MICROPHONE ARRAYS FOR COMPRESSED AIR LEAKAGE DETECTION

Petr Eret and Craig Meskell
Department of Mechanical and Manufacturing Engineering
Parsons Building, Trinity College Dublin, Ireland

ABSTRACT

Compressed air energy is expensive, but common in industrial manufacturing plant. However, up to 30% of the generated compressed air energy is lost due to leakage. Best practice requires ongoing leak detection and repair. Leak detection in the ultrasonic frequency range using hand held devices is possible only over short distances as associated high-frequency waves with do not propagate well. Pressurized air escaping to ambient also generates frequencies below 20kHz. In this paper, beamforming in the audible frequency range is tested as a tool for localization of compressed air leaks at larger distances. Both advanced time and frequency domain beamforming methods have been implemented in a variety of situations on a laboratory experimental rig with several open blows representing leakage in a noisy environment typical of a factory setting. The advanced time domain broadband beamformer gives clearer initial noise maps than narrowband frequency domain approach as the broadband nature of the leakage is better exploited. The advanced beamforming in frequency domain is more effective in spatial resolution. Based on these initial results it is concluded that the microphone array approach has the potential to be a robust leak identification tool.

1 INTRODUCTION

Compressed air is an expensive industrial utility. Over a long time period the associated operating energy costs are undoubtedly dominant part of the overall cost of a typical compressed air system. Nonetheless, compressed air is central to many manufacturing processes. It is used as a source of energy in pneumatic actuators, control valves and mainly in open blow applications such as fluidising, conveying, drying, cooling, purging, sealing and cleaning. The utilization of energy in the application side of compressed air system is poor in all situations, see for example Eret *et al*. [4]. Moreover, there is energy rejection in the form of heat during compressed air generation and energy loss from leakage in the rest of the system. The first means loss of a huge amount of low grade energy which is possibly recoverable, but the latter represents irreversible loss of the high quality energy with work potential. The overall simplified picture of the compressed air energy flows is shown for instance in Fig. 1 taken from Eret *et al*. [4]. Here one of the biggest consumers of compressed air is leakage, which accounts almost for 21% of the total generated compressed air and this result corresponds well with the best practices (20-30%) [8].

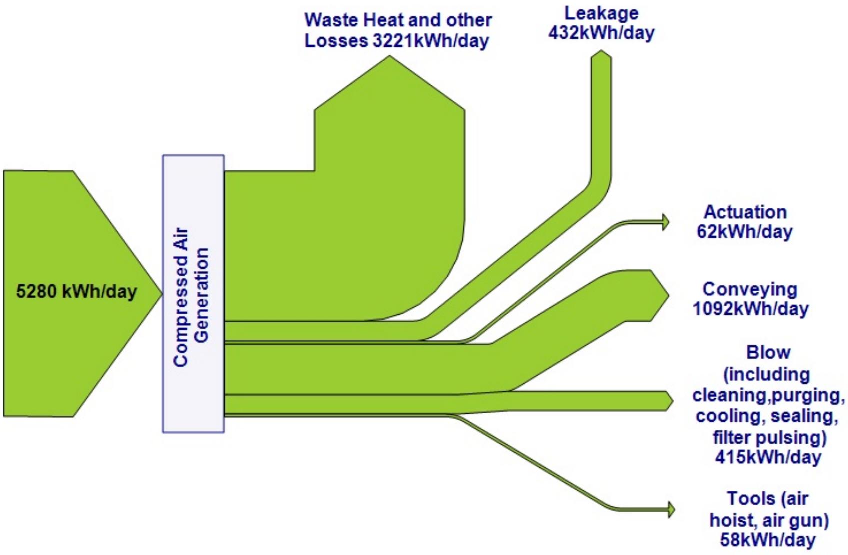

Figure 1: Example of compressed air energy flows, Eret et al. [4].

The air borne acoustics is important in the understanding compressed air leakage. Compressed air leaking to ambient atmosphere creates broadband noise in both audible and ultrasonic frequency range. The widely used tools for leakage localization in industrial compressed air systems are hand held ultrasonic sensors (usually operating around 40kHz). These instruments seem to be ineffective in noisy environments and must be operating at short distances, because high frequency waves do not have sufficient energy to propagate, see Wolstencroft and Neale [10]. As a result, a regular leak management programme is very unattractive and mostly missing on factory floors. The current study uses the concept of microphone array techniques operating in the audible frequency range (20Hz - 20kHz approx.) as an alternative compressed air leakage detection tool. The associated data processing methods (beamforming) are successfully applied in many aeroacoustic applications, where broadband noise sources are masked by larger ones and by undesired external noise. The objective of this work is to show the applicability of microphone array techniques to compressed air leak detection using a simple experimental rig with several open blows representing leaks in noisy environment.

