Measuring system for sound source location for a systematic design modification of electrical machines

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Abstract - Only with acoustic measurements according to the CE-rules electrical machines and drives are allowed to bring to market. Manufacturer and importer normally already possess a sound intensity measuring system to gage the sound power as stipulated in the CE-labeling among other things. With minor enhancements, given in this paper, a source location and a frequency determination of the source is to be operable with a conventional sound intensity measuring system, so that a design engineering of electrical machines for reduction of radiated sound power could be done.

Manufacturer and importer have to fulfill the CE-rules[1] of produced electrical machines and drives. Therein international regulations (conformity of the evaluation method) for the following sound measurement categories are specified:

1. $L_{p(A)}$: emission level at the place of employment
2. $L_{W(A)}$: sound power level
3. $L_{p(C)}$ Peak: local peak level

Measurements of 1.) and 3.) could be done by the sound pressure method with low time exposure and low expenditure. There are a lot of handy sound pressure meters (one-microfone-meters), which have a comparable technology like the block-diagram in figure 1. In contrast to sound pressure the determination of sound power $L_{W(A)}$ is more difficult, because sound power is a characteristic acoustic energy-property of the machine and independent of the distance of source, the acoustic environment and steady background noise. Sound power can be related to sound pressure only under carefully controlled conditions with special assumptions about the sound field, so in practice it is not possible with a sound pressure measurement. The acoustic measuring gives a lot of methods for sound power determination (sound intensity, sound holography, beamforming) but only sound intensity has to become widely accepted for sound measurements at electrical machines. With two closely spaced microphones (face-to-face pressure probe) and online data processing (CPB-Analyzer) it is possible to calculate the sound intensity vector $\vec{I}_r(t)$. Thus only the radiated sound power of the machine that goes through to an envelope area (measured area at the machine) will be obtained. Steady background noise will be completely averaged to zero, because the measured sound power outside the envelope area that penetrates into must leave after reflection at the floor or the machine. The desired sound power $L_{W(A)}$ of the machine is the intensity vector multiplied by the envelope area. Only sound intensity measurements

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1 CE-labeling 93/68/EWG

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Figure 1: Block-diagram of a conventional sound pressure meter
can be done on unfavourable environments (strong sound reflections), e.g. unfavourable location of the machine (difficult of access), big dimension of the machine and last but not least high background noise (production hall). So measuring sound intensity is possible in any sound field. The evaluation of sound power (see 2.) is to be done fast and user-friendly by the "swept measurement over a surface"-method.\footnote{DIN EN ISO 3744} Thereby the probe is uniform swept over the measured surface around the machine with a suitable long average time. With the measured middle pressure $p(t)$\footnote{$p(t)$ is not the mean effective pressure but the pressure in the middle between the two microphones of the probe} and the velocity $v(t)$ the sound intensity, more exact the sound intensity component $I_r(t)$, can be estimated.

### Available sound measurement system

The radiated sound power of a machine breaks the limitations of machine manufacturer or CE-rules in many cases, so action is needed to reduce noise. Machines and drives consists of various sub-assemblies, which radiates or absorbs acoustic sound. If structural engineering measures has to be done for reduction the radiated sound power, information in detail are essential on sound propagation and mechanism of sound radiation as well as the knowledge of the main source properties like position of sources, spectral composition of sound emission and the relative part of the complete sound power (each source). In many cases an intensity measurement system is available and it is used to determine the sound power $L_{W(A)}$. With the same system the following can be done:

- Noise source ranking (without modifications)
- Sound source localisation (modified measurement recording and special data evaluation)

### Noise source ranking

Small measurement surfaces will be defined (surface subdivision) which enclose single machine components. All the other noise radiating components (sound sources) can be treated as background noises as long as the noise is stationary. In order that strong radiated noise of subdivision surfaces can be found and furthermore the total sound power can be received by adding the partial sound power of every subdivided surface. Thus the noise source ranking\footnote{method standardization gives a measurement time limit for different kinds of particularities. Thus also a sub-surface limit is given.} is a time-consuming method which assigns to partitions of the machine or drive with the associated sound power without modification of measurement. But the result is still only ,,one value” of sound power for a part of the machine so that there is no indicator for the location of the source or the causes of noise radiation.

