

Selecting Sound Source Localization Techniques for Industrial Applications

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Sound source localization is a complex and cumbersome task that most acoustics engineers face on a daily basis. Today, a number of rather standard methods help accelerate this task. But there is no one-size-fits-all solution. This article describes the most common techniques and reviews vital criteria to select the best method for the job at hand.

The toughest challenge facing any acoustics engineer is figuring out where the sound originates – especially when there is considerable interference and reverberation flying around. Since the early 1990s, some rather standard and highly functional methods based on microphone arrays have matured, and today they are used throughout many industries. In general, the methods fall into three categories: near-field acoustic holography, beamforming, and inverse methods. Even though these basic techniques have undergone constant improvement, the problem remains that there is no “magical” sound source localization technique that prevails over the others. Depending on the test object, the nature of the sound and the actual environment, engineers have to select one method or the other.

This article reviews available techniques and explains how the methods have evolved over the years. Readers will be able to understand how to assess the quality of the measurement result based on two criteria – spatial resolution and dynamic range – as well as reviewing criteria to determine which method results in the best sound source localization for the job. The various methods discussed will be frequency range, distance to the source, physical properties of the sound source, and operational conditions. A number of examples are presented regarding the different techniques.

Assessing Localization Techniques

The ultimate goal of any technique is to accurately project the sound origin on an image of the test object. The sound source is represented as a red spot. Two important criteria help assess the quality of the measurement (see Figure 1):

Spatial resolution is the ability to separate two sound sources. It is expressed in centimeters. It represents the closest distance between two sources, where they still appear separately and do not merge into a single source. The lower the spatial resolution, the better the source localization.

Dynamic range expresses sound level differences in dB between real sound sources and surrounding mathematical artifacts inherent to the sound source localization techniques. The higher the dynamic range, the better the source localization. In beamforming techniques, the dynamic range is also linked to frequency – the lower the frequency, the higher the dynamic range.

Near-Field Acoustic Holography

Near-field acoustic holography (NAH) is a technique where the microphone array is placed relatively close to the sound source – in the near field. It provides good results over the entire frequency range. The near field can be described as the area that is closer to the sound source than one or two wavelengths of the highest frequency. NAH¹ was introduced in the mid-1980s and industrialized in the mid '90s.² It has by now become a well-known technique.

NAH measures sound pressure by arranging several microphones in a rectangular planar array. Microphones are regularly spaced both horizontally and vertically. The sound pressure in the plane is then back-propagated to the actual surface of the object. The spacing between the microphones determines the half-wavelength of the maximum frequency, and the size of the array determines the half wavelength of the minimum frequency. The spacing also

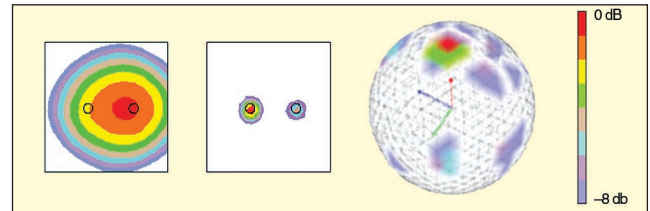


Figure 1. Spatial resolution and dynamic range.

determines the spatial resolution – a coarsely spaced array cannot accurately localize sources composed of the fine mechanics of a small object.

NAH has two major advantages:

- Spatial resolution is independent of frequency. It equals the microphone spacing in the hologram.
- Using the Dirichlet Green function allows propagation from the measured pressure field to a velocity field. This method supports sound intensity and sound power calculations for different zones or components.

The NAH method is a very precise engineering tool for source localization. However, it has some disadvantages:

- NAH can only propagate sound pressure to a surface that is parallel to the measured surface. The size of the propagation plane has to be identical to the measured plane. To localize a source on a complete vehicle, the measurement plane has to span the complete vehicle. For stationary applications and repeatable transient applications, such as slow engine run-ups or door slams, the data can be acquired in batches. As a result, it is possible to perform NAH measurements with a 20- to 30-channel data acquisition system.
- The higher the required maximum frequency, the closer the microphone spacing. Practically speaking, NAH can be inconvenient for higher frequencies due to the large amount of data required to achieve a good analysis.