2 APPLIED MICROPHONE ARRAY TECHNIQUES

Beamforming has become a standard method for creating spatial noise maps. The well known issues associated with beamforming such as undesired effects of sidelobes (image ghosts), poor resolution/contrast of the noise maps or weak sound sources masking have been gradually overcome by more advanced techniques, which will be used here for compressed air leak detection. In principle, beamforming can be performed in two computational domains - time or frequency.

The main advantage of the time domain approach is that it can directly deal with broadband signals and transients. However, this can be efficiently done by need of the higher sampling rates and processing of the huge amount of data. The drawbacks and benefits of beamforming in time domain are summarized by Jaeckel [6]. The simplicity of this approach is usually overlooked and only a few advanced techniques have been developed. Dougherty [3] presented modified "delay and sum" beamforming with diagonal deletion removing microphone self noise. This step leads to improvement of the contrast of the acoustic maps, but weak noise sources can be still masked by larger ones. Döbler and Schröder [2] introduced a simple technique to reveal uncorrelated weaker sources by subtractive signal decomposition. The principle is based on identification of the strongest source in the initial noise map. The reconstructed signal of the strongest source is sequentially translated by appropriate negative time delays and subtracted from all original microphone signals. The new map is calculated without the strongest signal and all related sidelobes. The technique cannot be used for removal of correlated sources, but suits well for separation of the broadband signals. Both advanced time domain techniques will be tested for compressed air leakage detection.

Beamforming in frequency domain is widely popular. This is caused by the fact, that advanced signal processing algorithms can be easily implemented. The crucial step is formation of cross spectral matrix and using deletion of the main diagonal it is possible to remove microphone self noise, which improves the resolution of noise maps by reducing levels of ghost images in beamformer output. By their fundamental frequency domain methods are mostly limited to processing narrow bands of frequencies and although several broadband approaches have been developed it is a common practice to apply these techniques for broadband signals provided a representative frequency range is chosen. The literature offers huge quantity of beamforming techniques in frequency domain from the simplest (conventional) beamforming to the very sophisticated approaches, so only selected methods are mentioned here. These are advanced deconvolution methods for mapping of acoustic sources, for example DAMAS [1] by Brooks and Humphreys has become a standard tool in aeroacoustic measurements. Another sophisticated deconvolution technique proposed by Sijtsma is CLEAN-SC [9], which can iteratively remove dominant sources from a noise map at the expense of relatively short additional computational time. Finally, Sarradj [7] has recently proposed very robust and fast technique for identification of uncorrelated noise sources. This orthogonal beamforming method bases on the eigenvalue decomposition of the cross spectral matrix and works in the signal modal subspace. The individual eigenvalues and eigenvectors of the signal subspace are linked to the noise sources. Beamforming in signal subspace resynthesized from those eigenvectors reveals the location of noise source while eigenvalues contain information about the strength of the source. Only the largest eigenvalues should be considered to get a number of potential sources. The technique offers a high resolution of the noise maps with identification of weak noise sources and will be used for compressed air leakage detection.

3 EXPERIMENTAL SETUP

3.1 Two open blows testing

A simple experiment has been carried out in order to verify correlation of two identical open blows of 4mm diameter at same pressure level as uncorrelated noise signals are easier to identify using all advanced beamforming techniques. Fig. 2 illustrates a simplified schematic of the test of the two open blows located half meter away from each other. The microphones are placed 10cm away from the open blow axis to avoid turbulence effect on signal reception. The signals are simultaneously sampled at 40kHz to cover full audible range (20Hz - 20kHz). The standard magnitude squared coherence between two signals is calculated by Welch's averaged, modified periodogram using periodic Hamming window method with 50% overlap for 100 consecutive blocks each with 4096 samples.

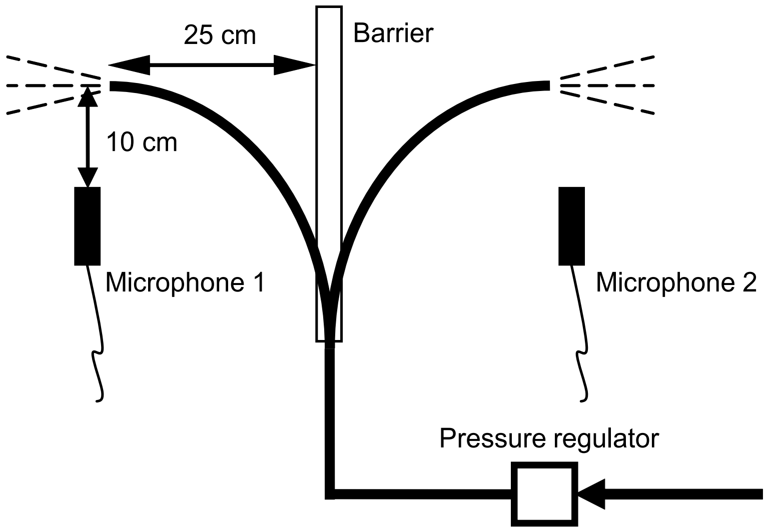

Figure 2: A schematic of two open blows test.

