Localization of Noise Sources in Electric Cookers Based on Sound Pressure and Intensity Measurements

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Abstract

The main aim of the study was to compare the features of acoustic maps created on the basis of measurements of sound pressure and intensity in a near acoustic field. Data for comparisons were obtained within the framework of acoustic tests of electric cookers. The results of these studies may help in the selection of acoustic mapping and optimization methods according to individual needs and/or requirements concerning selectivity, measurement bandwidth, dynamics and the ability to locate sound-emitting areas. The paper also presents the results of the spectral analysis of the dominant sources of noise in the cooker, which was helpful in identifying and locating paths of noise propagation from the inside of the cooker.

Keywords: electric cooker, acoustic pressure, sound intensity, noise source localization

1. Introduction

From the point of view of consumers, the class of household appliances is demonstrated, among other things, by the noise it emits. This concerns both devices with significant vibroactivity, such as washing machines or kitchen robots [1], as well as devices with medium and low vibroactivity, such as dishwashers or fridges [2]. The latter group also includes electric cookers. The generation of sound in these devices may be of different nature, e. g. aerodynamic noise (hot air circulation, cooling system) [3], mechanical noise (drive and spit gear), magnetoelectric noise (motors and induction heating systems) [4, 5] and thermal noise (resulting from the formation of stresses and their relaxation). As a consequence, producers carry out vibroacoustic (VA) testing of these devices. Their aim is to obtain information enabling identification of noise sources in prototypes and its reduction. VA tests may also be a tool for post-production quality control of products. In this aspect, the article compares two methods of obtaining information about local sources of sound emitted by devices: measurement of acoustic pressure in a near acoustic field and measurement of sound intensity. A freestanding stove with an electric oven and an induction cooktop was tested. The test results allowed us to specify the advantages and limitations of both measurement methods and their suitability for the above purposes.

2. Object of research

The object of the study used to compare the efficiency of sound source locations was a free-standing cooker with an induction cooktop and an electric oven. This device has components that may be local sound sources. Figure 1 shows the tested stove, the measurement grid used for measurements in a near acoustic field and indicates the components - sound sources.

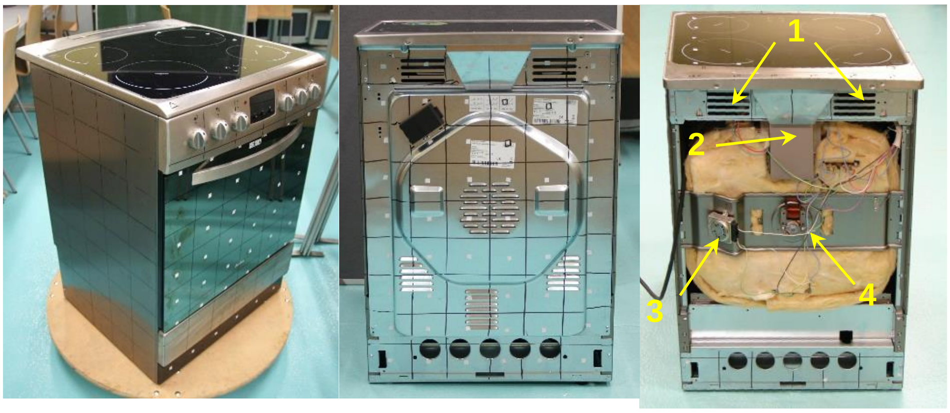

Figure 1. Tested object; view; rear wall with measuring grid and after removing the cover (1 – ventilation grilles, 2 – outlet duct from the oven, 3 – spit drive, 4 – motor for the hot air circulation fan)

Sound sources can be of a different nature. In the examined model of the cooker, the sources of mechanical noise are: fans, spit and electric motors partially driving these components. The motors also generate noise from magneto-electric phenomena. Noise of a similar nature is emitted by inductive heating fields.

There are 2 fans in the cooker. A centrifugal fan without a typical housing is used in the hot air circulation system. A second fan is located in the space between the oven and the cooktop and ensures air circulation. The fans are flow-through machines and therefore mainly emit aerodynamic noise. In the noise spectrum of fans, the components of the vane frequency and its superharmonics can be expected, as well as the broadband noise associated with the airflow. The noise from the inside of the oven propagates, among other things. through the outlet channel at the back of the stove (see Figure 1).

The views of the components in the tested stove and the octave spectra of the sound pressure levels recorded during their operation are shown in Figures 2 to 6. On the bar charts, gray color was used to distinguish the acoustic background level. The signals were recorded at a distance of approx. 100 mm from the working components. The comparison of spectra and A-weighted sound levels allowed to determine the dominant source of noise in the tested cooker.

