

Sound Power Troubleshooting Techniques

2011-01-1676

Published
05/17/2011

Chris Moon and DJ Pickering
Sound Answers, Inc.

Tony Frazer
Briel & Kjaer North America Inc

Chris Sievers and David Peffers
Vermeer Corporation

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doi:10.4271/2011-01-1676

ABSTRACT

Standard sound power test methods have existed for numerous years to allow for appropriate noise labeling of products for validation or for monitoring of changes. More recently, advanced methods such as acoustic holography and beamforming have also been successfully used for measurement of sound power and noise source identification. Sound power is a standard requirement for off-highway and agricultural vehicles, construction and power generation equipment, refrigeration and cooling devices, and many other consumer products. In the automotive industry, the engine and a few accessories (AC compressor, power steering pump) are tested for sound power. While sound power testing methods are well known and tests are conducted in most labs by efficient and often automated test procedures, the root-causing strategy in the case of lack of compliance to a specification is still mostly based on trial-and-error. This is likely due to the fact that engineers testing for sound power typically look at global, spatially and time averaged 1/3rd octave spectra of sound pressure and/or sound power, which are too coarse to provide meaningful diagnostic information. This paper describes a simple strategy that has been successfully used by many engineers to focus the troubleshooting and identification of countermeasures on the dominant contributions to the total sound power. Examples of this approach for a few different cases will be reviewed and its application to a large piece of construction equipment will be described with some details. The overall objective here is

to contribute to the product development process in terms of noise reduction.

INTRODUCTION

Sound power testing may need to be performed on various automotive and non-automotive products as part of a requirement for noise labeling or for usefulness in some level of noise source identification. A common need of many consumer products industries is for quiet products. An overall sound power, L_{W} , value can give a comparison method for how quiet a sound source is between competitors or previous components. An overall L_{W} value can also be used to judge the acceptability for human exposure to such a source. It is possible that in some industries, previous generation L_{W} levels may have been acceptable, but newer modes of machinery operation may now completely redefine levels for competitive industries.

There are multiple approaches for determining sound power values depending on the environment where the tests can be performed and the level of information needed from the test. Sound pressure-based methods are often the preferred method in controlled free-field environments but can also be used for some non-ideal, yet suitable free-field cases. Sound intensity-based measurement methods are an attractive alternative for cases where a sound source needs to be tested in-situ located near other sound sources and near reflective surfaces. There are numerous general issues, difficulties and limitations with these approaches that can be assessed prior to testing.

The availability of the intermediate sound pressure or sound intensity measurements used for the final L_W presentation can allow for some level of noise source identification. This can be limited by the spatial resolution of the number of sound pressure or sound intensity measurements (or area scans), but it may be sufficient for some level of noise source identification. Once measurements have been inspected and possible significant sound sources identified, often there are modifications that can be made to sources and/or paths to try and affect ultimately the overall L_W value. As always, these potential modifications should be considered in terms of their relationship with the overall design and certainly cost as well.

Modern methods like acoustic beamforming and nearfield acoustic holography (NAH) also exist for the determination of L_W values and noise source identification. These methods may allow for easier and more detailed noise source identification, especially in cases of large machinery size, complexity, and/or the time-variant nature of the sound radiation.

SOUND POWER TEST METHODS

The presentation of sound power is determined from the intensity of the sound source. This will either be from a non-gradient pressure measurement, a sound intensity probe or a beamforming array.

Testing in an idealized free-field environment will usually allow for a non-gradient, singular pressure measurement made at numerous locations on a known surface area surrounding the radiated source. These testing approaches will simply be described as ‘sound pressure-based methods’ since there is only a confirmed single direction of radiated sound and thus an ‘outward’ direction of sound intensity. This same test procedure can often be implemented in certain non-idealized free-field test environments if the environment can be shown to have minimal, or at least accepted, influence on any sound power calculations.

If the environment available for testing a radiating sound source is not an acceptable free-field environment, then other test methods may be suitable for sound power calculations. Testing with a pressure gradient approach using likely a sound intensity probe gives a vector presentation of sound intensity and may allow for testing in environments that may have some amount of sound energy flow towards the source to be tested. This non-ideal sound energy flow may be from environmental sound reflections or from other sound sources in the vicinity of the item to be tested. These test methods may be described then as ‘sound intensity-based methods’

Using whichever method, the sound power is then just determined using the sum of the magnitude or vectored intensity at each location multiplied with the area sections used for the measurements.

SOUND PRESSURE-BASED METHODS

Some test specifications in the ISO 3740 [1] series (3744[2], 3745[3], 3746[4]) allow for sound power determination using sound pressure in: essentially a free-field, hemi-anechoic, or anechoic environments. ISO 3740 gives a good description of which specification to use for different situations and depending on the grade of accuracy required.

When it comes to inspecting the radiated sound levels at various locations on a designated surface area, the most commonly referenced sound power ISO 3740 series specs are 3744 and 3745. The 3745 spec is described as the precision laboratory method and allows for spherical or hemispherical microphone arrangements in an anechoic or hemi-anechoic environment. It also gives calculations based on sound energy level (L_p) which can be more accurate for sound sources with transient events. The 3744 spec is an engineering grade method that describes measurements to be made over a reflecting plane and allows for hemisphere or parallelepiped microphone arrangements. ISO 3744 does not restrict measurements to be made in a laboratory but still does have background noise and environmental influence requirements and potential correction factors for each.

