NOISE SOURCE IDENTIFICATION USING MICROPHONE ARRAYS

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1 INTRODUCTION

Source localization using beamforming microphone arrays is now a standard measurement technique in the aircraft industry, where the measurements are used to provide information on sources of engine noise and airframe noise[1]. Applications include engine test beds, wind tunnel tests on airframe components and measurements on aircraft in flight, where the method has the significant advantage that it provides a means of source identification for the aircraft operating under representative aerodynamic conditions.

Although commercial microphone array systems are available for other applications[2], their use to date has been rather limited for typical engineering noise control problems, probably because there are cheaper and less involved measurement techniques available. This paper examines some of the advantages and disadvantages that could flow from the application of microphone arrays to the industrial noise problem.

2 THE BEAM FORMING METHOD

There are many types of multi-sensor source location methods, from simple binaural human hearing or two sensors sound intensity probes, through to near-field holographic methods and inverse source identification techniques. Of the methods available, beam forming is generally considered to be one of the simplest techniques to apply and interpret.

Given a wavefront incident on the microphone array, beamforming applies a frequency dependant phase correction to each microphone to correct for the propagation of the wavefronts from an assumed source location, figure 1. The correction could be based on an assumption of an incoming plane wave[2], or might be based on an assumed distance to a monopole source with spherical wave propagation[1].

The output of the beamformer is calculated from a summation over all channels, with the output being a maximum when the assumed location of the source coincides with the true source location.

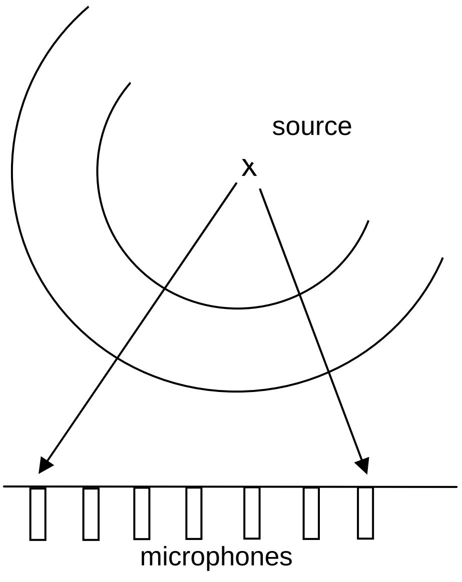


Figure 1 wave propagation from an assumed source location to the microphone array

For most of the data presented below the instrumentation and post processing was as follows:

- Data were digitised using a National Instruments PXI-4472 data acquisition system controlled by Labview. They are converted to engineering units using individual microphone sensitivity data, but no phase calibrations are applied.
- Time domain data are Fourier Transformed, and a matrix of cross-spectra between each pair of microphones is computed from

  $$C_{mn}(f)=\frac{1}{KW_s}\sum_{k=1}^{K}p^*_{m,k}(f)p_{n,k}(f)$$

  where K is the number of averages (200), W_s is the time window and * denotes complex conjugate; The CSM is optimised by replacing the diagonal with a column average.
- A grid of potential source points is defined in a scan plane, and a free-space Green's functions ***g*** for each microphone / grid point pair is defined, including the effect of flow if required.
- The array beamformer output power spectrum at each grid point is calculated using

  $$A=\frac{\mathbf{g}^T\mathbf{C}\mathbf{g}}{M^2}$$

  where M is the number of microphones and T denotes a Hermitian transpose matrix.
- For 1/3 octave band results calculations are made at a number of individual frequencies within each band and the average is computed.

2.1 1-D arrays

A linear microphone array is both easy to simulate and simple to build. The system shown in figure 1 comprises 24 electret microphones and was originally designed to be connected to a summing amplifier so that it could be used for manual source location, but can easily be connected to a data acquisition system so that beam forming software produces a noise map.

A simulation of the directivity of the array at 1kHz is plotted in figure 2, with the two plots being based on the two alternative assumptions about the shape of the wave fronts incident on the array, the first assuming that the distance is known so that the effect of spherical wave fronts can be included, the second assuming incident plane waves arriving from a distant source. Clearly, if the distance of the source is known then the resolution of the array is improved, but the fact that the plane wave assumption still gives good transverse resolution suggests that this array does not provide much useful information about the distance of the source from the array.

