Locating Noise Sources - A Comparison Between Different Noise Localization Techniques

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"Sound source localization tools have over the years become the single most important tools in acoustic analysis. Today's NVH[1)] engineers have a myriad of different noise source identification techniques available. Unfortunately, it is not always clear which technology is the best for which specific application. The paper presents some of the most popular with their specific advantages" [MM2003].

1. Classical Approaches

Sound Intensity Probes become attention within the last years. If we subtract the level of two, dense located, anti-phased microphones, we get a possibility to look for phase changes. This allows a directivity mapping of a single source. In case of many sources the method becomes critically. In such cases the old and simple stethoscope seems more practical.

But fast we will find a general problem of all near field approaches: Nobody can imagine, which emissions reach into the far field: it is not simple to decide, which contribution a source location carries to the whole emission going to a certain destination. Also observing instationary noise sources with single sensors is not simple.

2. Sound Pressure Mapping Using a Single Microphone

Supposed, we have stationary noise sources. Using a single microphone a surface can be scanned on a virtual grid. The method is cheap but not all the time reproducible. 3D-surfaces show distance variations between the surface and the microphone. The sound pressure varies with the distance. And in most cases it is not clear, how to scan complex surfaces. So the NVH-engineer *measures not the emission alone*, he also measures *indirect the distances to surface(s)*. If the room has reflections, diffractions or room-resonances the results become even more mystical.

To overcome the reproducibility problem on can use a XY-scanner, carrying the scanning microphone.

One of the most important advantages is the

- + *ultimate low price*
- + *body noise*

Disadvantages are

- ¬ *time consuming*
- ¬ *partially unclear results*
- ¬ *only working for stationary noise*
- ¬ *object distances influence the result*

To record a single event on different places simultaneously is not possible using one microphone. So it is not possible to record single events. Practically this means, that this method is applicable for wind tunnels and really continuous working engines.

3. Fourier Based Near Field Mapping with Arrays

To locate instationary noise sources, we need parallel, *simultaneous recordings* on a virtual grid or surface.

Normally we use a plane microphone array. Dependent on the calculation method it is common used to create *pressure or intensity maps*. If the whole surface is simultaneously scanned, single emissions can be detected, calculation the effective value or the intensity for each channel.

As closer the microphones scan the surface, as more details we can detect. But also as smaller the distance to the surface is, as more distance variations influence the result.

Near field measurements are predestinated for the analysis of *correlated sources*. Because of wave physics, correlated noise of different source locations can merge in greater

[1)] Noise Vibration Harshness

distances. On the other side, metal bodies create sometimes waves with long wavelength compared to the distance of sending locations (brake discs, turbo jet housings).

To measure correlated sources, it is necessary to bring the microphones very close to the object.

Practically such near field techniques are usable to observe sources like displays, transformers, violins, brake discs. But: correlating sources are mostly stationary – a single microphone can solve such tasks as well.

The price for using arrays is comparable high: there is no flexibility in the construction of the array. That means, different machine sizes need different array sizes. And they have no video camera on the array to document the object.

Positive:

+ *body noise*
+ *non-stationary noise*
+ *time saving compared to single mics*
+ *correlated noise sources*

Negative:

¬ *no video camera*
¬ *object distance influences the result*
¬ *very expensive*
¬ *fixed array size with highest inflexibility*
¬ *large amounts of data to store*
¬ *restricted resolution of localization*

4. (Fourier Based) Near Field Holography

We can encrease the resolution of localization of intensity maps introducing the phase information, if we ask for the phase information to improve the image quality by field theoretical approaches.

Going with recorded channels into Fourier space, a known, plane 2D-surface (microphone layer) can be transformed into a second plane – coefficient by coefficient, this way maps for noise pressure, particle velocity or noise intensity can be developed on a different plane or surface, see for example [JH95].