ISO 3741[5], 3743-1[6], 3743-2[7], and 3747[8] allow for a singular sound power value determination in a reverberant environment. This is not the focus of this paper since any surface area-based pressure measurements are not needed in a diffuse environment, and thus not available for any inspections that could be used for noise source troubleshooting.

The presentation of sound power values is often a useful point for discussion in terms of the uncertainty involved with a measurement. This is especially true when it comes to competitive product declarations of sound power. It is likely that unless otherwise declared, a sound power value presented only per an ISO series sound power specification will not have any uncertainty value added into the presented L_W value. These ISO sound power specs give detailed descriptions of common uncertainties, but references to other specs are required for actually determining the uncertainty for an actual measured machine or machines. ISO 4871 [9] is one example of a commonly referenced specification for making such uncertainty calculations for sound power or sound pressure tests. The common notation for sound power values that have attention placed on the uncertainty may be, $L_{WA,d} = L_{WA,m} + K$. Here, $L_{WA,d}$ is the *declared* A-weighted sound power, $L_{WA,m}$ is the *measured* A-weighted sound power for however many machines are available, and K is the calculated or assumed uncertainty value. Ideally, if a presented sound power value does include an uncertainty factor to it, then it will have the following wording, “DECLARED SINGLE-NUMBER NOISE EMISSION

VALUE” if a $L_{WA,d}$ value is given, or “DECLARED DUAL-NUMBER NOISE EMISSION VALUE” if both the $L_{WA,m}$ and K values are given. This entire discussion is presented because it has been the authors' experience that previous sound power tests performed on a machine actually included uncertainty value declarations, but the notation did not follow through with later experimenters. This presents an obvious difficulty during troubleshooting tests to try and recreate quoted sound power levels previously reported. It is also of note that tests for the European market require a declaration of the uncertainty with a sound power presentation per EC Directive 2000/14/EC [10]. Detailed investigations regarding the uncertainty of sound pressure-based measurements for sound power calculations can be found, for example, in Loyau [11].

SOUND INTENSITY-BASED METHODS

ISO 9614 series (9614-1 [12] and 9614-2 [13]) allow for sound power determination using sound intensity measurements. ISO 9614-1 describes making sound intensity measurements at discrete locations and 9614-2 describes sound intensity measurements for scanned areas. The environment is not at all specified in these specifications, but rather data quality indicators are required to be checked and presented to assess the acceptability of the in-situ environment likely needed for the test. When the sound intensity approach is deemed necessary, then these ISO specifications are now generally the main ones used since they require the check and reporting of the data quality indicators.

The main difference between the two ISO 9614 specs is that one describes testing at discrete points (9614-1) and the other describes scanning areas (9614-2) with a spatially averaged result, both on an enveloping surface surrounding the machine. When each specification is properly applied given the particular test structure, the reasons to select one method versus the other does not appear to be significant, but the 9614-2 scanning approach does seem to be more often requested and may be more practical in its setup and implementation. Due to the issue of possible near-field intensity circulation [14] that can affect the intensity estimation, 9614-1 requires a minimum distance from the surface of 0.5 m. This distance is reduced to 0.2 m for 9614-2 since the scanning approach can allow for some amount of compensation for the near-field intensity circulation [14]. This closer distance that is allowed with the 9614-2 spec may be advantageous for relatively low levels of intensity radiating from some types of machines, and due to issues in diffuse environments. Detailed investigations regarding the uncertainty of sound intensity-based measurements for sound power calculations can be found, for example, in Jacobson [15].

CHALLENGES WITH SOUND POWER TESTS

SOUND PRESSURE-BASED TESTING CHALLENGES

Some common challenges with the sound pressure-based approaches are:

1. Background noise requirements (issues with high background levels and/or low sound source levels)
2. Environmental sound reflections
3. Sound source sizing in anechoic environments
4. Source directivity

The main factors that are always addressed or commented on for sound pressure-based L_W tests are the background noise levels and environmental absorption/reflection characteristics. Both of these issues are frequency dependant.

The background noise is described by the K_1 correction. The requirement says that if the source measurements are greater than 15dB above the background measurement at all frequencies, then no background noise correction is needed. An empirically derived correction described in the specifications is applied when the difference between source and background levels is between 15 and 6 dB. This is something that may need to be monitored frequently in various environments, but potentially not as often in anechoic environments unless the source levels are very low. One common example of devices with very low operating sound pressures are spinning hard disk drives in computers. Devices such as these may require high sensitivity (~ 1000 mV/Pa) microphones that have a noise floor, for example, less than approximately 7 dBA at all frequencies within the audible range. Other sources of noise in the measurement chain should also be eliminated for such low noise test items.

If the background noise is defined as sufficient, then the last variable that can be changed to increase the source-to-background noise separation is the distance of the hemispherical or parallelepiped surface to the source. The smallest permissible distance is 0.25 m described in ISO 3744. Though, the trade-off is that the presentation of the low frequency range is compromised and should be investigated for importance based on measured spectra of the machine being tested. If the difference between source and background is less than 6 dB at some frequencies, then technically the results are not presentable for validation, but it may be argued that the frequency ranges compromised may have no measurable influence on the overall L_p (sound pressure level) or L_W average. Even if not technically valid according to the test specification, the tests certainly still can be performed from a troubleshooting standpoint if the

affected frequency range(s) are not relevant for the troubleshooting.