Door Slam Example. In the near field, NAH helps analyze impulsive door slams. In this case, a device is used that closes the door repeatedly at the same speed. The transient phenomenon becomes a repeatable transient. An array is then placed in the near field. In this case, the array has a microphone spacing of 8 cm, resulting in a 216×48 cm hologram. This limits the maximum frequency to 2140 Hz. The hologram in Figure 2 shows the sound source of the door slam at 512 Hz. NAH is best suited for this analysis. It offers the required spatial resolution at the low frequency of 512 Hz.

Air Pump Example. This example shows a small, 12-cm-wide air pump. The hologram size is 27×27 cm, derived from 3-cm spacing and resulting in a maximum frequency of 5700 Hz. Based on critical frequencies found in the spectrum, the various holograms pictured in Figure 3 show the rotating pump itself (left, 1150 Hz), the air outlet (middle, 430 Hz), and the air intake (right, 715 Hz). This example demonstrates that it is possible to propagate to frequencies with a half wavelength larger than the hologram size, as is the case for the middle hologram ($1/2 \lambda \approx 40$ cm). This still allows correct localization at the expense of less reliable quantification results. Besides that, with small structures, it is important to take the granularity of possible sound sources into account and match microphone spacing accordingly. In this case, the 3-cm spacing matches the size of the different small pump components.

Beamforming

Beamforming is a technique where the microphone array is placed in the far field. As a rule of thumb, the far field is defined

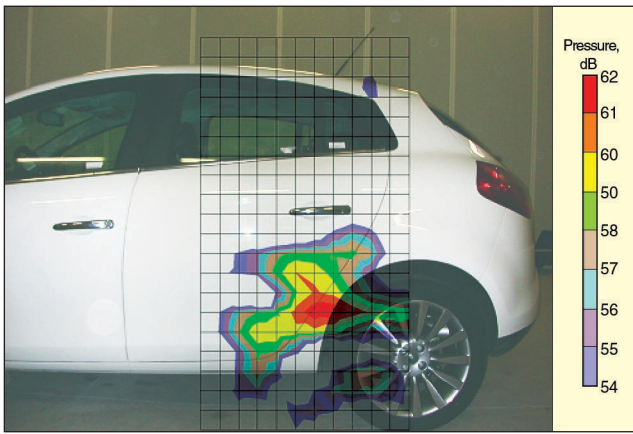


Figure 2. Door slam with NAH.

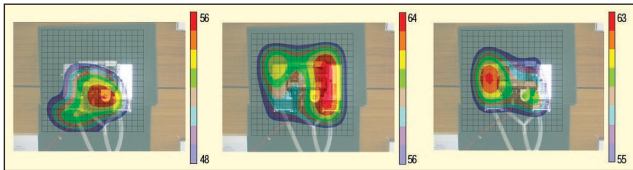


Figure 3. Pump, air intake and air outlet analyzed with NAH, all at -8 dB dynamic range.

as being further away from the source than the array dimensions or diameter. The area between near field and far field remains a gray zone. In the near field, sound waves behave like circular or spherical waves, while in the far field, they become planar waves.

Numerous microphone configurations are possible in beamforming arrays. In general, the configuration is usually a trade-off between dynamic range and source localization accuracy. To get the best of both worlds, select a circular array with a pseudo-random microphone distribution.

The beamforming technique was first developed for submarines and environmental applications. In the far field, sound waves hitting the array are planar waves. Under these conditions, it is possible to propagate the measured sound field directly to the test object. All microphone signals measured by the beamforming array are added together, taking into account the delay corresponding to the propagation distance. The pressure can be calculated at any point in front of the array, allowing propagation to any kind of surface. Beamforming is sometimes called “sum and delay,” since it considers the relative delay of sound waves reaching different microphone positions.

Beamforming requires that all data be measured simultaneously. It is typically done with a measurement system of 40 channels or more. Beamforming has the following advantages:

- Propagation does not relate to the size of the measurement array. The test object can be larger than the array. With an array of 0.5 m in diameter, it is possible to propagate pressure to an entire car. Since all data are measured simultaneously, results can be viewed only minutes after data acquisition.
- Because of the relatively fast acquisition and analysis speed, beamforming lets engineers evaluate several configurations in a limited amount of time.