### Sound source localisation

A measuring system was developed which received a matrix of intensity levels (near field measurements) from many equally spaced points on the measurement surface. It consists of the conventional (available) sound intensity measuring system (intensity probe, data processing and data storage) and special developed additional components:

- semi-automatic SPS probe track system
- interface (SPS-PC)
- extensive data processing
- visualization (2D-contour/3D-plots)

With these enhancements it is possible to find out the location and the frequency of the source or the sources. Furthermore, a statement about sound propagation can be issued by use of various visualization parameter\footnote{measured each with a distance about 0.05m over the center of loudspeaker} (intensity matrix, maximum intensity, measuring error $F_{+/-}$, row measuring error, intensity over all frequencies as well as positive intensity and negative intensity). Thus in combination with noise source ranking and sound source localisation a systematic design modification of electrical machines for reduction of radiated sound power can take place.

### Examination of measuring system

To illustrate the measuring system for sound source localisation two loudspeaker with constant distance together ($x=0.2m$) were gaged. The radiated sound intensity is about $I = 51dB$\footnote{at a frequency of $f = 1kHz$, independently adjustable.} at a frequency of $f = 1kHz$, independently adjustable. Sound source location was done by measuring the matrix of intensity levels with the intensity method very close to the surface of the speaker (probe-speaker distance: 0.05m), so that the signal-to-noise ratio increases.\footnote{A special developed semi-automatic probe SPS track system was utilized to measure the intensity of points on the surface (0.1$m^2$) with a grid of 0.025m. Thereby a conventional sound intensity measuring system was used. If the data evaluation of measured values is done with the special developed data processing and visualisation, sound sources (source) and their characteristics can be detected. The visualisation (3D-plot and 2D-contour) of the intensity matrix $L_I$ is shown in fig. 2. The same measured} A special developed semi-automatic probe SPS track system\footnote{was utilized to measure the intensity of points on the surface (0.1$m^2$) with a grid of 0.025m. Thereby a conventional sound intensity measuring system was used. If the data evaluation of measured values is done with the special developed data processing and visualisation, sound sources (source) and their characteristics can be detected. The visualisation (3D-plot and 2D-contour) of the intensity matrix $L_I$ is shown in fig. 2. The same measured} was utilized to measure the intensity of points on the surface (0.1$m^2$) with a grid of 0.025m. Thereby a conventional sound intensity measuring system was used. If the data evaluation of measured values is done with the special developed data processing and visualisation, sound sources (source) and their characteristics can be detected. The visualisation (3D-plot and 2D-contour) of the intensity matrix $L_I$ is shown in fig. 2. The same measured
values are used to get the visualisation of the maximum intensity matrix $L_{1\text{max}}$ in fig. 3. Now the sound sources (loudspeaker) appear.

Figure 2: conventional evaluation (sound intensity $L_I$)

Figure 3: special evaluation (maximum sound intensity $L_{1\text{max}}$)

Also the frequency $f = 1kHz$ of the located source (absolute position of grid on the right in fig. 3 $x$-position=8, $y$-position=4) can be found out with the analysis as spectral intensity allocation shown in fig. 4.

Figure 4: spectral intensity allocation of MP 68 ($x$-position=8, $y$-position=4)

In the above illustration the negative intensity level corresponds with the measured intensity towards the source and the positive intensity level with intensity that penetrates the envelope area (background noise).

**real Measurement**

The following sound intensity measurements were accomplished with a conventional measuring equipment. The intensity probe was placed in a distance of $d = 12mm$ to the machine which results in a specified measuring range of $40 - 5000Hz$. A 1/12 octave narrow band resolution with dB(A)-report was selected for the CPB-Analyser (Constant Percent Bandwidth) which results in 234 single measurements. In every measuring point the intensity of 90 sub-frequency-ranges were determined.

The gaged asynchronous machine was fed with a pulse width modulated converter at a frequency of $f_T = 3kHz$. In the following two working points of the machine will be compared.

- **“silent”**: The engine has low noise radiation at the base frequency of $f = 37Hz$ (motor operation mode below the synchronous frequency)
- **“loud”**: The engine has high noise radiation at the base frequency of $f = 57Hz$ (motor operation mode above the synchronous frequency)

The sound intensity level is measured with the conventional measuring equipment. An arithmetic summation of the intensity values from the sub-bands with a following level determination is processed. These values can be plot in 3D diagrams which are displayed in figure 5 and 6.