The presented spectra largely facilitated the analysis of acoustic maps in terms of identification of noise sources and paths of noise propagation from the inside of the stove.

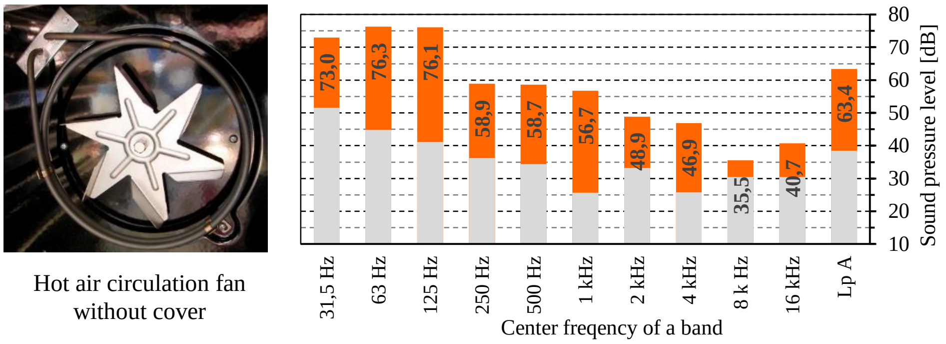

Figure 2. Octave spectrum of the noise of the hot air circulation fan

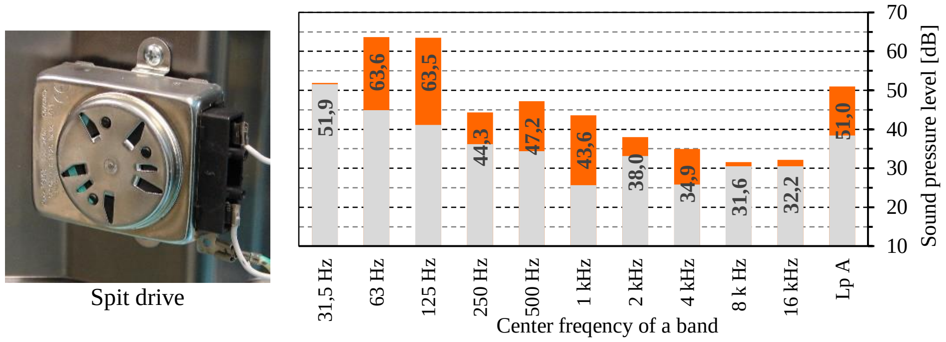

Figure 3. Octave spectrum of the noise of the spit drive

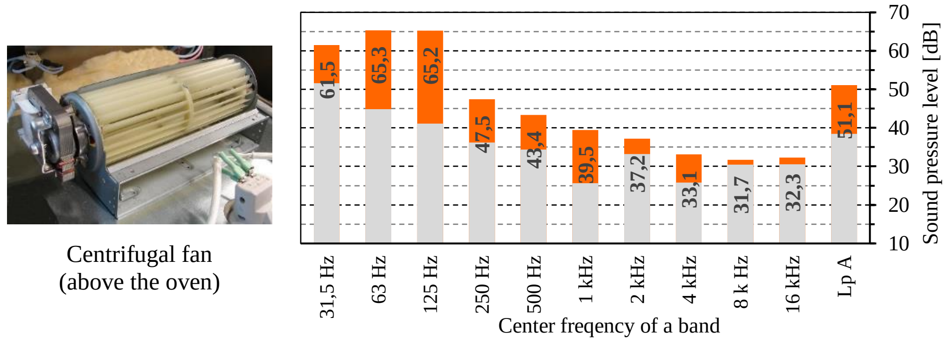

Figure 4. Octave spectrum of the noise of the centrifugal fan

Induction heating field
(without glass faceplate)

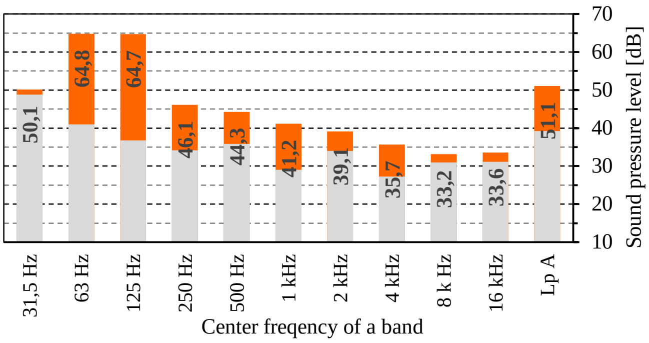

Figure 5. Octave spectrum of the noise of the induction heating field, continuous operation