Testing outdoors in the presence of wind is sometimes unavoidable and challenging. The use of windscreens is often not solely sufficient. Careful acquisition and repeatability tests may be necessary to ensure that no turbulence-induced noise has been added into the results. This may also require immediate post test background noise checks for all mic positions after each sample or test iteration. Shielding of the wind may be attempted, if physically possible, though the environmental correction, K_2 , should not be altered beyond what is allowed in the specifications.

The environmental correction, K_2 , is usually addressed for non-anechoic environment tests. Anechoic chambers ideally have been validated for a defined frequency range to not have a need for a K_2 correction. Though, any changes made to a chamber may invalidate the initial rating. The K_2 correction may be needed in other types of environments and is checked with the reverberation time in the test environment. Attempts may be made to the environment to reduce the correction to be less than the specification, but this may be too difficult of a task in some environments.

The size of a hemisphere or parallelepiped measurement surface that may be placed inside of an anechoic or hemi-anechoic chamber is often an issue. A 4 meter radius is often a practical limit for a hemisphere placed inside of many common sized hemi-anechoic chambers. The difficulty comes in getting too close to the chamber's wall or ceiling wedges such that the sound field is no longer a free-field. Prior to testing, a sound source may be placed in the center of the hemisphere to inspect any close-wall effects. Measurements near the wall can be compared versus intermediate distances to inspect for 6 dB differences as a function of distance doubling/halving. If the free-field radiation prediction does not hold true for microphones approaching the room wedges, then the sound pressures at these locations will be overestimated. This is a frequency-dependant inspection and the results may be entirely sufficient for a test frequency range that does not include the lowest of frequencies.

It is common for some types of machines to exhibit high amounts of source directivity. This is especially the case for exhaust pipes from machines with engines. The specifications require that for the selected microphone positions, the difference in dB between the highest and lowest L_p measurements does not exceed the number of microphones. This is to eliminate a highly directive source from being placed in-between microphone locations. The required inclusion of additional microphone locations may then potentially aid in any noise source identification process and troubleshooting.

SOUND INTENSITY-BASED TESTING CHALLENGES

Some common challenges with the sound intensity-based approaches are:

1. Background noise issues (issues with high background levels and/or low sound source levels)
2. Environmental sound reflections due to close proximity of walls and structures
3. Testing near machinery air flow inlets and exhaust ducts.

The data quality indicators from the specifications, or so-called 'field indicators' are discussed here since their inspection gives an indication of the data quality and thus may define any realistic capability for noise troubleshooting using sound intensity data. The data quality indicators from the 9614-2 test specification (scanning approach) are only discussed here.

The $F_{+,-}$ indicator is a limit on negative partial power. This indicates the amount of negative intensity in the measurements and the allowance is based on the degree of accuracy described in the specification. Negative intensity is defined as intensity directed towards the sound source of interest that is being measured. The existence of negative intensity should be eliminated as much as possible. The placement of absorptive/barrier materials between suspected environmental sources of negative intensity can potentially help this issue. The measurement distance from the source may also be decreased to help this issue provided it is not believed that any near-field circulating intensity is encountered.

The partial power repeatability check is $|L_w(1) - L_w(2)|$, where $L_w(1)$ is a scan of an area done horizontally (or vertically) and $L_w(2)$ is a scan of the same area done vertically (or horizontally). If the frequency dependant differences exceed the specification, then the scan area may need to be reduced and/or the measurement time for the scan increased. Certainly, a difference here of $L_w(1) - L_w(2)$ could be due to machinery repeatability rather than scanned surface repeatability, so the machinery's repeatability (time invariance) should also be confirmed.

The F_{pI} indicator is the probe's frequency dependant pressure-intensity index in the particular test environment at each measurement location. This is simply $F_{pI} = L_p - L_I$. The L_p is approximately L_I in essentially a free-field environment. L_I is less than L_p in cases of a diffuse testing environment, if there are other noise sources operating in the environment, or if there are angled sound source inputs to the probe's position. It is often described along with the dynamic capability index of the probe, L_d . Where, L_d is just the pressure-residual intensity index determined during calibration, with a bias error factor

subtracted from it. These bias error factors are described in 9614-2 and depend on the grade of accuracy required for the test. L_d is ideally a large value and then wherever the pressure-intensity index, F_{PI} , is less than the L_d indicates a valid measurement per 9614-2. A F_{PI} value that is less than 5 dB is desirable if possible. When the F_{PI} values are greater, or much greater than 5 dB, there are two main issues to possibly address with the test. First, the limit of the sound intensity probe and acquisition system to detect actual low intensity should be considered, as determined by always knowing the L_d during the test. The calculation of intensity is based on the phase difference of two pressure measurements. Phase difference can be introduced due to phase mismatch of the two microphones as well as phase difference between acquisition channels. Ultimately then this is a residual intensity in the measurement system below which physical intensity cannot be determined. Secondly, the F_{PI} value can describe the reactive or diffuse nature of the test environment. Acoustically reactive or diffuse environments can result in little net intensity flow from an item of interest. Numerically, small net intensity flow is the same as small intensity flow, thus it can be below the capabilities of the test equipment to detect. Improving the dynamic capability of the measurements may be difficult to address. If the small intensity values are due to actual low levels of intensity of the source during operation, then potentially the measurement distance of the probe to the surface can be reduced if no intensity circulation is present. If the small intensity values exist with a large F_{PI} index value, then the environment is possibly highly reverberant and thus may be difficult to alter. Placing absorptive materials on walls may help this issue to some extent, and again, moving the measurement surface closer may also help.