3.2 Microphone array for compressed air leak detection

A new microphone planar array with a small camera has been built for the core of the experimental work. The irregular pattern of 25 microphones has been used to avoid ghost images typical of a regular array. Fig. 3 shows the front view of the positions of the microphone over relatively small aperture designed for practical reasons. The signals from Senheiser electret microphones with 20Hz-20kHz band pass are amplified before simultaneously sampled using National Instrument data acquisition system. The instrumentation is similar to that used by Garcia-Pedroche and Bennett [5]. The data is stored on PC and processed using Matlab. The leaks are represented by small open tube blows connected to an already existing panel with several pneumatic components. The compressed air is supplied at pressure of 9 bar(a) approximately and reduced down to desired levels using pressure regulator. The whole experimental setup is located in the reverberant environment of running machines in the background, so

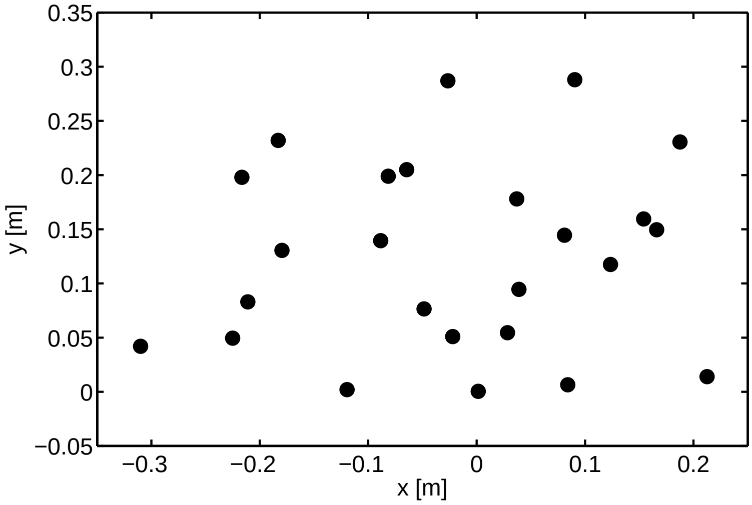

Figure 3: Array pattern

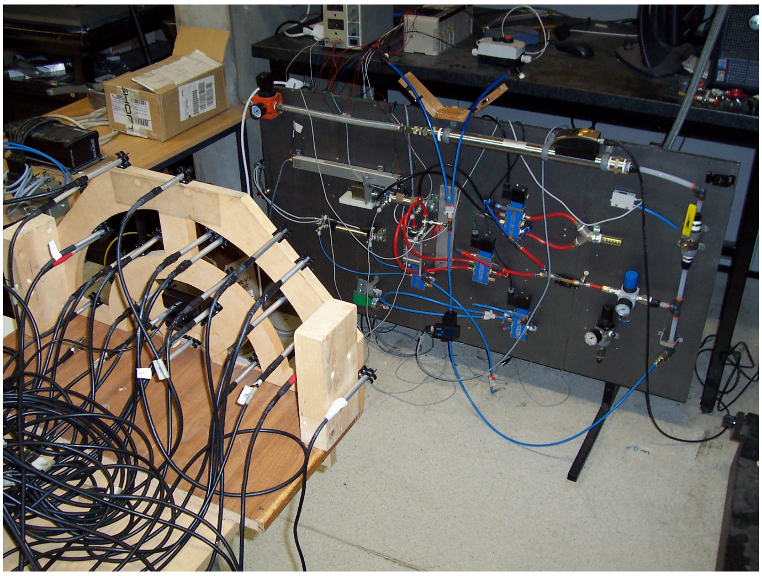

Figure 4: Experimental setup.

measurement conditions are similar to those of industry. Fig. 4 depicts position of the microphone array and the pneumatic panel under investigation, which is currently 1 m away from the sensors. The beamforming tests were carried out over scan plane of 0.4m x 0.4m with step resolution of 0.01m. Following the experience of Jaeckel [6] the sampling rate for the time domain beamforming was set high. Although it is recommended to use sampling rate of 192kHz to cover the audible frequency range, our system can operate up to 100kHz. The necessity of high sampling rate was compensated by small amount of data (1000 points) to provide fast calculations (in the order of seconds). The raw time signals have been high pass filtered (frequencies up to 2kHz removed) to reduce the effect of the background (running ventilators). However, there is a space for improvement of the time domain technique as only half of the suggested frequency rate is used; this would lead of course to finer noise maps. The sampling rate for frequency domain beamforming was set to 40kHz and time duration of the data acquisition was 0.5 second. The raw time data was band pass filtered (1kHz) with central band frequency of 15.5kHz, because beamforming at higher frequencies provides more accurate estimation of noise source location.