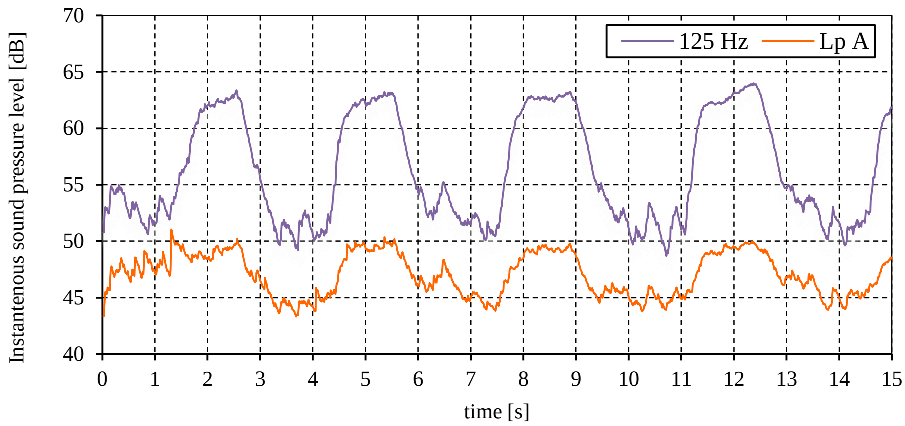

Figure 6. Changes in the sound pressure levels recorded during the cyclical switching on of the heating field (50% power)

When the oven is heated, crackling occurs due to the relaxation of stresses caused by the thermal expansion of the elements in the oven. This noise has an impulse character and is characterized by significant changes in instantaneous sound levels. Examples of changes of the sound pressure level recorded inside the oven in the initial phase of heating are shown in Figure 7a. The octave spectrum of noise in the heating phase (averaged over a 30-second signal sequence) is shown in Figure 7b.

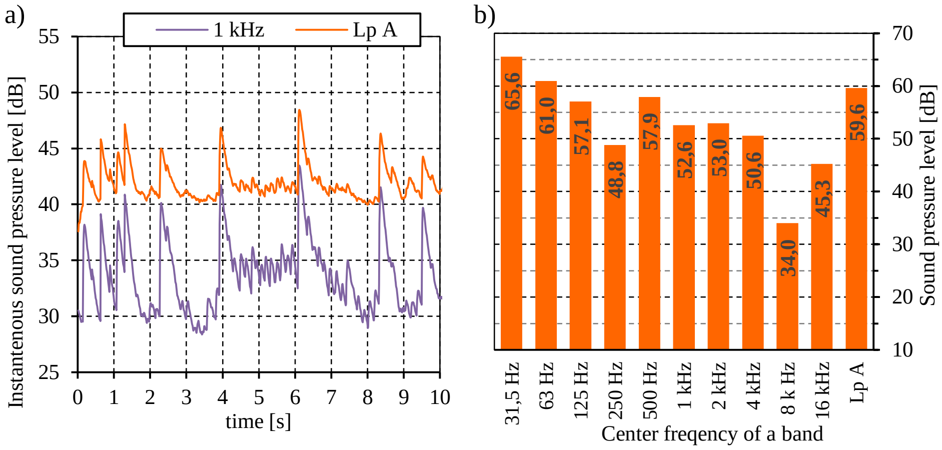

Figure 7. Changes in sound pressure levels and the octave spectrum of noise during the preheating phase of the oven

Impulse noise associated with oven heating in comparison with the noise emitted by the presented components has also important components in higher frequency bands (up to 4 kHz).

3. Methods for locating noise sources

The main purpose of the study was to compare the effectiveness of two methods used to identify and locate paths of noise propagation from inside of the oven. The noise mapping methods were compared in qualitative and quantitative terms based on:

- sound pressure measurements in a near acoustic field,
- measurements with an intensity probe.

3.1. *Sound pressure measurements*

Measurements of acoustic pressure in the near acoustic field of the cooker were performed with the use of a condenser microphone GRAS 40AN (polarizing voltage: 200V) with a SVAN 01A preamplifier cooperating with a SVAN 912AE analyzer. During the measurements, the following analyzer settings were used:

- FUNCTION 1/1 Oct (type of analysis),
- RMS_DET Slow (time characteristics),
- A.REPEAT Off (auto-repetition),
- AVERAG. Linear (type of averaging),
- AV.TIME 20s (time of averaging).