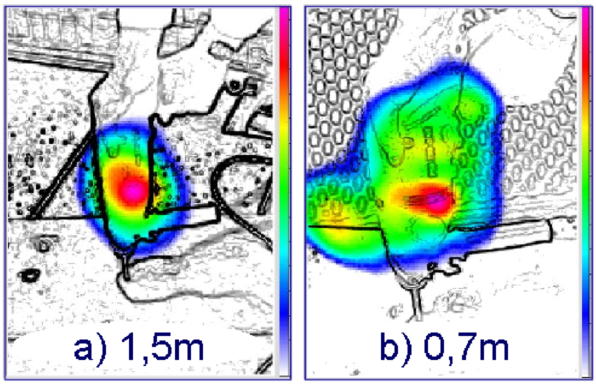

Fig. 1: The holography problem: Dipole emission of a drilling machine, recorded from different distances a) and b. Records: Ring32, Ø70 cm. G. Heinz, GFaI, Febr. 20, 2002

Using any phase information, we are suspecting sources, that produce in-phase (monopole-like) signals. If only some sources produce anti-phased (dipole-like) emissions (Fig.1) for left and right microphones, *the method fails*. Practically all pipe-like structures (covers, e-motors, silencer, turbo, alternator, pumps…) with a distance smaller the array size produce this fault more or less partially. (The author found this problem inspecting a drilling machine with the Acoustic Camera: From far (Fig.1a) it maps good, as more closer we come (Fig.1b), as more the source image is smearing away).

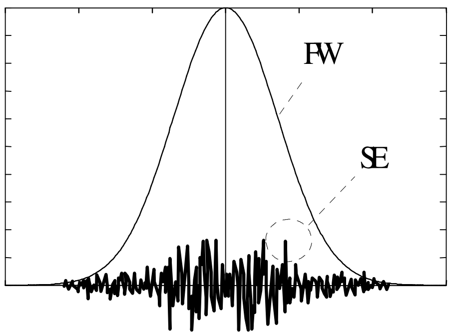

Fig. 2: Single emission SE overlayed by a large, averaging fourier window FW

Practically each machine has a lot of different dipole-like sources, so nearfield holography works best for the mapping of monopoles (for example loudspeakers) – not for real machinery.

Asking the *instationary noise* question again, we find, that the *way into Fourier domain anticipates this aim*. Large Fourier-window sizes restrict the possibility to map single emissions dramatically, Fig.2.

Reasoned by theoretical background, the microphones need to be on a plane surface. 3D-surfaces or spherical arrays makes some trouble.

Positive:

+ *perfect mapping of monopoles (for example loudspeakers)*
+ *correlated noise sources*

Negative:

¬ *no real sources (dipoles)*
¬ *fixed array size, no size flexibility*
¬ *no video camera*
¬ *single emissions and non-stationary noise limited by Fourier transformation*
¬ *extreme huge computational power, large amounts of data*
¬ *plane arrays only*

5. Laser Vibrometry

In difference to noise emission tools there is a wide used tool that records very precise the movement $x(t)$ of a surface point by usage of a single laser beam.

The general problem of vibrometry approaches is, that the relation between a single movement function $x(t)$ and the noise pressure $p(t)$ is normally unknown, especially, if we go far away from the object.

Scanning laser vibrometers, moving the laser beam in *X*- and *Y*-direction, extend possible tasks to map whole regions of a machinery. Stationary excitement supposed, this allows for example the mapping of brake discs. But the analysis of single events needs a parallel recording at different positions.

Positive:

+ *correlated noise sources*
+ *body noise (dense emissions)*
+ *not influencing the source*

Negative:

¬ *expensive*
¬ *for stationary noise only*
¬ *surface movement, not acoustic emission*
¬ *limited observation grid*
¬ *the gradient dx/dt is limited by the interference counter bandwidth*

6. Laser Vibrometry Arrays

By analogy to the microphone discussion: to map instationary noise, we mostly have to observe a lot of source points simultaneously.