The difference of sound intensity $\Delta L_I = 20dB$ between the two figures is remarkable. The increasing of the base frequency from $f = 37Hz$ up to $f = 57Hz$ raises the sound intensity by the factor of 10, the sound power even by the factor of 100.

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*Br*uel & Kjær-Measurement system with Software Pulse Labshop V6.0

*the area of one measuring point is $0.1495m^2$ with a grid of $0.025m$ in each direction*
Extended evaluation of the measurements
With special software several more information about the character and the properties of the sound sources can be gained from the measured data. First of all the sources of the sounds can be located with the 2D isobaric plot. After that the associated frequencies can be determined with the evaluation at preselected measurement points (see figure). In the background of the 2D-plot the contours of the machine are displayed to locate the sound sources on the surface of the machine.

Three possible sound sources (Q1-Q3) can be found at the "silent" ($f = 37\, \text{Hz}$) operation point (see fig. 7). With the spectral intensity allocation the associated frequency can be determined.

Table 1: Sound sources at $f = 37\, \text{Hz}$

<table>
<thead>
<tr>
<th>x-axis</th>
<th>y-axis</th>
<th>description</th>
<th>MP</th>
<th>frequency</th>
</tr>
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<tbody>
<tr>
<td>11</td>
<td>8</td>
<td>Q1</td>
<td>193</td>
<td>434Hz</td>
</tr>
<tr>
<td>15</td>
<td>8</td>
<td>Q2</td>
<td>197</td>
<td>434Hz</td>
</tr>
<tr>
<td>14</td>
<td>4</td>
<td>Q3</td>
<td>92</td>
<td>434Hz</td>
</tr>
</tbody>
</table>

Figure 7: Sound sources at $f = 37\, \text{Hz}$

With the spectral allocation of the intensity at one measuring point (MP), for Example Q1 / No. 193 (see figure), it can be achieved that the converter frequency of $f_c = 3k\, \text{Hz}$ has no effect on the radiated sound power. In fact it is a magnetic excited sound with $f = 434\, \text{Hz}$.

Selective interpretation of one frequency-band
With parametric adjustment of the software several more information about the direction of the sound source intensities can be displayed.

It can be shown that the highest intensity of radiated sound power is at the base-frequency of $f_b = 37\, \text{Hz}$.

Table 2: Sound sources at $f = 57\, \text{Hz}$

<table>
<thead>
<tr>
<th>x-axis</th>
<th>y-axis</th>
<th>description</th>
<th>MP</th>
<th>frequency</th>
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</thead>
<tbody>
<tr>
<td>15</td>
<td>6</td>
<td>Q4</td>
<td>145</td>
<td>649.4Hz</td>
</tr>
</tbody>
</table>

Figure 9: Sound source Q4 at $f = 57\, \text{Hz}$
at $f_{\text{max}} = 434\ \text{Hz}$ and at the base-frequency of $f_b = 57\ \text{Hz}$ at $f_{\text{max}} = 649.4\ \text{Hz}$. With this result the possible sound source of the Extended evaluation can be validated to assure sound sources. The opted setting of the CPB-Analyser (1/12 octave narrow band resolution with a measuring band of $40-5000\ \text{Hz}$) results in 90 sub-frequency-bands. The selective interpretation of one frequency-band is processed with a calculation of the intensity-matrix from the intensity-values at one frequency. If the polarity of the intensity is considered, the positive (sink) and the negative (source) intensity-matrix can be calculated. With these matrices the part of the sound emission and immission of the measured area from the overall sound intensity can be displayed.

The 3D-Plot (contour) for the “loud” operating point of the machine at $f = 57\ \text{Hz}$ is displayed in figure 10.

With this method the position and the direction of the sound radiation can be displayed in a better and more accurate way than the intensity-matrix in figure 4. In the 3D-Plot of the negative intensity instead of the absolute intensity the area of “reactive” sound intensity at the frequency of $f = 649.4\ \text{Hz}$ is well cognizable. In this area no sound radiation take place (circulation).

With the knowledge of the place and frequency of sound radiation detailed design modifications of the machine can be done. With the presented method these additional information can be achieved with the standard intensity measurement system, which is available in most cases for the CE-Certification. Only the recording of the measurement-points has to be done by an automated linear axis in combination with adequate data processing equipment.

References