Scanning of the kitchen walls with a microphone was carried out at a distance of 100 ± 1 mm from the surface of the tested object. For the rear panel, which is not flat, the distance of 100 mm was determined from the heptagonal embossed plane (see Fig. 1). Octave analysis was performed in the full acoustic band, however, the subject of comparisons were sound pressure levels in octave bands with mid-band frequencies from 63 Hz to 2000 Hz, which resulted from a limited band of intensity measurements. The assumed 20-second averaging time was sufficient due to the stationary nature of the emitted noise. The measuring grid was composed of 228 sub-areas with dimensions as close as possible to a square with a side *a* = 100 mm. The surface of the cooktop was divided into 30 fields (5 columns and 6 rows), side walls - 45 fields (5 columns and 9 rows), and the front and back of the stove - 54 fields (6 columns and 9 rows). The total measurement time was 76 minutes, this time did not include preparatory and finishing activities and time related to moving the microphone between subsequent measurement fields. In order to obtain reliable results with this method, it was necessary to guarantee a sufficiently low level of acoustic background (minimum 10 dB less than the level of noise emitted by the object).

An example of a map of sound pressure levels is presented in Figure 8. Due to the location of dominant sound sources in the back wall of the stove, the comparison of methods was based on acoustic maps of the back wall.

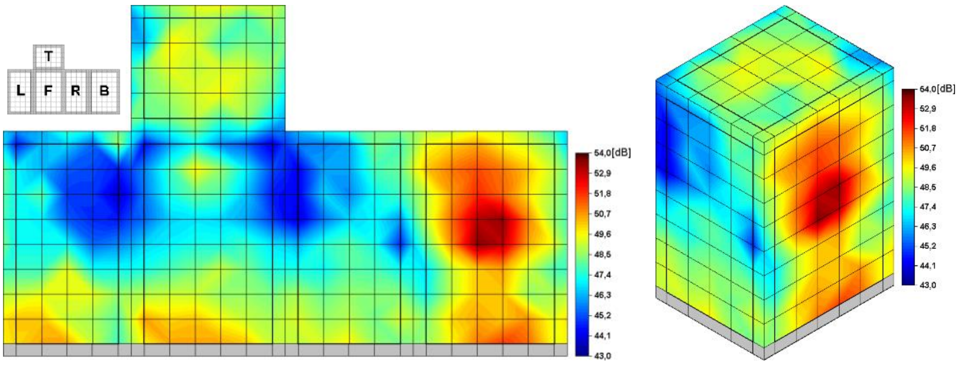

Figure 8. Map of sound pressure levels in an octave with a mid-band frequency of 250 Hz, in a developed view and in isometry

3.2. *Sound intensity measurements*

Sound emitting areas can also be located based on sound level maps. In this case, measurement at discrete points method was used [6]. It involves measuring sound intensity with a two-microphone probe (Fig. 9) at a short distance from the tested surface. For comparative purposes, an analogous measuring grid with uniform density was adopted. The normal component of the averaged sound intensity was measured, both its active part related to the energy radiated by the source and the reactive part related to the circulating energy (not radiated outside) [7].

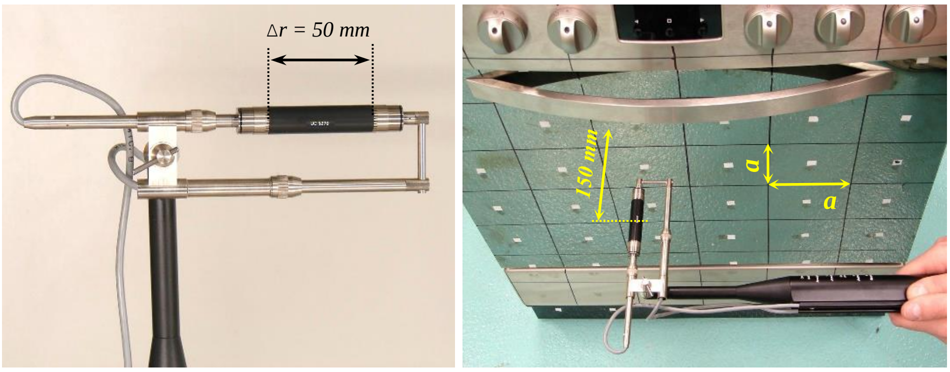

Figure 9. Two-microphone sound level probe with a separator of length Δr; carrying out measurements

Sound intensity is a vector that expresses the flow of sound energy through a unit surface. It is defined as the time-averaged product of the sound pressure and the speed of the particle [7]:

$$\vec{I} = \overline{p(t)\vec{u}(t)}, \tag{1}$$

or the time-averaged product of the sound pressure and particle speed in the direction r:

$$I_r = \overline{p(t)u_r(t)}, \tag{2}$$

where: $p(t)$ – instantaneous sound pressure at the point, $\vec{u}(t)$ – particle velocity at the same point, and the bar indicates time averaging.