We need an expensive laser array. Comparable to microphones we can inspect instationary surface movements also for single events. But such tools are very expensive.

Positive:

+ *correlated sources*
+ *single emissions and non-stationary movements*
+ *flexible point settings by software*

Negative:

¬ *most expensive technology*
¬ *limited observation grid*
¬ *limited number of channels*
¬ *surface movement, not acoustic emission*
¬ *the gradient dx/dt is limited by the interference counter bandwidth*

7. Fourier Based Far Field - (Inverse) Beamforming

By difference to near-field methods, this method shows a new quality: distance variation and deepness-structure of engines influence the results only week, because the distance to the engine is larger.

Phased array beam formers (RADAR, SONAR) are steered by the phase differences between different sinus waves for different antennas. If we invert the process using a Fourier- decomposition, we can ask for emission sources using the *inverse* beam forming technique.

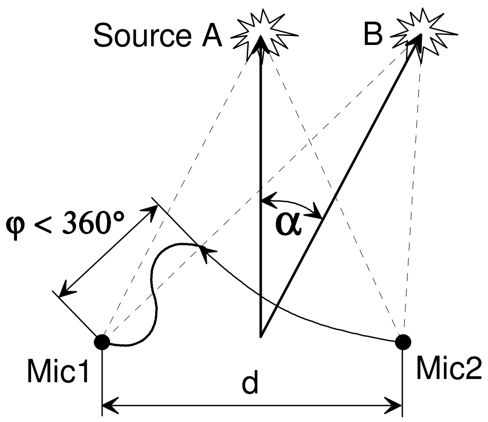

Fig. 3: General problem of beamforming. For wavelength between millimeter and meter the array size d has to varry in the same range

The horizon of frequency based approaches (holography, beamforming) restricts each Fourier coefficient within a phase range φ between 0° to 360°, Fig.3. If we need a constant panning or view angle α for all frequencies, we need array sizes in the same relation as the frequencies varry, that means in the range between millimeter and meter (100 Hz 3.4 m, 10 kHz 3.4 cm, 100 kHz 3.4 mm). There are severall techniques to solve this problem [WD01]. Normally the microphones are grouped, for longer waves we take each n-th microphone only. Therefore we need a lot of not efficiently used microphones. For superdirectivity approaches or optimum beamformers [VT02] the problem is solved by generation of additional aliasing patterns that can partially be removed by the following calculation step. Localization systems get normally on different channels waves of higher frequencies delayed by more then 2π.

Because of general definitions of Fourier decomposition only a infinite long periodical signal is valid for the beamforming algorithm, so the *possibility to resolve single events appears limited.*

Also the Fourier transformation is closed coupled to *averaging Fourier windows* – restricting the time resolution in movies and limiting the quality of the results.

So Fourier-based approaches, like beamforming *need additional channels to compensate this lacks*.

Because of the conversion of all time functions of all channels into Fourier-space, the method needs also additional computational power.

Also the Fourier conversion restricts time and frequency range of each calculation.

For more see for example [WD01].

Because of a physical merging-wave problem, it is not possible to map correlated noise – but this is a *general fare field measurement problem.*

Positive:

+ *object distance variations (3D-surfaces) have neglectable impact on results*
+ *no object size flexibility problem*
+ *dipole-like sources*
+ *video-camera possible*

Negative:

¬ *limited frequency range*
¬ *limited time resolution*
¬ *inefficient used channels*
¬ *high channel numbers (40…160): heavy, big and expensive*
¬ *no single emissions*
¬ *non-stationary noise restricted*
¬ *large amounts of data, slow*
¬ *correlated sources are not allowed*

8. Acoustic Camera

In difference to B&K's proclamation[2)] between (inverse) Beamforming and the Acoustic Camera using totaly different theoretical foundations.