Although the electret microphones used here have some variability in amplitude and phase response, most microphones in a batch are reasonably well matched. This means that good directional characteristics for the array can be achieved with only an amplitude calibration, and variations in phase response (less than 10º phase error was typical) can be neglected. The larger the number of microphones the less important phase errors will be so that the cost of adding channels is controlled entirely by the data acquisition system.

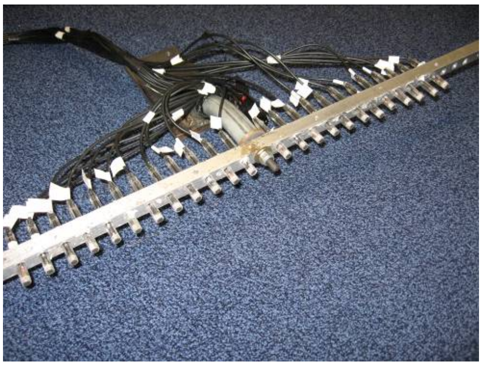
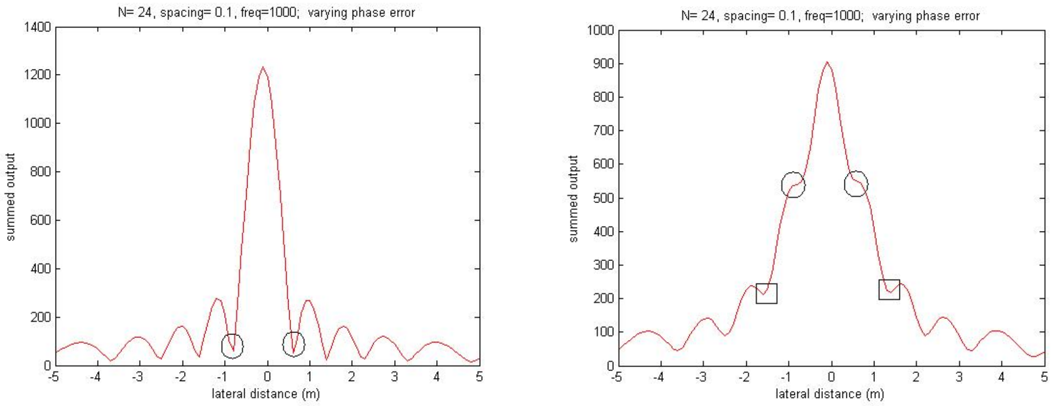


Figure 1 A simple linear microphone array

The spatial sensitivity of the array and the level and position of the side lobes is controlled by the microphone spacing and the total array length, and hence also the number of microphones. Ideally this would be optimised for particular applications.



(a) incident spherical wave

(b) incident plane wave

Figure 2. Directivity of a 1D linear array based on different assumed source distances

2.2 2-D arrays

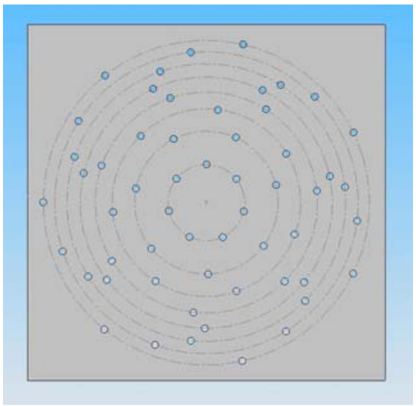


Figure 3 Distribution of 54 microphones in the UoS wind tunnel microphone array.

The hardware shown in figure 1 incorporated a swivel so that the array could be rotated through 90º, effectively giving the measurement characteristics of a cross shaped array when used to view a steady source of noise. This design was chosen for particular practical reasons, but for most applications requiring a 2D array the microphones would commonly be distributed on a multi-arm logarithmic spiral as shown in figure 3, a design that has much better suppression of the side lobes that so easily confuse the noise maps[1].

As for 1-D arrays, the spatial sensitivity of the beam is controlled by the diameter of the array and the spacing of the microphones

2.3 Arrays for other applications

For other applications, such as sound propagation in aero-engine intake ducts, there are a number of specialised array layouts that provide more information about the spatial characteristics of the sound field. Arrays for duct acoustic measurements on aero-engines may be wall mounted arrays, in which case they resolve the axial and azimuthal characteristics of the sound field and infer the radial modal content, or may be mounted outside the duct on a flow control screen which provides information about the circumferential and radial characteristics of the sound field directly[3].