The active part of the intensity measured in the direction r may be expressed as [8]:

$$I_r = \frac{-p_{\mathrm{RMS}}^2}{\rho c k} \cdot \frac{\partial \varphi}{\partial r}, \tag{3}$$

where: p_{RMS} – rms value of sound pressure, φ – phase between pressures measured by two microphones, ρ – density of the medium, c – speed of sound in the medium, k – wave number.

In measurement practice, when using a two-microphone intensity probe, the intensity is determined in the frequency domain from the formula [7]:

$$I_r = \frac{-1}{\rho\omega\Delta r}\mathrm{Im}(G_{AB}), \tag{4}$$

where: ω – frequency, Δr – distance between microphones, $\mathrm{Im}(G_{AB})$ – the imaginary part of the mutual spectrum of sound pressures measured in points A and B.

The reactive part of the intensity can be defined as [9]:

$$\vec{J} = \frac{1}{2}\mathrm{Im}(p\vec{u}^*), \tag{5}$$

where u^* indicates the complex conjugate of u.

However, in the direction *r* the reactive part of the intensity can be determined as [8]:

$$J_r = \frac{-1}{2\rho c k} \cdot \frac{\partial p_{\mathrm{RMS}}^2}{\partial r} \tag{6}$$

It is also worth mentioning another possibility of creating sound intensity maps. If the sense of the intensity vector (negative values of the intensities obtained in the measurements) is taken into account, the acoustic energy absorption areas may also be determined.

In order to compare the results of the intensity method with the method of acoustic pressure measurements, the intensity measurements at the points of the measurement grid were used. Only the normal component to the measurement area was taken into account, which required proper maintenance of the probe direction during the measurement. Wherever possible, measurements were taken using a tripod. A constant distance of 150 mm between the probe and the object surface was maintained during the measurement (see Figure 9). The averaging time at each of the measurement points was 60 seconds.

The measurements were performed with B&K 3548 sound intensity probe coupled with B&K 2144 real-time frequency analyzer. The frequency range of the spectral analysis was related to the linear response of the probe: 31.5 Hz to 1250 Hz. In this band the highest levels of noise emitted by components of the stove were present, shown in Figures 2, 3 and 4. This limitation also resulted from the use of a separator between microphones with a length of Δr = 50 mm. The use of separators with a length of 12 mm or 6 mm would allow to obtain results in higher frequency bands of 125 Hz to 5 kHz or 250 Hz to 10 kHz respectively [10, 11]. Measurement of sound intensity in the band from 31.5 Hz to 10 kHz would require the use of at least 2 separators with lengths of 6 and 50 mm.

4. Results (acoustic maps)

The acoustic maps of the back wall of the stove were analyzed in order to compare the described methods. Acoustic maps for bands from 125 Hz to 2 kHz are presented. These are the bands in which the noise emitted by the components shown in Figures 2, 3 and 4 was expected to be visible.

For intensity measurements with a 50 mm separator, the map in the 2 kHz band is for illustrative purposes only (this band is outside the linear range). The results may be affected by an error of up to approx. 3 dB [11].

The following conclusions can be drawn from the comparison of the acoustic maps:

- Both the pressure and intensity maps in the 125 and 250 Hz bands clearly show the sound emission area in the middle of the rear wall. This is very likely to be due to the noise emitted by the motor driving the hot air circulation fan (see Fig. 1).
- The 1000 Hz band shows the area of noise emission from the ventilation duct from the oven (see Fig. 1).
- In the upper part of the map of sound pressure levels in the 2000 Hz band, two local noise sources can be distinguished - ventilation grilles. On the other hand, the intensity level map does not distinguish between these two point sources of noise. It should be noted, however, that measurements in this band exceed the linear range of operation of the intensity probe (for a 50 mm separator).

- In the 500 Hz band, the local maxima occur in different areas, which results in a low correlation coefficient between the maps in this octave. It is also difficult to unambiguously link local maxima with a specific component.