4 RESULTS

4.1 Two open blows testing

Fig. 5 shows averaged coherence spectra for selected system pressure levels with the frequency resolution of 10Hz. The background noise at zero gauge pressure captured by microphones is causing several high coherence intervals along frequency axis due to running of the machines (distinctive tonal sounds) in the test room, which can be seen from Fig. 5a. With increasing pressure the open blow noise is dominating over background noise and true character of the flow induced noise can be revealed, because coherence tends to be more flat (Fig. 5b). The constant low coherence at higher pressure levels (Fig. 5c) indicates, that the same compressed air open blows do not correlate in full frequency range. This fact can be also intuitively translated to compressed air leaks appearing at different pressure levels as will be clear from microphone array measurements mentioned later. The behavior is summarized in Fig. 6, where mean coherence over the investigated frequency range for each tested pressure level is shown. The result means that compressed air open blows representing leaks are satisfactory uncorrelated noise sources by nature and thus advanced beamforming techniques can be well utilized to distinguish between them.

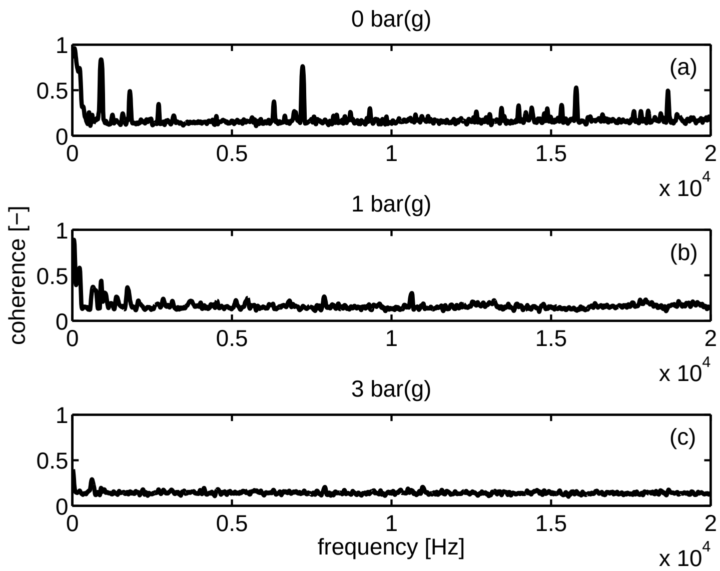

Figure 5: Coherence at various pressure levels.

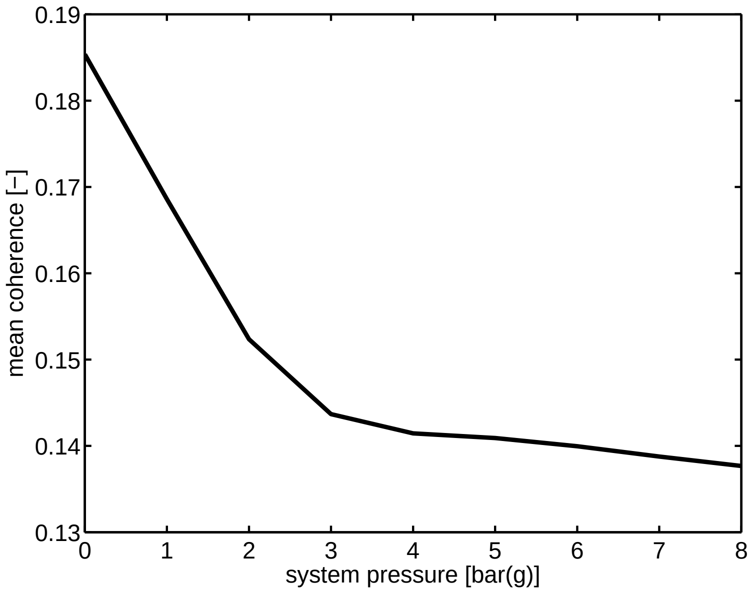

Figure 6: Mean coherence over audible frequency range at various pressure levels.