3 RECENT APPLICATIONS IN AIRFRAME NOISE RESEARCH

There has been a long history of applying source location methods to engine noise[4], but in recent years there have been a number of EC funded research projects aimed at the control of airframe noise from the landing gears and high lift slats and flaps [5,6]. These sources combined are now one of the dominant noise sources for modern aircraft in the landing approach configuration.

3.1 Flyover measurements

Using an array to identify sources on an aircraft in flight is a complex operation, requiring the aircraft to glide down a particular flight path with engines at idle (generally a 5º glide slope to a position 150m overhead), with a laser tracking system monitoring exact position and speed at each moment through the measurement period. Besides the beamforming processing, the data may also be corrected for Doppler shift, deviations from the flight path, etc.

The quality of the images depends on many factors, some of which are controllable through careful testing, but others being less controllable. One factor which is inherently not controllable is the loss of coherence as the sound propagates through the atmosphere, which results in an apparent loss of energy. Another factor which affects the usefulness of the resulting noise maps is that the microphone array tends to pick out strong localized noise sources, such as the landing gears and slat side edges shown in figure 4, or tonal noise from cavities[7]. This reduces the apparent importance of lower level distributed sources, such as trailing edge noise, which may be just as important as they are extend over large areas.

Despite the difficulties, flyover tests do provide useful information that cannot be gathered in any other way, and microphone arrays are now part of the instrumentation armoury.

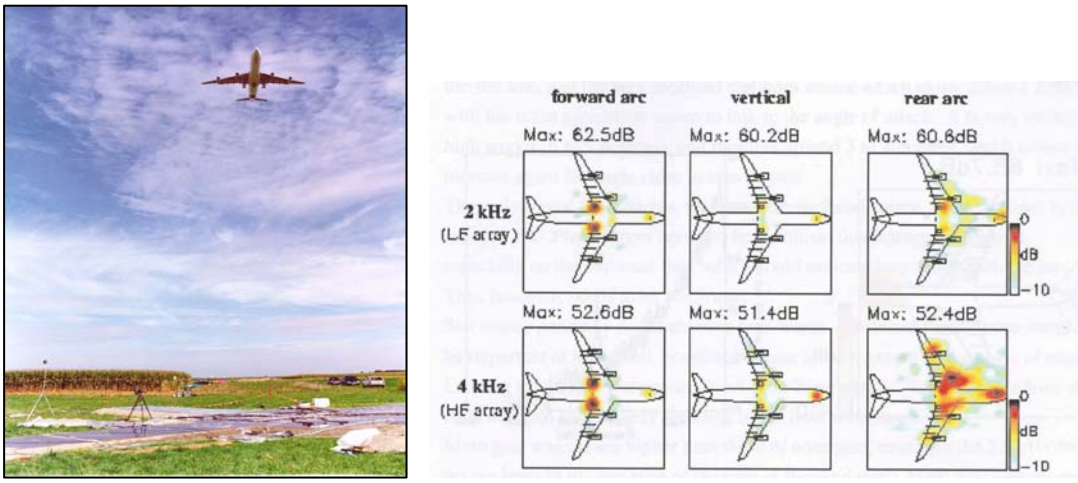


Figure 3 Measurement of airframe noise

3.2 Measurements in wind tunnels

Testing on full scale aircraft is expensive and all sources are present simultaneously, thus the research on particular aspects of the airframe noise problem was for a number of years carried out in open jet aero-acoustic wind tunnels, such as the DNW facility in the Netherlands that is capable of wind speeds up to 85m/s (190mph) over an 8m x 6m cross-sectional area.

Given the availability and cost of such facilities as the DNW however, microphone arrays are now used to enable testing in more easily available closed section aerodynamic wind tunnels, such as the 7' x 5' wind tunnel at Southampton University shown in figure 4 with a ¼ scale landing gear installed[8].

Compared with flyover measurements, this environment provides a more straightforward application of microphone array measurements. The tunnel itself is quite noisy but, with the beamformer focussed on the landing gear, noise propagating up the tunnel is suppressed. Also, although flow noise over the microphones themselves may be significant, the analysis method suppresses this as it is incoherent between the microphones. Figure 4b) shows for example the changing distribution of noise sources on the bogie of the landing gear as the bogie angle is changed.