Overcoming the most important problems of beamforming and holography, the restrictions with averaging Fourier-windows, wave numbers and worst time functions can be solved only by working in time domain. So the (original, GFaI) Acoustic Camera[3)] *works as*

2) im-pulse, B&K Österreich, Febr. 2004, S.5: PULSE –Beamforming: "Beamforming oder auch in manchen Kreisen akustische Kamera genannt" engl.: "Beamforming or in some circles also called Acoustic Camera"

3) www.acoustic-camera.com - the term "Akustische Kamera" was 1997 introduced for the machine, that creates worlds first acoustic images - for our new GFaI-technology by the science reporter of the "Berliner Zeitung", Dr.

the first system worldwide in time domain using a new algorithm basing on *H*einz *I*nterference *T*ransformation (HIT).

But now the expense for parallel recording with arrays instead of using a single scanning microphone – to record and locate also *instationary* noise sources – is charging off.

All restrictions of Fourier approaches disappeare: we can define anyone large view angles for each frequency, we have no frequency or phase limitation, there is no fundamentale influence between array size, panning angle and microphone distance.

A closer view behind projection- and reconstruction-theory shows, that the interference transformation is not independent of the time function type, Fig.4. There is one best mapping time function – the single pulse and one worst mapping – the sinus. All other time functions laying between them. The tragedy: The hole acoustic theory is constructed on sinus waves in Fourier spaces (beamforming, holography) – using the worst mapping time function type.

The algorithmical idea is to construct a pseudoinverse wave field with interference integrals approximating the original source distribution best. The solution is a simultaneous work forward and backward in time domain. This way the algorithm is an improved optical projection without lacks, like the limitation near the axis.

Resulting we get a *E*quivalent *N*oise *P*ressure (ENP) plane of maximum emissions of the object.

The method comes from 3D nerve system simulations. So microphone and screen co-ordinates are generally three-dimensional.

Important for the user: interference integrals do not differ between photos or movies. It is possible to compute interference integrals (photos) and pseudo-inverse wave fields (ultra-slow motion, max. 192.000 *i*mages *p*er *s*econd (*ips*) in the same way, only varying the *ips*-parameter.

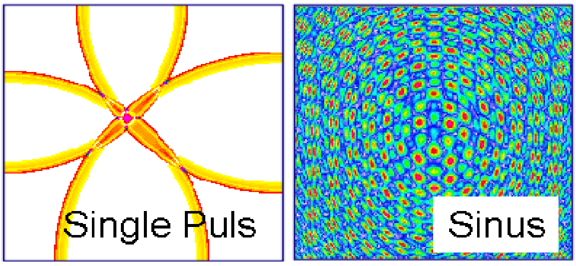

Fig. 4: Self interference location of a single impulse (left) and corrupting cross interferences in a sinus time function simulation (right). 4-chnl pseudo- reverse wave fields, G. Heinz 1995

To produce an A-weighted acoustic film or image, a time consuming Fourier transformation is not necessary, so the method is very fast.

Compared to beamforming, missing algorithmic lacks enables the technique to take only *a third of the channels* for comparable image qualities within a given time – a strong argument for performance, speed, reliability, weight, volume and price.

A lot of outstanding highlights demonstrate the performance of the system: there exist a lot of records with 30 channels (wind power plants, giant excavators, airplanes, helicopters) with a quality, never reached by any beam-forming team worldwide.

Slow motion movies up to the sample rate of recorded time functions are possible. Also the image calculation is simpler, over all we get a computation time saving by a factor greater than one hundred compared to beamforming. So the technology is the *first enabling a real time calculation* (live preview) of acoustic images.

It produced worldwide the first acoustic images and movies of many practical things over very far distances [Hz96], the first noise reflections could be visualized [B737].

In 1997 the term "Acoustic Camera" [BZ97] and in 1999 the term "Acoustic Photo- and Cinematography" was introduced for the GFaI-technology [ASA99]. Different other

Michael Ochel, [BZ97]

teams (TNO[4]), US-DER[5]), Lufthansa/DLR[6]) for example) in the last years copied the term "Acoustic Camera", although they are using beam forming algorithms. And we are afraid, some teams copying our algorithms and call it "beamforming". But: working in time domain, one have to implement the HIT. (Like I know there is only one Acoustic Camera working in time domain until now, the GFaI's).