4.2 Microphone array for compressed air leak detection

Open blows near to each other at low pressure levels

Two closely located (6 cm vertical separation) open blows with small volumetric flow rates (10 and 12 Nl/min) have been tested. The flow rates have been measured by Festo SFAB and Testo 6442 flow meters. The static pressure of 1.05 bar(a) was measured before tubing bifurcation using a small SMC pressure transducer; pressure level at main pressure regulator is slightly higher due to the pressure drop. The open blows were blowing in the opposite directions; lower open blow downwards approximately 30 degrees off the vertical axis. For a human observer standing beside the microphone array these leaks were undetectable due to the overwhelming background noise. Still output from beamforming was satisfactory. Fig. 7 shows time domain beamforming with diagonal deletion for better image contrast. Similarly, the output from conventional beamforming in frequency domain with removal of microphone self noise is shown in Fig. 8. It is apparent, that time domain method gives better noise map as frequency domain beamformer is affected by sidelobes. However, signal decomposition failed in both cases even when one source has been relocated. At slightly higher pressure level of 1.1 bar(a) and flow rates of 15 and 18 Nl/min orthogonal beamforming starts to perform well in terms of the spatial resolution. Figures 9 and 10 show the first and second mode respectively. The peaks in the noise maps match well with the positions of the open blows. The spatial resolution of the advanced frequency domain method surpasses considerably time domain technique. At this point it should be noted, that the estimation of the leakage position is preferred to the generated sound pressure level and associated leakage flow rate. The experience revealed, that open blow with relatively small flow rate can generate more noise at the same pressure level than bigger one depending on the direction of the flow, inner geometry of the end piece and open blow surroundings.

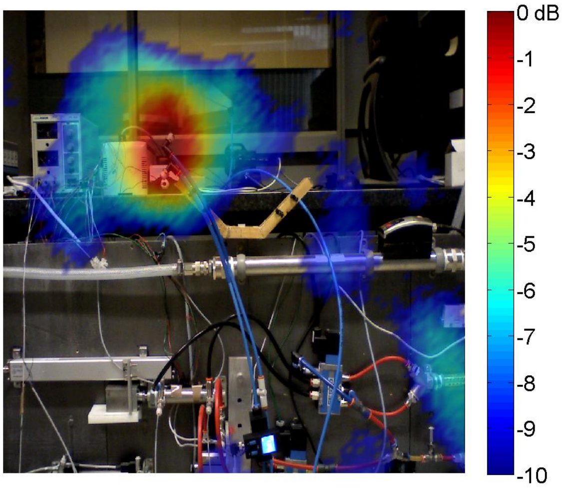

Figure 7: Time domain beamforming with diagonal deletion (2-20kHz): two close open blows at low pressure level.

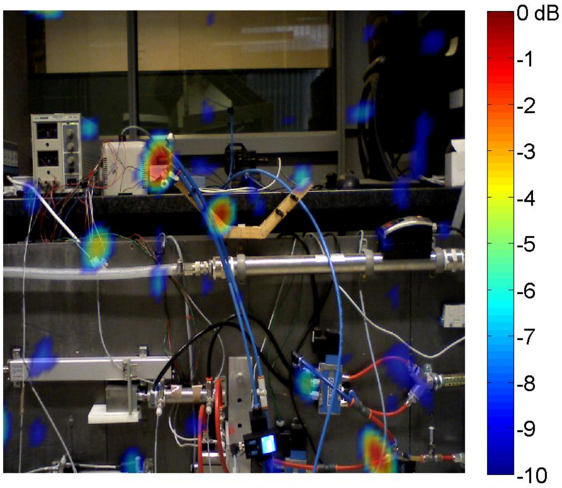

Figure 8: Frequency domain beamforming with diagonal deletion @15.5kHz: two close open blows at low pressure level.

Open blows at different positions

Fig. 11 shows noise map calculated from time domain beamforming for two locally distinct (35 cm apart) open blows at pressure of 1.3 bar(a). Now the signal subtraction is also possible in the time domain as shown in Fig. 12 after first iteration of the successive main source deletion. For the sake of interest the noise map is shown without diagonal deletion to demonstrate a poor

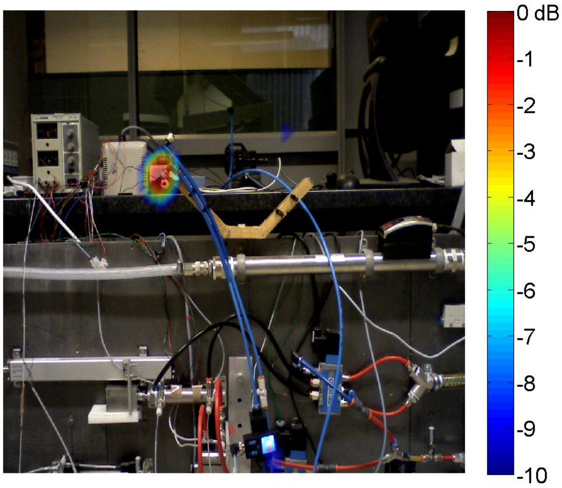

Figure 9: Orthogonal beamforming @15.5kHz: two close open blows at low pressure level, first mode.