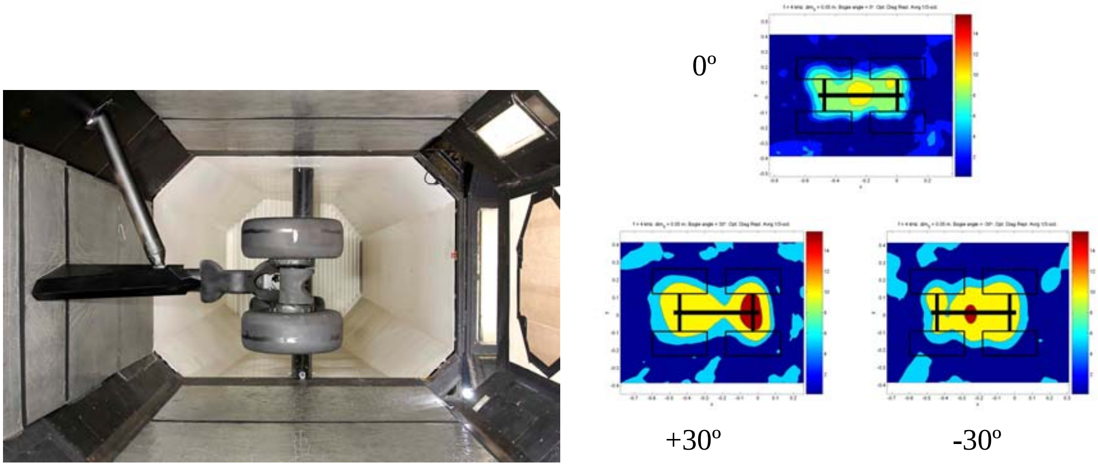


Figure 4 a) Model scale main landing gear installed in the Southampton University wind tunnel and aligned with the flow, also showing the microphone array installed behind the circular cloth screen on the right. b) distribution of noise sources on the landing gear bogie for three bogie angles.

4 APPLICATION TO ASSESSMENT OF INDUSTRIAL NOISE

Generally in any noise control problem, whether an industrial plant, a workshop or a single machine, correctly identifying the dominant sources of noise is crucial for the design of cost effective treatment. This section outlines some preliminary results from a current MSc project at ISVR aimed at assessing the suitability of beam forming methods for the industrial noise problem.

Although it is clear from section 2 that the choice of microphone array configuration should generally be guided by the nature of the measurements to be undertaken, the starting point for this project was the existing spiral array from the wind tunnel. Given the difficulty of plant noise measurements the project has also concentrated on the workshop and single machine problems.

4.1 Identification of noise sources on a machine

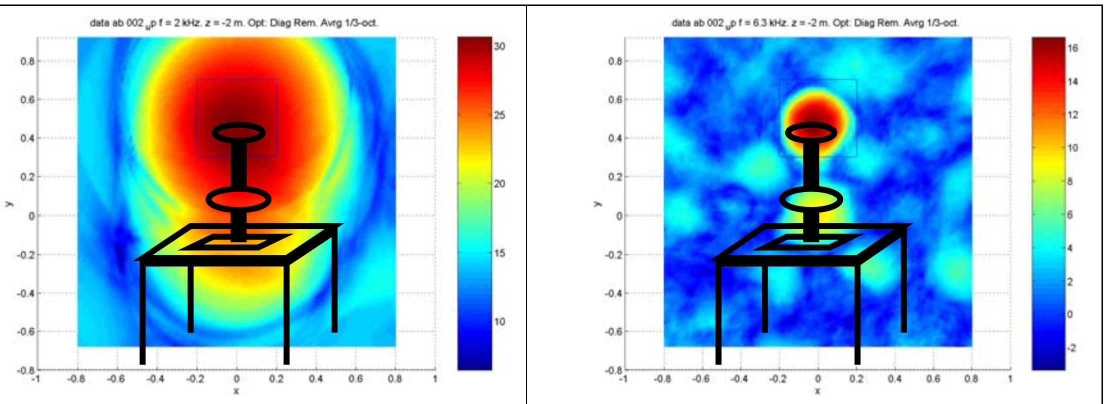
The ‘machine’ chosen for a first application of the measurement technique was a bench-top pillar drill, figure 6, which was used to drill a small metal sheet. Separating the noise of a workpiece from that of the machine is a common problem, sometimes necessitating intricate tests using sound intensity measurements or temporary enclosures of parts of the machine, and so this is a potentially useful application of the array measurements.