This flexibility has some negative aspects:

- The spatial resolution is proportional to the wavelength:

$$\text{Spatial Resolution} = \frac{d}{D} \lambda$$

where d is the distance between the source and array, D the array diameter, and λ the wavelength. In an ideal situation, when the antenna is at a distance D to the source, the resolution is equal to the wavelength. If the array is placed farther from the structure, the resolution becomes worse.

Generally, beamforming is only usable at frequencies above 1000 Hz. Beamforming cannot be used to calculate sound power and proper source ranking cannot be done with this technique.

Operational Engine Noise Example. This example analyzes

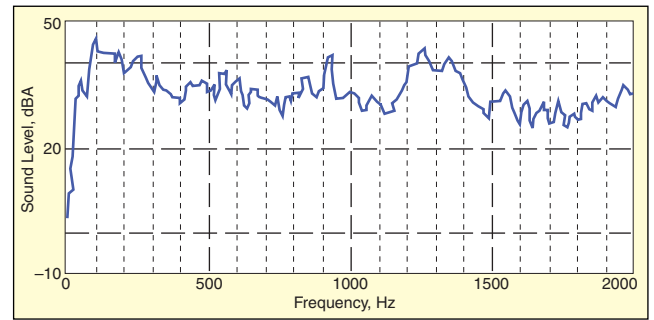


Figure 4. Frequency spectrum of engine run-up.

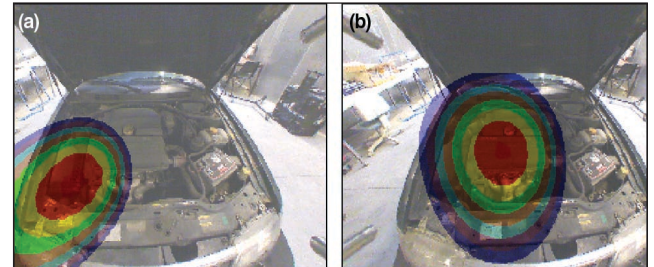


Figure 5. Accurate localization of sound sources for 925 Hz (left) and 1250 Hz (right).

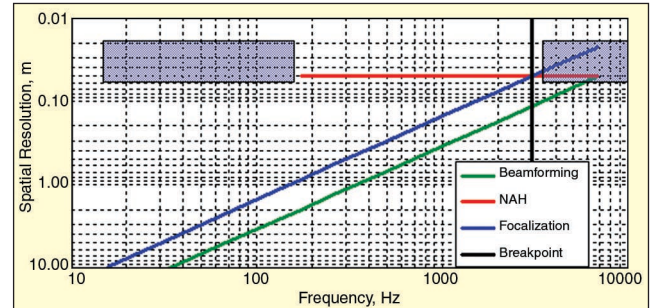


Figure 6. Spatial resolution versus frequency for different techniques.

results of an engine run-up in neutral gear inside a semi-anechoic chamber. The goal is to identify tonal components that appear repetitively in the complete time sequence. These components, identified at 925 Hz and 1250 Hz, can be seen in Figure 4 (selected time spectrum). Figure 5 clearly identifies noise sources on the crankshaft pulley (left) and a noise source on the engine core (right).

Inverse methods

Inverse methods are newer sound source localization methods. They solve a system of equations:

$$p = Hq$$

where p represents the sound pressure measured at the microphone array, and q represents the localization on the volume velocity or sound distribution on the source. p and q are related through a transfer function H . Inverse methods solve this system, where q is determined by calculating the inverse of the transfer matrix H and multiplying it by p .

The inverse boundary-element model (IBEM) is one of these methods. It inverts the wave propagation matrix at a high computation cost. IBEM is rarely used because of its high computation time. However, when reducing models to a simplified monopole source distribution, the transfer matrix becomes easy and fast to calculate. This reduction method is called the equivalent-source method (ESM) or distribution.^{3,4}

Recent Advances in Sound Source Localization

Near-Field Focalization. The limitations and drawbacks of NAH and beamforming are summarized in Figure 6. The red curve shows that NAH has a constant spatial resolution, given a fixed microphone spacing (2.5 cm in this example). This spacing limits

the maximum frequency to 6800 Hz ($340 \text{ [m/s]}/0.05 \text{ [m]}$). For low frequencies, the array size should equal the half wavelength of the lowest frequency (1 m array in the example, 170 Hz). For beamforming, the maximum frequency is also limited by the spacing of the microphones and the density of pseudo-randomly distributed microphones in the array. The spatial resolution for beamforming improves with a frequency increase, as the green line shows.