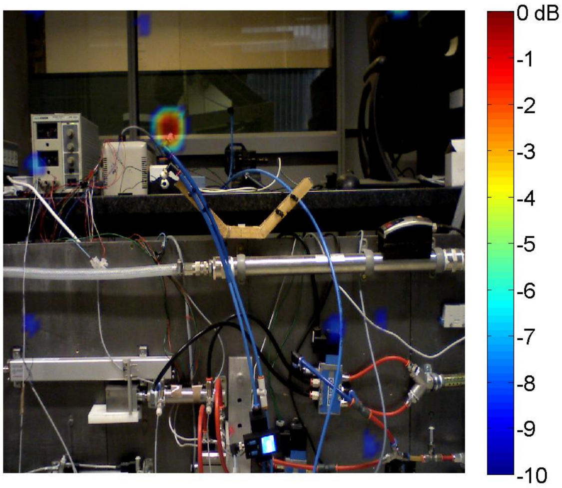

Figure 10: Orthogonal beamforming @15.5kHz: two close open blows at low pressure level, second mode.

contrast resolution. In general signal decomposition performs more effectively in the frequency domain approach due to the very robust eigenvalue decomposition. However, Fig. 13 depicts the same situation based on conventional beamforming and reveals drawback of the narrow band beamforming. The power intensities of the two sources are reversed, which would suggest, that weaker source is generating more energy in the frequency range under investigation than stronger one. When different frequency band pass is chosen for beamforming, then the noise map corresponds to the result from the time domain (not shown here). Nevertheless, estimations of noise source position are accurate in both cases, which is of importance.

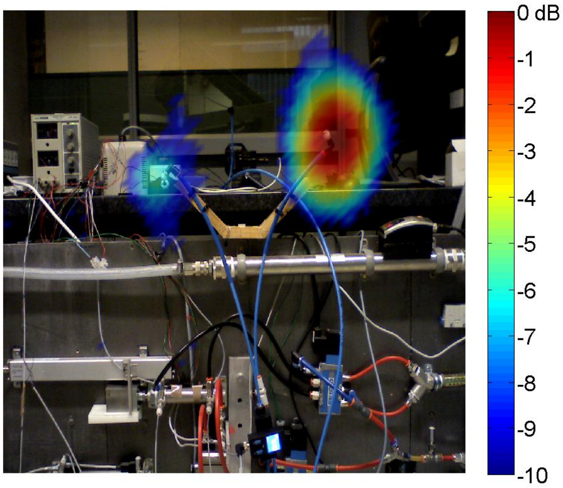

Figure 11: Time domain beamforming with diagonal deletion (2-20kHz): two open blows at higher pressure level.

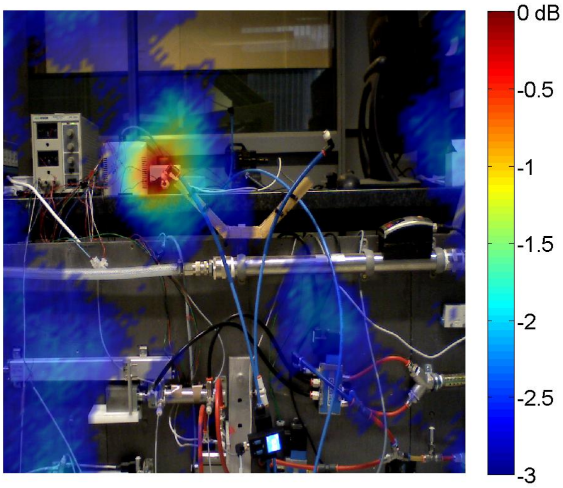

Figure 12: Time domain beamforming (2-20kHz): after successive deletion of the main source on the right.