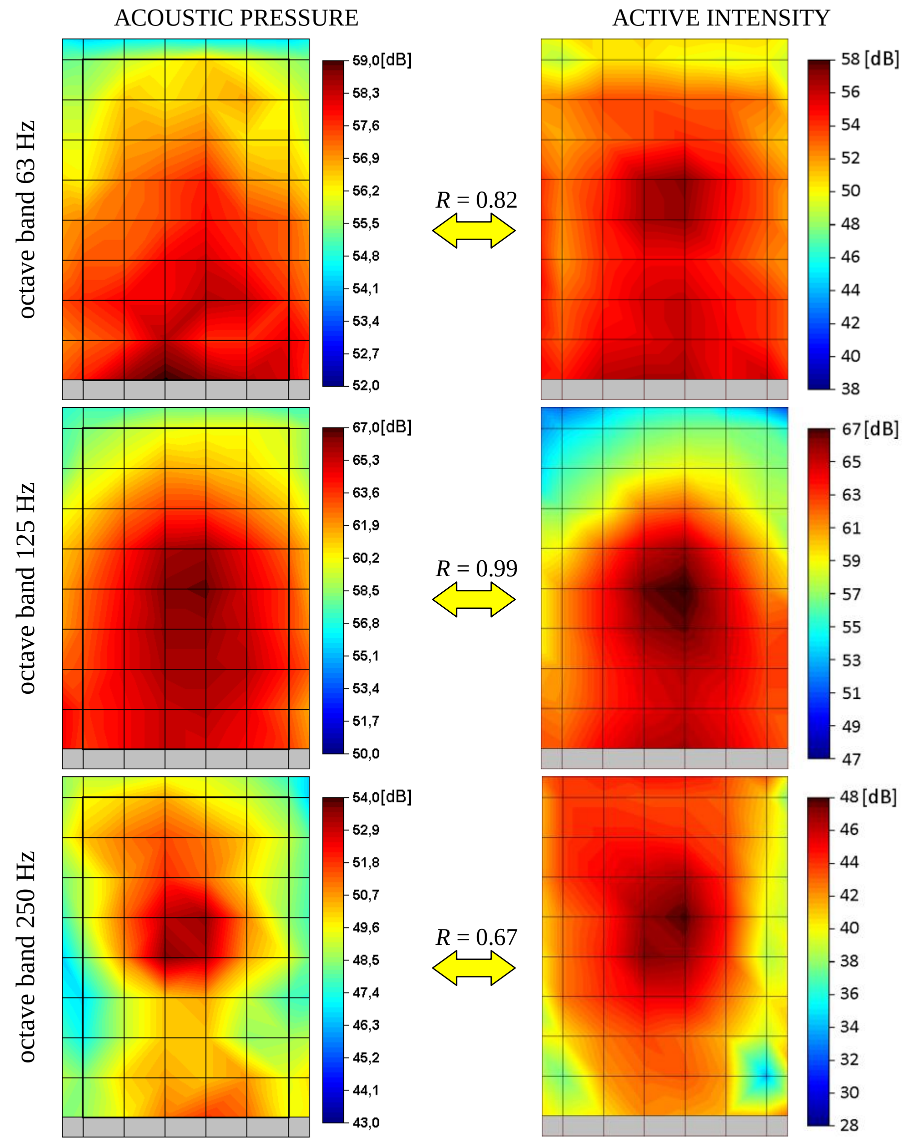

Figure 10. Comparison of acoustic maps based on the results of measurements of sound pressure and intensity in a near acoustic field; octaves 63 Hz, 125 Hz and 250 Hz (R – correlation coefficient between maps, the graphics were prepared in scilab-6.02 environment [12])