Techniques to improve NAH and beamforming are focused on covering areas depicted with transparent purple rectangles. NAH has good resolution over the entire frequency range, but is limited in hologram size (array size should match $\frac{1}{2}$ wavelength at the lowest frequency) and number of microphones needed for high-frequency measurements. Beamforming lacks resolution at the lower frequencies.

Near-field focalization (NFF) is a beamforming technique based on near-field measurements.^{5,6} It either reprocesses already acquired NAH data or allows the beamforming array to be moved closer to the sound source. In the near field, the sound waves no longer arrive at the microphone as planar waves but as spherical waves. The original beamforming back-propagation is reformulated to deal with these waves. NFF improves the spatial resolution to 0.44λ . Its performance is depicted by the blue line in Figure 6.

In practice, this implies that, compared to beamforming, spatial resolution is improved by a factor of two over the entire frequency range. This technique is very useful for wide-angle beamforming acoustic cameras that can zoom into a sound hot spot, providing high-definition source localization. It also lowers the threshold of the minimum frequency at which beamforming can be employed.

Figure 6 shows that, compared to NAH, there is no benefit of using focalization in the lower frequency range. However, there is a break-even point at which the spatial resolution of NAH is equal to focalization. Above that frequency, focalization improves spatial resolution. In fact, at the NAH frequency limit, NFF improves spatial resolution by a factor of two. Obtaining the same accuracy with NAH would mean that the spacing between the array microphones should be increased by a factor two. This translates to four times as many microphones and requires a larger number of measurement channels, which increases hardware investment and maintenance costs. Using focalization after the break-even point for NAH data means improved results at a lower cost.

Spherical Beamforming. Another recent development in sound source localization is a technique that can be applied in complex, reflective sound fields, such as the interior of a vehicle or the cabin areas in trains and airplanes.

An adequate technique for interior sound source localization is called spherical beamforming. Spherical beamforming uses a far-field beamforming technique suited for free-field conditions in an interior cavity, which is a reflective sound field. Spherical beamforming does not make use of a flat, two-dimensional array but employs a spherical array. Therefore, the spherical beamforming technique helps identify the exact position of a sound source in the surrounding space.

Knowing that spherical beamforming requires a spherical array to scan surrounding sounds, one still has to make a further design choice by selecting an open or closed sphere. Naturally, one might tend to select an open sphere, since 2D arrays used for traditional beamforming are also open arrays. However, verifiable experiments point out that when compared with closed spheres, open spheres suffer from poorer spatial resolution in the lower frequencies and from a lower dynamic range in the mid and high frequency ranges (see Figure 7).^{7,8}

Using the actual geometry of the interior allows spherical beamforming to back-propagate the measured sound to the geometry. Back-propagating sound to a location that is further away or closer to the spherical array than the actual sound source leads to errors and lower dynamic range.^{7,8} So, using the actual geometry of the interior has clear advantages over using a virtual sphere around the acoustic antenna.

As beamforming techniques show poor results in low frequencies, an exciting recent improvement to spherical beamforming is the adaptation of an inverse method, or the equivalent source

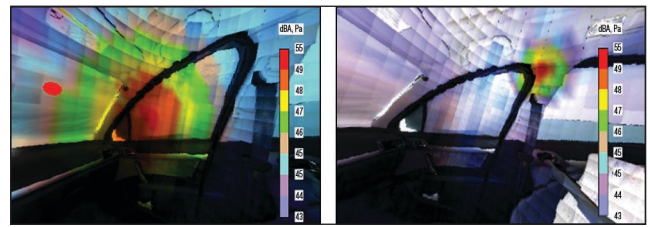


Figure 7. Low-frequency spherical beamforming analysis on the left mirror (-7 dB), and mid-high frequency analysis on the right B pillar (-6 dB).