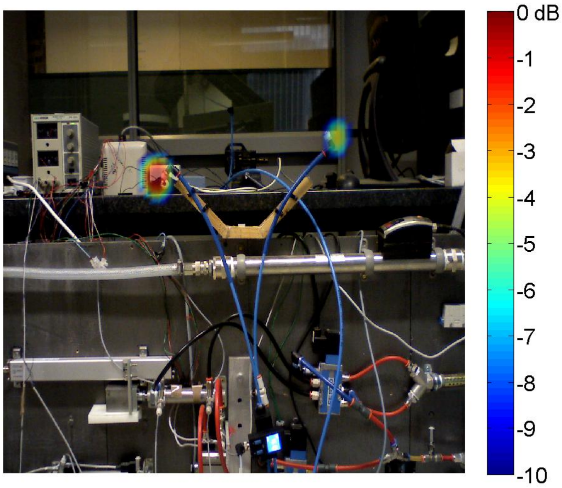

Figure 13: Frequency domain beamforming with diagonal deletion @15.5kHz: two open blows at higher pressure level.

Effect of the dominant noise source behind the scan plane

A situation with two open blows located in the scan plane (open blow on right is throttled) and a far away dominant source was investigated at measured pressure of 1.57 bar(a). A dominant open blow was placed 2 meters away from the microphone array (i.e. one meter behind the scan plane) close to the glass wall. The open blow was directed towards the wall in the angle of 30 degrees to excite reflections. For a human observer standing beside microphone array only this dominant source was obvious. Fig. 14 shows result from time domain beamforming with diagonal deletion. The locations of all three sources are clearly visible and no significant reflections on the glass wall can be seen. This can be attributed to the broadband character of the open blow as energy is dispersed in the large space. Fig. 15 shows noise map based on conventional beamforming with diagonal deletion. Despite of the better resolution of the map the ghost images are present and locations of the minor sources unclear as they are masked. The application of orthogonal beamforming offers a better picture on the leak locations. Figures 16, 17 show positions of the peaks of the second and third mode, which are fully corresponding with the locations of the open blows.

5 CONCLUSIONS

The microphone array technique has been used as a compressed air leak detection tool operating in the audible frequency range. The technique has been demonstrated on a laboratory experimental rig with several open blows representing leakage. Both advanced time and frequency domain beamforming methods have been implemented in a variety of situations. The time domain approach seems to perform better for generation of initial noise maps especially in a noisy environment, due to the fact that the broadband nature of the leakage is exploited. The narrow-

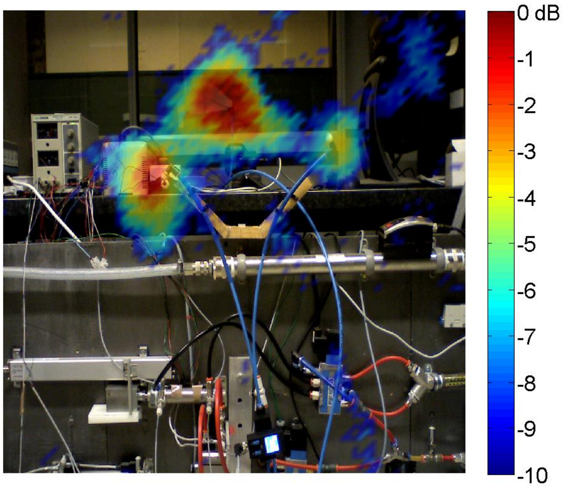

Figure 14: Time domain beamforming with diagonal deletion (2-20kHz): two open blows with dominant source in the behind.

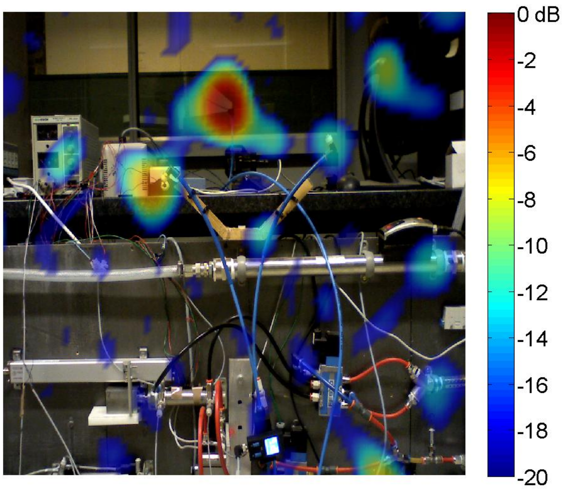

Figure 15: Frequency domain beamforming with diagonal deletion @15.5kHz: two open blows with dominant source in the behind.

band frequency domain orthogonal beamforming is more effective in signal decomposition and spatial resolution. However, performance of the time domain beamformer can be improved by higher sampling rates. The preliminary results have shown the applicability of the concept and suggest, that the microphone array approach has the potential to be robust leak identification tool.