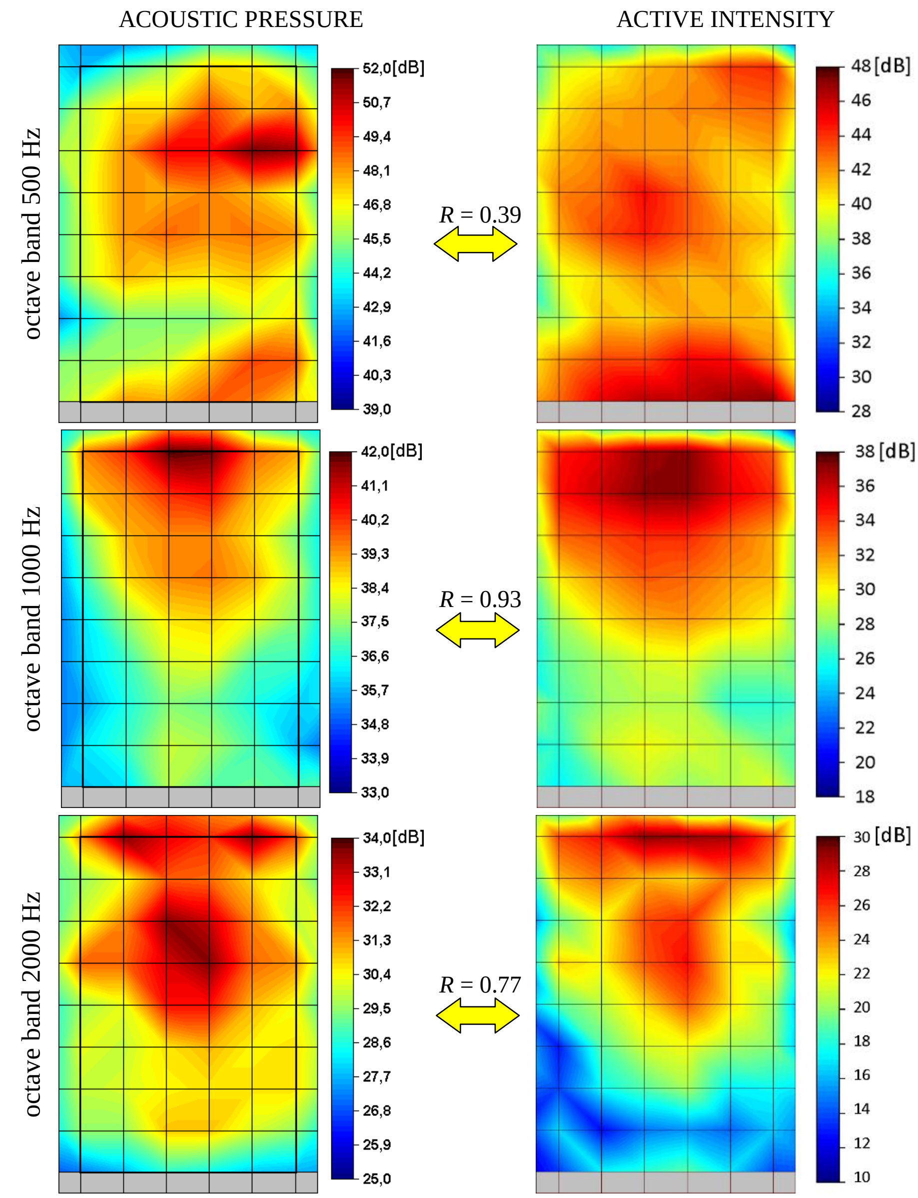

Figure 11. Comparison of acoustic maps based on the results of measurements of sound pressure and intensity in a near acoustic field; octaves 500 Hz, 1000 Hz and 2000 Hz (R – correlation coefficient between maps, the graphics were prepared in scilab-6.02 environment [12])

From the point of view of the assessment of the effectiveness of the location of areas emitting sound on maps obtained by the two methods, it was advisable to estimate the dynamics and selectivity of maps. To estimate the dynamics, the maps (bands: 125 Hz, 250 Hz and 1 kHz) for which the highest differentiation of levels was noted and where the areas emitting sound were clearly visible were taken into account. To compare the selectivity in terms of location capabilities, a map for an octave of 125 Hz was selected, characterized by a well visible local sound source. To estimate the selectivity, the criterion of a 3 decibel drop in the levels in the local maximum environment was adopted. The obtained result was related to the measuring grid size *a*. The results of the assessment of selectivity and dynamics of acoustic maps made by two methods are presented in Figure 12 in Table 1.

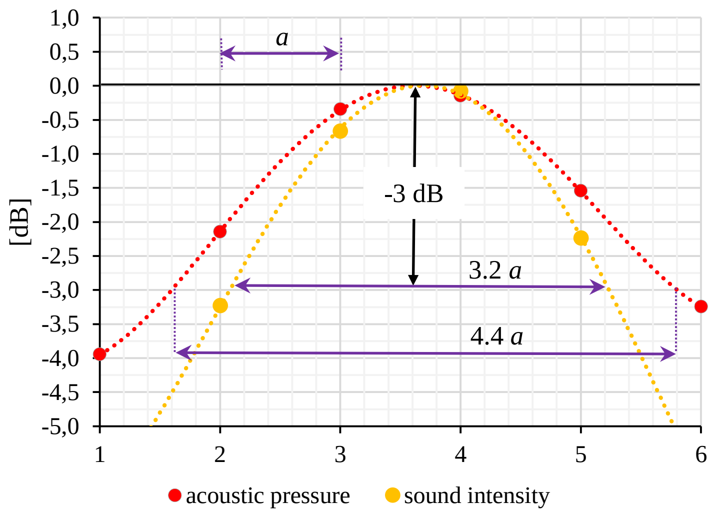

Figure 12. Example of comparison of selectivity of acoustic maps,
octave 125 Hz, polynomial interpolation

Estimation of the selectivity of the source location was made, for example, for maps in the 125 Hz octave band, where the highest pressure and intensity levels were recorded, and in the central part one local noise source was clearly visible. The selectivity of sound source location based on acoustic maps is better for intensity measurements. It is related to the grid size and is 3.2 *a* (for pressure measurements the selectivity is 4.4 *a*). These values are only estimates but this regularity applies to other maps in other octave bands.