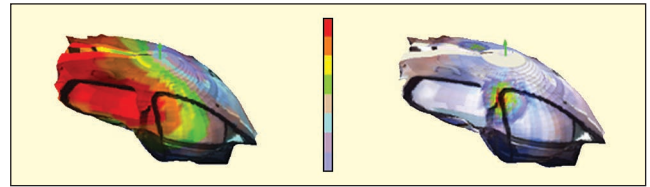


Figure 8. Frequency analysis (500 Hz) with spherical beamforming (left) and ESM (right) at -6 dB .

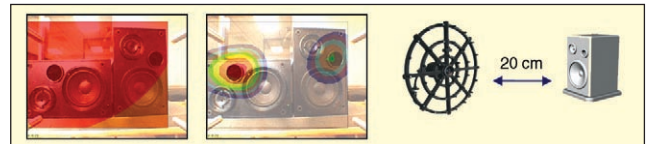


Figure 9. Source localization 60-70 Hz: focalization (left) and irregular NAH (right).

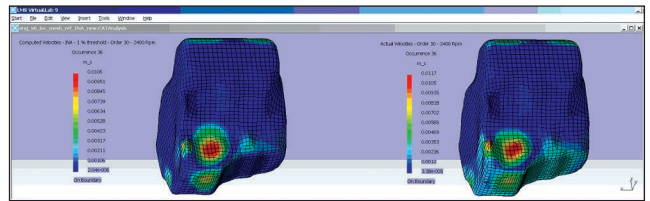


Figure 10. INA-computed volume velocities on the left, measured on the right.

method (ESM). This method is used in a closed cavity with a solid sphere. Principle component analysis (PCA) is applied before the ESM to deal with the uncorrelated characteristic of noise source distributions. The propagation matrix to invert through ESM includes the sphere diffraction. The noise source distribution takes the geometry of any cavity instead of the usual two-dimensional map. The results of ESM at low frequencies not only show a far better spatial resolution compared to spherical beamforming and spherical harmonic beamforming. They also provide information about the sound power level. At higher frequencies, localization performance using ESM are similar to spherical beamforming but has the advantage of combining noise mapping and sound quantification together in one shot (see Figure 8).

Near-Field Acoustic Holography with Irregular Arrays. NAH requires a rectangular array with evenly spaced microphones, both horizontally and vertically. Horizontal and vertical spacing can be different. However, NAH cannot be performed with a beamforming array, because it is not rectangular and it has a pseudo-random microphone distribution. To overcome this, the problem is rewritten as an inverse method. The transfer function in this formulation includes both propagated and evanescent wave functions, and needs an optimal and stable PCA-based regularization, which includes evanescent wave filtering.

Figure 9 shows results for both focalization beamforming and irregular NAH techniques using the same circular 36-microphone array measured at the same distance of 20 cm. This provides a very low frequency analysis band of 60-70 Hz.

NAH using irregular arrays covers the purple square in Figure 5. Together with beamforming and focalization, it covers the entire space defined by good spatial resolution and wide frequency range with a single hardware investment.

Inverse Numerical Acoustics. Inverse numerical acoustics (INA) is a method that reconstructs the surface normal velocities

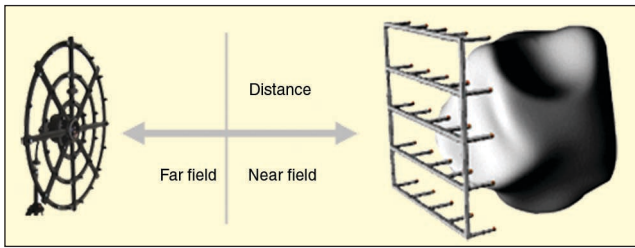


Figure 11. Distance to object determines technique.

on a vibrating structure from the sound measured in the near field around the structure. This is of particular interest when the structure is rotating or moving, too light or too hot to be instrumented by accelerometers. The use of laser vibrometers is often impossible due to the complex shape of the source. The retrieved surface normal velocities can later be used to carry out source ranking for different panels of the structure and to predict the pressure in the far field.