Since 1999 an *automatical video overlay* is implemented [HI99].

Again because of the physical merging-wave problem, also here it is not simple to map *correlated noise sources*, like displays, transformers, violins, brake discs. Although the acoustic camera is influenced of the problem, it is possible to cover object parts to eleminate correlating signals.

The worlwide patented technology is the first with pin-compatible arrays for all industrial purposes. Each arry has a video camera, the interface of all arrys is the same (MicBus/USB). To map all technical objects between razors and ICE-trains, the Acoustic Camera is the first system offering five different array types for all object sizes and real measurement problems between 10 cm and 300 meter:

- *Disc32* *10 cm...1 m*
- *Cube32* *30 cm...1 m (3D)*
- *Ring32* *1...3 m*
- *Portable32* *1...3 m (reflexiv)*
- *Star36* *10...300 m*

A lot of interactive tool ideas between space, time and frequency offer a complete new acoustic tool world: virtual noise lab, live preview, local decomposition, image-spectrum- interaction, time-film-interaction, line-scan etc.

Positive:

+ *single emissions clear observable*
+ *no restrictions in time domain*
+ *no restrictions in frequency domain*
+ *no limits in array geometry*
+ *any sized aperture angle to 360°*
+ *full-automatic video image overlay*
+ *smallest channel numbers (32…36)*
+ *lowest price, weight, volume*
+ *fastest image calculation*
+ *limited real-time ability*
+ *ultra slow motion movies*
+ *dipole-like sources (all sources)*
+ *arrays for most sizes and tasks*
+ *3D-coordinates inherent*
+ *fastest array technique*
+ *sparse influence of object deepness*
+ *high object size flexibility*
+ *frequency range[7]) 100Hz...90 kHz*

Negative:

¬ *correlated sources with restrictions*

References

[ASA99] Heinz, G., Döbler, D., Nguyen, T.: Acoustic Photo- and Cinematography basing on the H-Interference Transformation (HIT). ASA'99: 137th meeting of the Acoustical Society of America, 2nd Conv. European Acoustics Ass. and 25th German Acoustics and DAGA Conference at TU Berlin, Germany, March 14-19, 1999. Abstract in: Acta Acoustica, p. S363, paper 4pPAa12, S. Hirzel Verlag, Suppl. 1, Jan/Feb. 1999, Vol. 85. ISSN 1436-7947

[B737] http://www.acoustic-camera.com/presse/contents/geo.htm

[BZ97] http://www.acoustic-camera.com/presse/contents/bz.htm

[HI99] http://www.acoustic-camera.com/presse/contents/dirk_99.jpg

[Hz96] http://www.acoustic-camera.com/historie.htm

4) http://www.tpd.tno.nl/smartsite463.html

5) http://www.eurekalert.org/features/doe/2001-08/dnnl-nac062002.php

6) http://www2.dlr.de/EN-AT/Das_Institut.htm, http://213.198.75.194/de/html/ueber_uns/mobilitaet/drehscheibe/aktiverschallschutz/, http://www.zeit.de/archiv/2002/52/T-Flugl_8arm

7) it depends on the specification of the array, usage of microphone type, coordinate-tolerances etc.

[JH95] Joergen Hald: Spatial Transformation of Sound Fields (STSF) Techniques in the Automotive Industry. B&K Technical Review No.1 –1995. pp.1-23

[MM03] Maroquin, Marc: A Comparison of Seven Different Noise Identification Techniques. B&K North America, 2003-01-1690

[VT02] Van Trees, H.: Optimum Array Processing. Wiley, 2002

[WD01] Brandstein/Ward: Microphone Arrays. Springer 2001