Investigations on the effect of sound power due to sound sources near a reflecting plane can be found, for example, in [16, 17, 18]. Monopole investigations will show that due to the combination of the wave number, k , and distance to the reflecting plane, d , then low frequency and low distance of the source to a reflecting plane leads to an approximate doubling of the sound power. Numerically there could be cases of mid to higher frequencies along with very small distances to a reflecting plane leading to the same doubling effect, but these cases are not likely to be encountered in most practical test situations. Based on these types of calculations, it should be assumed that source to reflecting plane distances within several meters may cause there to be a reverberant environment and thus little net intensity flow. Positioning the test structure away from these reflecting surfaces and/or placing absorptive materials on the surfaces are the options to improve this situation if the test setup allows for it.

The suggested distance away from the measurement surface for overall structure or surface sound power tests is described by the 9614-2 specification as 0.2 m. There are currently no

specified detailed guidelines for defining the proximity of the probe to the test surface and there are numerous examples of tests performed anywhere from 20 mm to 0.5 m. The possible presence of frequency dependant circulating intensity is a real issue, so inspection on a case-by-case basis should be performed if close testing distances are deemed necessary for sound power tests. Most modern analyzers allow for real-time inspection of the spectral contents and also (+) and (-) intensity differences using color such that the distance normal to measurement surface may be inspected to find if there are any data problems as a function of proximity. This should be done carefully since the results at one area may not be the same as other areas on the machine. A reasonable approach for most large machinery structures tested in-situ over broad frequency ranges is to start with the spec defined distance of 0.2 or 0.5 m and monitor the F_{PI} index along with the dynamic capability index. If the data is not acceptable and the reverberant nature of the environment cannot be improved, then the distance from the probe to the surface should be reduced to see if an improved F_{PI} index can be achieved.

Since these described data quality indicators serve as the guidelines of the acoustic environment for sound intensity-based sound power tests, it is important that these indicators be surveyed as much possible on any previously untested machine/environment combination. Scanning various areas on all sides of the machine can allow for these data quality indicators to be assessed in a pre-test manner such that test setup adjustments can be made prior to the full test being performed. Again, the F_{PI} index should always be monitored along with knowledge of the dynamic capability index.

The test validation of these sound intensity based measurements for sound power results can be at times tedious for in-situ environments. Though, it is much easier to perform noise source identification, troubleshooting and design modifications if the best possible sound intensity data has been acquired.

Sound intensity testing near air inlet or exhaust outlet pipes or ducts is common for systems with engines or air handlers. Windscreens are usually specified for testing near machinery, but they cannot eliminate all amounts of pseudo-intensity generated due to the interaction of airflow on the probe's microphones for higher flow rates. The 9614-2 spec describes that no direct flow sound intensity scanning should be done if the airflow is greater than 4 m/s. Certainly, comparisons should be done with any higher flow rate to confirm if there is an issue. Edge scanning just outside the flow and then just inside the flow may show obvious differences in the spectrum if the flow is a factor. A machine's known volume flow rate for a known surface area may be used to approximate the mean flow velocity.

A common approach for determining the sound power of larger machinery's high flow inlet or exhaust ducts is to direct the large duct systems for testing into a reverberation room. This can be a time consuming approach to do during multiple stages of the development cycle, especially for large machines. One possible alternative is to scan the surrounding region of the duct that is not directly in the flow. Assuming that flow and sound propagation are in the same direction, then an estimation of the intensity in the presence of flow can be described assuming plane waves in one-dimensional mean flow [19] as,

$$I_{\text{flow}} = I_{\text{indirect}}(1 + M)^2$$

where,

I_{flow} , is the estimated intensity in the presence of flow

I_{indirect} , the intensity scanned near to, but not in the direct line of air flow for the test machine

M, is the mean Mach number for the direct flow

A 4-sided scanned region around the duct can be, for example, on an arc path area, where a representation is shown in Figure 1. This basic method could allow for an easier approach to make intensity comparisons between different design configurations, or possible correlation of L_{W} with reverberation room results.

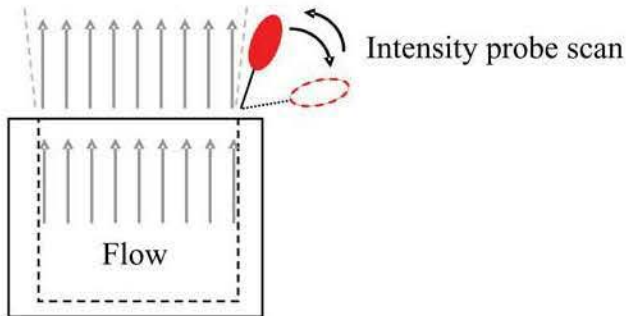


Figure 1. Scanning approach for measuring sound intensity near airflow with flow velocity greater than 4 m/s

NOISE TROUBLESHOOTING WITH SOUND POWER TESTS

The use of either multiple sound pressure or sound intensity measurement locations for determining sound power also allows for some amount of sound source identification studies to be performed. Once these measurements have been inspected and possible sources identified, often source and/or energy flow path modifications can be made to affect the radiated sound and ultimately the overall L_{W} .