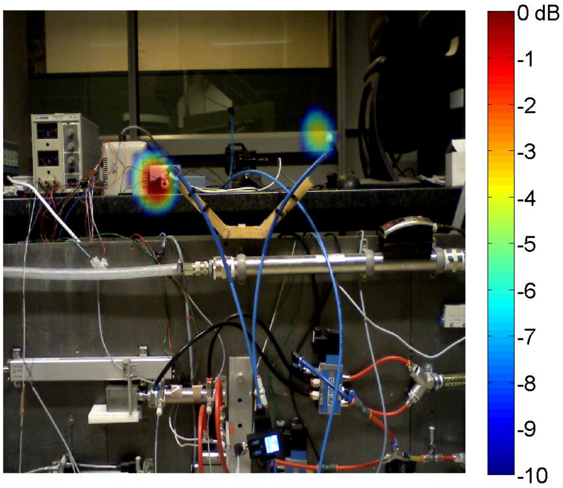

Figure 16: Orthogonal beamforming @15.5kHz: two open blows with dominant source in the behind, second mode.

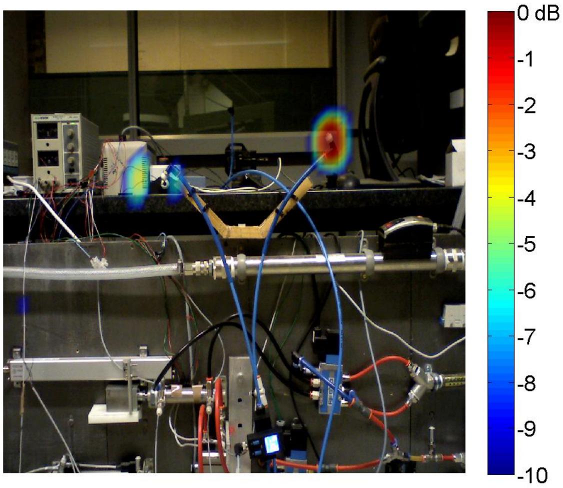

Figure 17: Orthogonal beamforming @15.5kHz: two open blows with dominant source in the behind, third mode.

6 ACKNOWLEDGMENTS

The research is cofunded by IRCSET and Intel. The authors are very grateful for financial support.

References

[1] T. F. Brooks and W. M. Humphreys, Jr. “A deconvolution approach for the mapping of acoustic sources (DAMAS) determined from phased microphone array.” *J. Sound Vib.*, 294(4-5), 856–879, 2006. doi:10.1016/j.jsv.2005.12.046.

[2] D. Döbler and R. Schröder. “Contrast improvement of acoustic maps by successive deletion of the main sources.” BeBeC-2010-19, 2010. URL `http://bebec.eu/Downloads/BeBeC2010/Papers/BeBeC-2010-19.pdf`, proceedings on CD of the 3rd Berlin Beamforming Conference, 24-25 February, 2010.

[3] R. P. Dougherty. “Advanced Time-domain Beamforming Techniques.” AIAA-2004-2955, 2004. 10th AIAA/CEAS Aeroacoustics Conference, Manchester, Great Britain, May 10-12, 2004.

[4] P. Eret, C. Harris, G. O’Donnell, and C. Meskell. “A practical approach to investigating energy consumption of industrial compressed air system.” *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 226(1), 28–36, 2012. doi:10.1177/0957650911423173.

[5] M. Garcia-Pedroche and G. J. Bennett. “Aeroacoustic noise source identification using irregularly sampled ldv measurements coupled with beamforming.”, 2011. 17th AIAA/CEAS Aeroacoustics Conference (32nd AIAA Aeroacoustics Conference), Portland, Oregon, USA, 6–8 June, (AIAA-2011-2719).

[6] O. Jaeckel. “Strengths and weaknesses of calculating beamforming in the time domain.” BeBeC-2006-02, 2006. URL `http://bebec.eu/Downloads/BeBeC2006/Papers/BeBeC-2006-02_Jaeckel.pdf`, proceedings on CD of the 1st Berlin Beamforming Conference, 22-23 November, 2006.

[7] E. Sarradj. “A fast signal subspace approach for the determination of absolute levels from phased microphone array measurements.” *J. Sound Vib.*, 329(9), 1553–1569, 2010. doi:10.1016/j.jsv.2009.11.009.

[8] SEI. “Compressed air technical guide.” Energy agreements programme - special working group on compressed air, Sustainable Energy Ireland, 2007.

[9] P. Sijtsma. “CLEAN based on spatial source coherence.” *Int. J. Aeroacoustics*, 6, 357–374, 2007.

[10] H. Wolstencroft and J. Neale. “Characterisation of compressed air leaks using airborne ultrasound.”, 2008. Proceedings of Acoustics 2008 (AAS’08), 24-26 November 2008, Geelong, Victoria, Australia.