INA is a unique and hybrid solution, since it combines experimental sound pressure data in the near field, measured by a microphone array with acoustic transfer vectors (ATVs) obtained from simulation. The technique is based on the inversion of transfer relationships, which are obtained from an acoustic BEM formulation. Typically, only a limited set of microphone points are used in the near-field pressure measurements, which means the INA problem is usually underdetermined, resulting in a non unique solution for the surface vibrations. Using singular-value decomposition (SVD) with appropriate truncation, the most physically meaningful solution can be extracted (see Figure 10).^{9,10}

Selecting Localization Techniques

As previously noted, there is no universal solution for accurate sound source localization. Depending on the object under study and the noise problem, the most appropriate technique has to be selected. The selection criteria are: frequency range of interest; distance measured to the source; physical properties of the sound source; and operational conditions.

The first thing an acoustics engineer would do is measure the sound of the object under study with a single microphone from a relevant position, usually in the far field. From a single microphone spectrum, a number of critical peaks or frequency ranges can be identified, resulting in a minimum frequency (f_{min}) and a maximum frequency (f_{max}).

As a general rule, near-field techniques should be preferred when possible, since they often provide the best results in terms of dynamic range and spatial resolution. The combined near-field acoustic holography and near-field focalization approach (combined NAH-NFF) delivers optimal results, because NAH is the most suitable technique in the low and mid frequency range and NFF the most appropriate for higher frequencies.

Here the question needs to be answered as to whether it is possible to measure close enough to the source in the near field. As a rule of thumb, this is at a distance d equal to one or two wavelengths of the highest frequency f_{max} (see Figure 11).

Combined NAH-NFF requires that the array's dimension match the object size, since it back-propagates sounds perpendicularly to the array's surface. The array dimension in turn determines the number of required microphones and measurement channels. The array width depends on the size of the object and the minimum frequency of interest. For objects that are too big to reasonably match the size of an array, it is possible to use NAH and NFF to perform measurements in different patches until the full surface of the object is covered. In that case, the object's position has to be stationary. If the position is not stationary, it should at least be a repeatable transient condition, such as a run-up function of rpm or a repeatable impulsive noise, such as a door slam. If the minimum frequency of interest requires an array, which is far wider than the object, combined NAH-NFF still allows using an array that is of the same width as the test object. This yields correct source localization at the expense of less reliable source quantification.

The spacing between microphones will be determined by the

maximum frequency of interest and the granularity of the sound sources. If the maximum frequency is very high, the spacing becomes very small. Microphones that are placed too close to each other can cause interference in their respective sound fields. So the recommended relative position of microphones should not be less than 2.5 cm. If the granularity of the sound sources is small (all the small components in a door lock), then the microphone spacing should be adapted to this even if this is not needed for the maximum frequency. Too few points on the hologram do not accurately pinpoint which component is the sound source. In both cases, the ideal number of microphones sometimes outnumbers the availability of transducers and acquisition hardware.

As seen, there are some cases where combined NAH-NFF is not practical:

- It is not possible to measure in the near field
- The array size becomes too big
- It is not possible to measure in patches due to rapidly changing operational conditions

In these cases, a beamforming solution will be chosen. A good strategy is to first use classical beamforming like a far-field, wide-angle acoustic camera to get a global view on where the sound sources are located. As a next step, the acoustic camera is moved into the near field (at ± 20 cm) for a zoomed view of these sound sources using focalization. Finally, further refinement in the low and mid frequencies can be obtained using NAH for irregular arrays with the same data.


Conclusions

This article covers the sound source localization techniques commonly available today. It was shown that there is no one-size-fits-all solution. Selecting the proper sound source localization technique is a task that needs to take into account the frequency range of interest, distance measured to the source, physical properties of the sound source, and its operational conditions.

Combining NAH and NFF shows a clear advantage, since it measures in the near field giving the best spatial resolution and dynamic range over a wide frequency range. It uses a regularly spaced array. The cases where combined NAH and NFF is not possible are always of a practical nature and related to the source; either because of physical properties (dimension and granularity) or operational behavior.

Beamforming with focalization is a good alternative for such cases, providing results with good spatial resolution and dynamic range, depending on the frequency range. It uses an array with pseudo-random distributed microphones. Beamforming obtains analysis results in a single-shot, wide-angle measurement, making it an ideal tool for both troubleshooting, offering a quick preview, as well as in-depth, root-cause analysis using irregular NAH.

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