NOISE SOURCE IDENTIFICATION

When sound pressure based methods are used for sound power calculations, the octave or 1/3rd octave spectra can usually be inspected for insight into possible noise source(s). These results could be obtained from one of the ISO 3740 specs mentioned. The overall averaged spectra can first be inspected to decide if the reason for the overall L_{W} level is due to some narrowband contents or broadband contents. An example of an overall averaged L_{W} 1/3rd octave spectrum for a 10-microphone hemisphere arrangement is given in Figure 2.

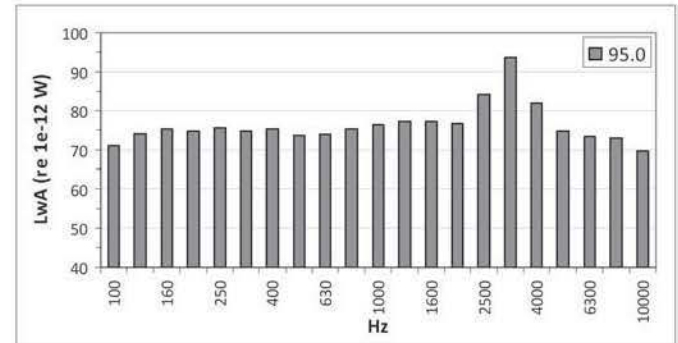


Figure 2. Overall averaged L_{W} 1/3rd octave spectrum for a 10-mic hemisphere test

The overall L_{WA} is 95.0 dBA and is mostly due to the 93.5 level in the 3150 Hz band. Lowering the level of sound power in this band will have the greatest effect in reducing the overall level.

Having the individual microphone sound pressure data available for inspection is often useful in highlighting possible directionality of the sound source's radiation. Figure 3 shows the basic 10-microphone positioning from ISO 3744 and Figure 4 shows the L_{pA} (A-weighted sound pressure level) responses in the 3150 Hz band for the 10 microphones for this tested machine.

Inspection of Figures 3, 4 along with knowledge of the actual component's orientation set up in the microphone grid can show the possible areas to focus on for noise reduction attempts. Here, there was a large radiating component and multiple, attached metal panels that were radiating in the 3150 Hz band. The main radiating component was on the same side as microphones 1, 4, 5, and 8, which show some of the higher L_{pA} levels. Microphone 6 also had a high level and was located on the other side of the machine. It had a mostly unobstructed thru-passage for the sound coming from the main radiating component. Note also that Microphone 10 on the top of the machine doesn't show much contribution and eliminates the need to focus on sound radiation in that direction.

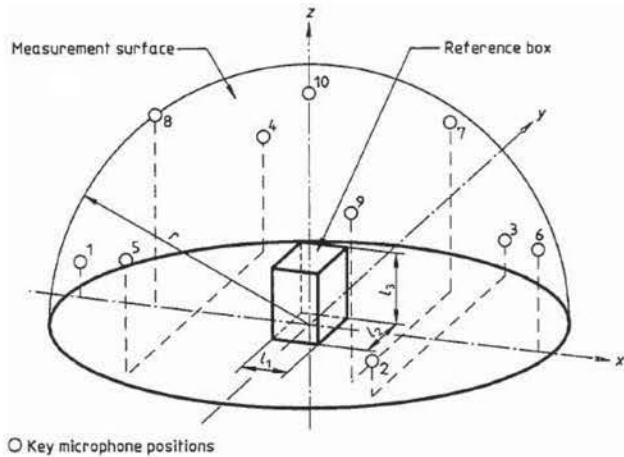


Figure 3. ISO 3744 10-microphone hemisphere arrangement

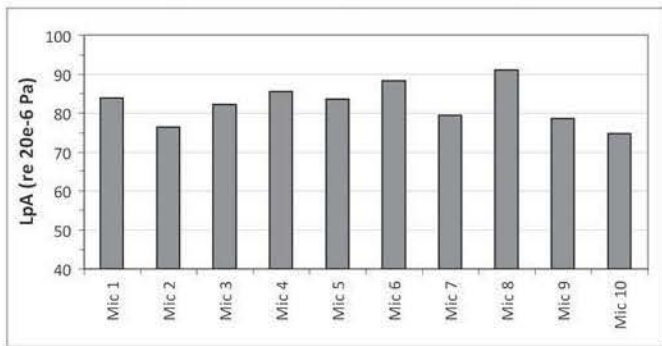


Figure 4. L_{pA} responses in the 3150 Hz band for the 10 microphones per ISO 3744

Figure 2 shows mostly a single $1/3^{\text{rd}}$ octave band response that was affecting the overall high L_{w} value. In this case it was a component in resonance, but the issue could certainly be a forced response for other machines. Affecting the reason for the high level will bring the $1/3^{\text{rd}}$ octave bands mostly to the same level. At that point, if the overall L_{w} level still needs to be reduced, then either a collection of narrowband contents or overall broadband contents would need to be addressed. In this particular case, for only a target L_{w} validation requirement, addressing the resonant component would bring the overall component within the required target.

It is often very useful to have all of the sound pressure/power data in a spreadsheet format at the time of testing so that logical attenuations can be proposed for any number of frequency bands. This can allow for judgments regarding how effective proposed modifications or treatments may be in the overall L_{w} summation.

It is of note that even for expected straight forward L_{w} validation tests, often additional processing formats and tests

can be performed in conjunction with validation tests. Most modern signal processing analyzers can be set up to simultaneously process not just overall averaged octave or $1/3^{\text{rd}}$ octave results, but also narrowband data, and time history or time-frequency results as well. Also, additional transducers such as tachometers, accelerometers, or other microphones can be set up to perform other analyses during steady state operation or speed sweeps. Examples may be order tracking or coherence-type analyses to aid any troubleshooting work that may be planned or unplanned.