Table 1. Maximum and minimum levels and map dynamics

octave	pressure level [dB]			intensity level [dB]		
	L_{max}	L_{min}	ΔL	L_{max}	L_{min}	ΔL
125 Hz	66.5	58.0	8.5	67.0	53.4	13.6
250 Hz	53.5	46.8	6.7	47.9	33.9	14.0
1000 Hz	41.9	35.5	6.4	37.3	24.5	12.8

From the data in Table 1 it can be concluded that the maps made using the intensity method are more dynamic than the maps made using pressure measurements. It can be estimated that the dynamics of the former is on average by approx. 6 dB higher.

The conducted research allowed to compare the properties, advantages and limitations of the presented two measurement methods being the basis for the creation of acoustic maps. Such a comparison of maps obtained during the tests of electric cooker is presented in Table 2.

Table 2. Comparison of the characteristics of the methods used to locate the sources of noise emitted by the stove

	Intensity method	Pressure measurement
Measuring band	Depends on the length of the separator, 31.5 Hz – 1250 Hz (Δr 50 mm); 125 HZ – 5 kHz (Δr 12 mm); 250 Hz – 10 kHz (Δr 6 mm)	20 Hz – 20 kHz; Wider bandwidth possible
Measuring time at one point	60 s	20 s, or shorter
Number of measuring points	216	216
Total time of measurement	216 min (1 separator, limited bandwidth) 432 min using 2 separators (e.g. Δr 50 mm and 6 mm, band from 31.5 Hz to 10 kHz)	72 min in full acoustic range
Possibility of use in industry	Can be used with most appliances [13], according to IEC 60704-2-10 [14] cannot be used for inspection of cookers	Limited, requires a separate measurement room, preferably with acoustic adaptation
Impact of the measurement environment	Insignificant impact of interferences	Significant influence of acoustic background and interferences and, to a lesser extent, of the sounds reflected in the test room
Experience of the measuring operator	Required extensive experience and knowledge of sound intensity measurement and analysis	Required basic knowledge and skills in the field of acoustic measurements and analysis
Automation of measurements	Possible with automatic probe positioning system (measuring frame, industrial manipulator)	Possible with automatic microphone positioning system (measuring frame, industrial manipulator)
Interpretation of results (shown in the form of a map)	Easy based on the active part of the intensity; not intuitive based on the reactive part of the intensity	Easy (intuitive)
Determination of the sound power level	Possible in a near acoustic field, in the presence of interfering sources and under any ambient acoustic conditions [15] e. g. based on ISO 9614 [16]	Possible after taking into account the influence of background noise and reflected sounds, required fulfillment of conditions concerning the measuring environment, e. g. based on ISO 3746 [17]
Equipment	Advanced, rather expensive	Commonly used, moderate cost
Dynamics	higher	lower
Selectivity	higher	lower

5. Conclusions

The results of the research may be helpful in the selection of the method of acoustic mapping and optimization of operations depending on individual needs and/or requirements concerning selectivity, measurement bandwidth, dynamics and ability to locate sound-emitting areas.

To sum up, it can be concluded that the intensity method allows to obtain maps with better selectivity and dynamics compared to the pressure level maps. However, obtaining results in the band from 20 Hz to 20 kHz is guaranteed by sound pressure measurements (the upper limit of the measuring band is only limited by the linear microphone bandwidth). The use of the intensity probe allows to create maps in a range up to approx. 10 kHz. In this case, it is necessary to use 2 separators Δr = 50 mm and Δr = 6 mm. The consequence of this is at least 2 times longer time of measurements (assuming the same measurement time - averaging time).

An alternative way of creating intensity maps enabling to avoid this inconvenience is to use a *Microflown* probe. It guarantees measurements up to approx. 11 kHz [15].

The results concerning dynamics and selectivity are for illustrative purposes only and are related to a specific object. For more accurate results, targeted research is required.

Acknowledgment

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