First running the motor without drilling provides the noise maps presented in figure 7a) and 7b) for two frequencies, from which it is clear that the motor is generating the noise. Next making a measurement whilst a small metal sheet is being drilled, figures 7c) and 7d), shows how at these frequencies the dominant noise is now radiated from the workpiece.

The maps provide useful subjective information, but are difficult to interpret quantitatively. The best way of assessing changes is to carry out an area integral of the maps over the upper and lower portions of the drill as shown by the dotted lines. Carrying out the area integration at each frequency allows us to plot a contribution ‘spectrum’ for each area, figure 8. It is important to note that this spectrum is not a true far-field noise spectrum, as there is a frequency weighting that is dependant on the characteristics of the array, the noise mapping software and the integration area. However, the relative level at each frequency may be considered to be a true reflection of the relative contributions of each zone.

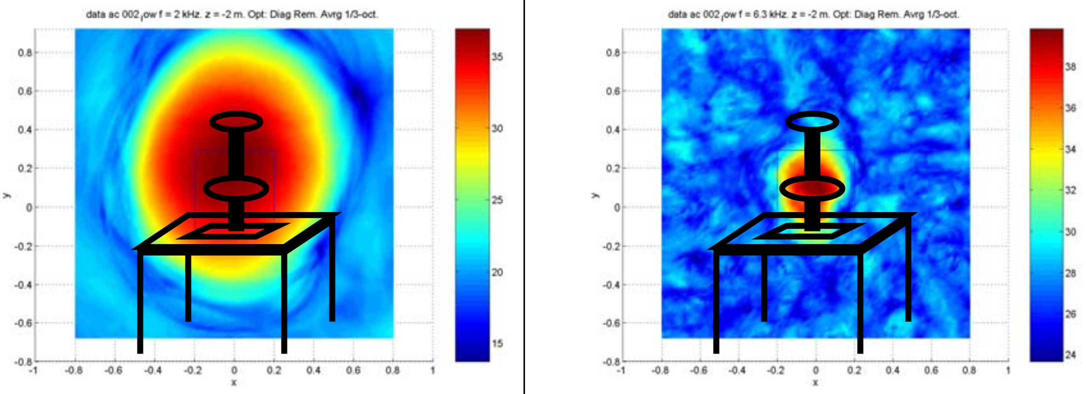
Figure 8 shows clearly how high frequency noise is dominated by radiation from the workpiece when it is being drilled. At low frequencies it appears that noise is emanating equally from the upper and lower areas, but it must be borne in mind that the resolution of the array is poor in that frequency range.

Figure 6 Pillar drill



(a) motoring, 2 kHz

(b) motoring, 6.3 kHz



(c) drilling, 2 kHz

(d) drilling, 6.3 kHz

Figure 7 noise maps of the pillar drill, either motoring or drilling a work piece.

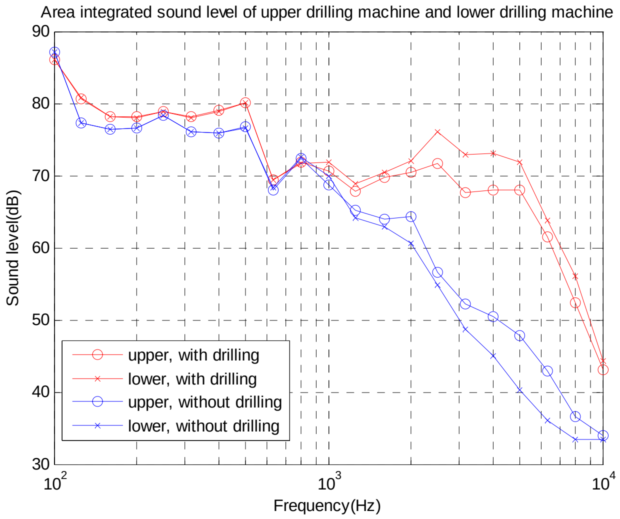


Figure 8 Relative contributions from the upper area around the motor and the lower area around the workpiece, with and without drilling.

The data presented here were recorded in the idealized environment of an anechoic chamber, but similar measurements in a reverberation chamber proved to almost as effective in identifying the relative contributions.