When a sound power test is performed using sound intensity techniques, the noise source identification capabilities can usually be increased compared with the 10-20 microphone arrangement sound pressure approaches due to:

- (a). the likely increased spatial resolution that comes with most grids set up for intensity scanning
- (b). the vector presentation of sound intensity can give greater insight into outward radiating noise sources
- (c). the capabilities of most modern software packages to easily show intensity color maps for scanned surfaces.

A sound intensity scan per ISO 9614-2 is shown in Figure 5 for one surface of an operating machine. A 3×4 grid was set up per a supplier's specification and each of the individual areas were scanned with a sound intensity probe. The colormap shown represents the interpolated outward (and inward) radiating intensities measured for the entire surface in the selected 630 Hz $1/3^{\text{rd}}$ octave band. Selecting the location number '2' on the colormap in the Figure 5 shows the $1/3^{\text{rd}}$ octave plot for that particular scanned area. Here, inward flowing intensity towards the tested item is chosen to be shown in red. This was an indication of a nearby external component with a greater level in this 100 Hz band compared with the item under test.

The dominant level is shown in this 630 Hz band and was a suspected component located where the highest intensity levels are indicated in yellow on the colormap. Here, the sound intensity approach for a standard sound power validation purpose was needed due to a relatively difficult in-situ acoustic environment. The sound intensity scans logically also gave insight into noise source identification.

As was mentioned for the sound pressure based approaches, it is common to also perform other analyses simultaneously for additional data insight. A narrowband analyzer can also be set up for other studies like tonality calculations for some machines. If desired, time-history files can also be acquired from the two mics used in the sound intensity probe for any other post-processing or even listening study needs. Utilizing some reference signal(s), here the data can be presented in terms of the so-called selective intensity to highlight intensity that is coherent with the reference(s). The location of any

such references may be from previous knowledge or assumptions. Also, it is almost always advisable or required to do some level of pre-screening of the machine for validity of the test environment. During this pre-screening, data can be saved and assessed for possible structure measurement locations to be used as references for any selective intensity measurements.

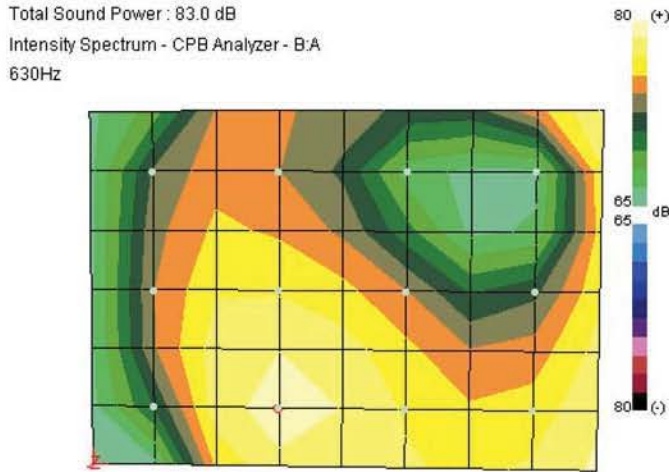


Figure 5. Sound intensity scan colormap (top) and 1/3rd octave (bottom) results for a machinery face per ISO 9614-2

SOURCE, PATH AND PACKAGING MODIFICATIONS

A more detailed case example of how this data can be viewed for noise source identification with the intent of modifying possible sources is shown for a horizontal drilling machine shown in Figure 6. This data is based on sound pressure based testing for L_{W} .



Figure 6. Horizontal drilling machine (courtesy of Vermeer Corporation)

Figure 7 shows a top-down view of a 12-microphone, 16 meter radius hemisphere used to acquire the sound pressure data for an overall L_{W} calculation. The testing was performed outdoors with the standard K_1 and K_2 corrections inspected but not needing to be implemented due to the environment selected for testing.

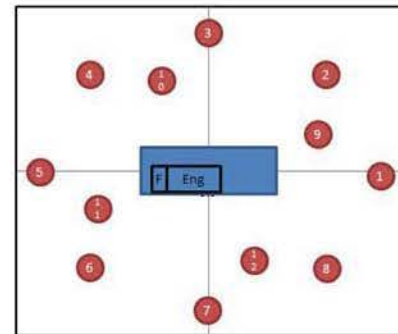


Figure 7. Top-down view of a 12-mic setup for testing the L_{W} of a horizontal drilling machine. The engine location is noted.

Microphone locations 5 and 7 have a proximity and directionality near to the engine and its cooling fan. The contents in the 315 and 400 Hz 1/3rd octave bands are the highest contributors to the overall L_{W} level.

Once initial inspections of the possible directionality of radiated sound is completed using the available microphones, then modifications to the structure can be performed in conjunction with additional investigation tests. All tests are ideally performed with the L_{W} microphone array still intact so that retesting can be performed whenever a modification is made so that the end effect on the overall L_{W} can be inspected. Also, if simultaneous acquisition is not possible for all required microphone positions, then any select microphone locations that may be dominant in the overall L_{W} summation can potentially be used for the modification studies to assess the effectiveness of any modifications. The on-line processing capabilities of modern analyzers can allow for making changes to a structure for investigation and then quickly acquiring new data for individual microphone

comparisons and then also giving immediate output of the overall L_W .

