction of motion is virtually obtained, thus the available hardware can be arranged properly to increase the resolution in all the space directions.

Secondly, the problem of relative phase mapping has been examined and two techniques have been proposed: the PMMS and the PMGIB methods. Both these methods represent an innovation in the state of the art technique, as no other technique is able to get the phase information.

Finally hybrid techniques have been presented in their application to aeroacoustic issues. They are based on the integration of data acquired by different kinds of sensors: in this way the same object is seen by different points of view. Basically, they refer to the case in which sound pressures acquired by microphone arrays are related to reference signals representative of structural or fluid–dynamic mechanisms that are thought to be the causes of the sound field measured. Reference signals can be, as in the presented applications, measures of vibration or fluid–dynamic quantities. At first, the coherent beamforming is presented and used to separate the aeroacoustic contribution of the sound field generated by a wind turbine rotor. Next, beamforming and causality correlation were applied to investigate the sound produced by a laminar separation bubble on a laminar airfoil.

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