4.2 Identification of source contributions in the work place

The second application of the array was a set of measurements in the University of Southampton engineering department workshop, figure 9. The two aims here were firstly to determine whether the array could identify the location of the pillar drill in an otherwise quiet workshop, and then to try using the array to identify the operation of the individual workshop machines during normal working.

Whilst the array had successfully located a noise source even in the reverberation chamber, the measurements in the workshop provided a severe test of the system because of the scattering of sound by the many obstructions and the relatively low roof.

Figure 9 array measurements in the UoS engineering workshops

In simple circumstances, e.g. a machine in clear line of sight from the array (figure 10a), the direction of the noise of the noise source was correctly identified. In circumstances where the source was partially hidden behind an obstruction however, figure 10b), some noise comes from the true position of the machine, but the map is dominated by noise from other directions representing energy reflected from the roof, end wall of the workshop or from the surfaces of other machines.

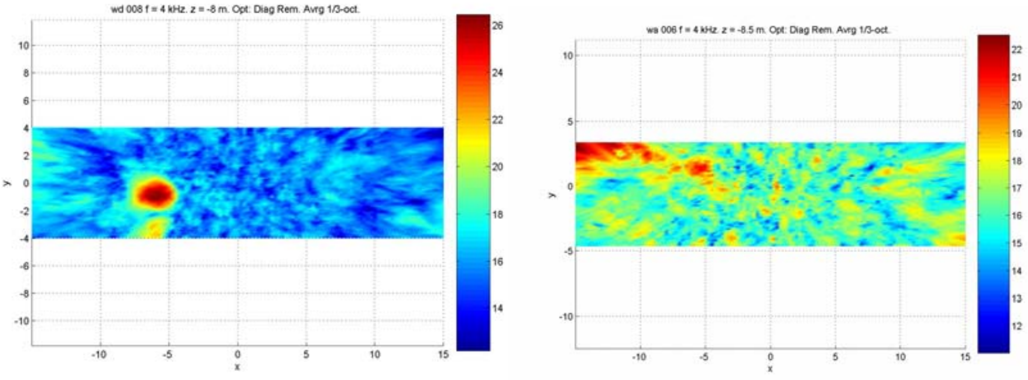


Figure 10 a) workshop machine operating in line of sight from the array b) pillar drill hidden behind the workshop machine at x=-5.

5 CONCLUSIONS AND POTENTIAL PITFALLS

The preliminary results presented have been chosen to suggest some possible benefits in using microphone arrays for identification of industrial noise sources, the most significant of which is that information about the relative importance of various sources is always valuable

However, problems that are apparent here or might be expected to occur in other situations include:

- Physical shielding of one source by another, although an array in the roof with better lines of sight might help.
- The effectiveness of the workshop measurement method is dependant on the dimensions of the room. This might require a different configuration of array, with sensors distributed over a wider area
- Correlated noise sources on different parts of the same machine will create directivity patterns that might confuse the array.
- Measurements on time varying noise processes may not be suited to the frequency domain method outlined here.

6 REFERENCES

1. T.J.Mueller(Ed). Aeroacoustic Measurements, Springer, Berlin, 2002
2. Brüel & kjær, Technical review, No.1-2004
3. Castres, F.O. and Joseph, P.F. Mode detection in turbofan inlets from near field sensor arrays Journal of the Acoustical Society of America, 121(2) pp 796-807
4. Fisher, M. J.; Harper-Bourne, M.; Glegg, S. A. L. Jet Engine Noise Source Location: The Polar Correlation Technique. Journal of Sound and Vibration 51(1), 977, p 23-54
5. Dobrzynski W, Chow L. C., Guion P., Shiells D. A European study on landing gear airframe noise sources, 2000, AIAA conference paper 2000-1971
6. Dobrzynski W.M., Schöning B., Chow L.C., Wood C., Smith M.G., Seror C. Design and Testing of Low Noise Landing Gears. 2006. International Journal of Aeroacoustics, vol 5 no. 3, 233-262.
7. Guerin S., Michel U., and Siller H., Saueressig G. Airbus A319 Database from Dedicated Flyover Measurements to Investigate Noise Abatement Procedures, 2005, AIAA paper 2005-2981
8. Smith M.G., Fenech B. Chow L.C. Molin N, Dobrzynski W, Seror C .Control of noise sources on aircraft landing gears. 2006. AIAA paper 2006-2626