Figure 8 shows both 1/3rd octave and narrowband sound pressure results for the two most dominant microphone positions shown in Figure 7. Having the narrowband data along with a basic knowledge of the frequencies due to engine operation and rotating components allows for different response frequencies to be highlighted in more detail.

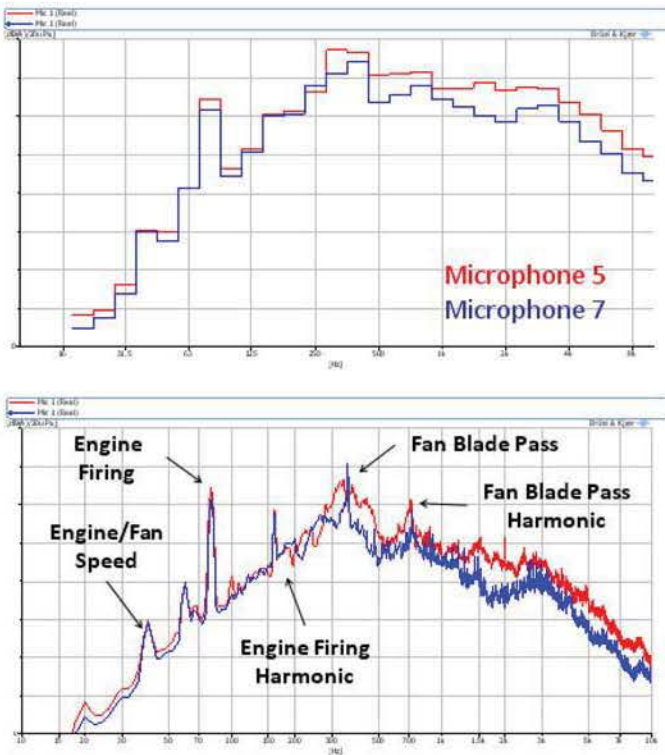


Figure 8. 1/3rd octave (top) and narrowband (bottom) data for 2 mics of a 12-mic L_w test

Some general, common modifications that can be inspected for many types of machines are:

1. Operating speed changes to simulate realistic actual speed changes or to simulate fan changes that could be implemented
2. Turning sub-component systems off
3. Classical lead or leaded foam wrapping approach for subcomponent sources
4. Separating mechanical from electrical induced issues by cutting electrical power to any motors for coast-down tests
5. Internal component isolation additions or modifications
6. Adding panels for noise reduction if previously non-existent
7. Increasing casing or panel thickness

8. Reducing noise leaks in paneled enclosures or housings
9. Absorptive or barrier treatments (local and/or global)
10. Panel damping treatments
11. Inlet/exhaust (cooling systems or engine related) flow treatments
12. Inspecting inlet/exhaust volumetric chamber changes
13. Redirecting inlet/exhaust flow
14. Structural modifications to affect resonance conditions
15. Removing some components

All of the inspected tests and final design approaches for this particular case are not discussed here, but an example of a basic investigation for this structure is shown in the 1/3rd octave plots in Figure 9. A temporary mechanical deflector was placed over a forward-facing cooling fan to investigate the effect at microphone 5. It was directed towards microphone 7 so that the effect of the fan's blade-pass frequency could be confirmed with a physical test. The total SPL at microphone 5 is reduced by 1.4 dBA and it is increased by 1.5 dBA at microphone 7, which is in the modified direction of the flow noise from the temporary deflector.

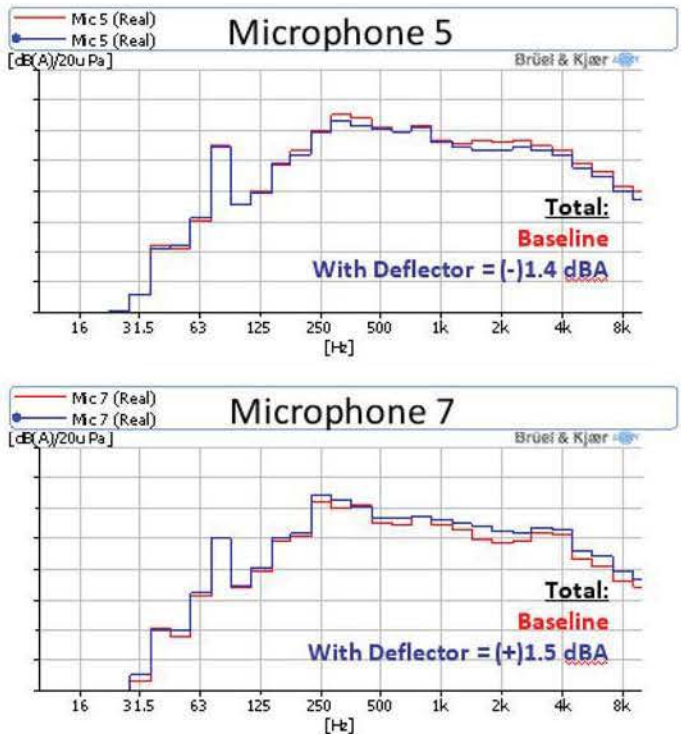


Figure 9. Basic SPL comparison due to the placement of a flow deflector

An overall summary of this basic troubleshooting process using sound pressure based tests is then:

- Perform baseline measurements on the machine with the full set of microphone positions. Simultaneous acquisition for the often numerous microphone positions is desirable if possible. Initially assess the repeatability of the measurements with multiple runs. This can later help to decide on the reality of small dB changes in the results due to modifications made to the structure.
- In conjunction with the overall L_W value, inspect the individual microphone locations for any evidence of directionality in the sound radiation.
- Note any existence of narrowband and broadband contents. Develop a tabular list of possible reasons for the spectral contents based on the machine's operating characteristics, flow cavities, etc.
- Perform any modification or treatment tests on the machine. Re-evaluate the overall L_W and individual microphone responses for effectiveness of the treatment.
- Either solely try a completely different attempt or retain any previously successful attempt(s) and cascade them with new attempts simultaneously. Continue until a target is achieved or no additional attempts are possible.
- Potentially perform a “peel off” series of tests where some or all treatments/modifications are removed/reversed to see the effect of various different combinations of treatments or modifications.
- Discuss with product engineers the reality of actually implementing any treatment or modification approaches.
- Perform any other types of investigation tests to understand the noise/vibration characteristics of the machine.

Other tests that may then ultimately be needed to more completely understand the characteristics of the machine are, for example:

- localized total or selective sound intensity scans
- localized frequency response functions (FRF)
- overall modal or operating deflection shape (ODS) analyses

MODERN SOUND POWER TEST METHODS

ACOUSTIC BEAMFORMING AND NEARFIELD ACOUSTIC HOLOGRAPHY

As described in Washburn, et al. [20], Acoustic Beamforming can be used for total sound power calculations as well as

noise source identification. In that study, sound power measurements were made on heavy construction equipment using a number of microphones in a hemispherical arrangement. Beamforming measurements were then made on each side; front, back, left, right and top, and the measurement techniques compared favorably. Beamforming measurements by definition provide sound pressure level maps, but an accurate pressure-to-power conversion can be made assuming all of the sources are Omni-directional point sources just behind the calculation plane. It was shown that Beamforming could be used not only for noise source identification, but also for a total sound power calculation.

Figure 10 shows data from a study designed to evaluate the power radiating into a truck cab. Instead of measuring inside, a source was placed inside the cab and intensity was measured outside. The first side that was measured revealed a leaky door seal, which was quickly modified before measuring.

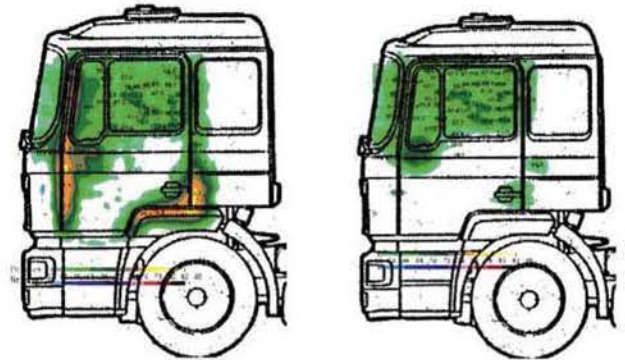


Figure 10. Acoustic beamforming results for a door seal investigation. Baseline (left) and after modifications (right)

For sources smaller than approximately 1-2 meters cubed, Nearfield Acoustic Holography (NAH) can be a useful technique for measuring total sound power and noise source identification. Traditional NAH is performed on an equally spaced rectangular grid of microphones. An FFT is used to transform the time-domain signals from each microphone to the frequency domain, and then at each frequency a spatial Fourier transform is done from the frequency domain to the Wave or K-domain. This transform is done to solve the wave equation. One convenient product of this transform is particle velocity. Since pressure is measured and particle velocity is calculated, intensity (sound power / area) can be calculated and total sound power integrated over the measurement area. NAH measurements can also be made on all sides of the source and total sound power can be calculated.

CONCLUSIONS

Sound power tests are frequently required for comparing the sound output for many types of machines. If a sound pressure based approach is performed, then multiple microphone positions are available to use for some amount of sound source directionality inspections. This knowledge can then be used to do basic noise source identification and modification investigations. Sound power testing using sound intensity methods provide another level of detail for noise source identification. Acoustic Beamforming and Nearfield Acoustic Holography then can also be used for more complicated structures or operating conditions. A basic procedure for inspecting various types of data has been shown here along with some possible examples of modifications that can be performed on machines to affect the sound power output.

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CONTACT INFORMATION

CHRIS.MOON@SOUNDANSWERS.NET

TONY.FRAZER@BKSV.COM

DJ.PICKERING@SOUNDANSWERS.NET

CSIEVERS@VERMEER.COM

ACKNOWLEDGMENTS

Thanks to Gabriella Cerrato at Sound Answers for her input into this work and also Todd Freeman at Sound Answers for some of the project work presented here. The help from other Brüel & Kjaer and Sound Answers personnel is appreciated.

DEFINITIONS/ABBREVIATIONS

L_w

Sound power

$L_{WA,m}$

Sound power level, A-weighted, *measured*

$L_{WA,d}$

Sound power level, A-weighted, *declared*

K

Uncertainty

K_1

Background noise correction

K_2

Environmental correction

L_p

Sound pressure level

L_{pA}

A-weighted Sound pressure level

$F_{+,-}$

negative partial power indicator

F_{pI}

pressure-intensity index

L_d

The dynamic capability index

I_{flow}

Estimated intensity in the presence of flow

$I_{indirect}$

the intensity scanned near to, but not in the direct line of air flow

M

the mean Mach number for the direct flow

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ISSN 0148-7191

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