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**Jan WARCZEK[1]**

# IDENTIFICATION OF RATTLE NOISE SOURCES IN THE VEHICLE CABIN USING AN ACOUSTIC CAMERA

**Summary.** Driving comfort in the car cabin depends on the prevailing acoustic climate. The occurrence of various types of intermittent noises is a common phenomenon observed by users of motor vehicles. In the cabins of motor vehicles, a local source of non-stationary noise due to the propagation of sound waves in the air and in the structural structure makes it practically impossible to determine its location organoleptically. The article presents the use of an acoustic camera to locate noise sources. Research was presented in the field of recognizing the location of sources intentionally introduced into the cabin and identifying spontaneous sources caused by operational wear. The obtained results confirmed the usefulness of using an acoustic camera in identifying noise sources, however, the presence of apparent sources may in some cases result in incorrect diagnoses.

**Keywords:** acoustics of car cabins, rattle noise sources, acoustic camera

## 1. INTRODUCTION

Being in the cabin of a vehicle that performs a transport task is always associated with receiving auditory sensations caused by operational factors and related to unintended physical phenomena related, for example, to residual energy conversion processes. Sounds that occur as a result of the operation of the drive system or aerodynamic effects are usually perceived by

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users as an indispensable element of using a given means of transport. However, all types of sounds that are not related to the functioning of the transport device are perceived negatively as unwanted noises. A typical example of bothersome sounds that negatively affect people staying in vehicle cabins are various types of impacts coming from mechanical sources (e.g. vibrations, impacts, friction) and electrical sources (e.g. magnetic, magnetostrictive) [28].

The occurrence of various types of discontinuous noises is a common phenomenon observed by car users [19]. Particular intensification of this type of phenomena is observed with increasing operational mileage (including repairs carried out in the meantime). Vehicle users often report faults in the form of various types of squeaks, creaking and grinding noises. Apart from the direct cause of such noises, the key issue is to determine the location of their direct source.

In the cabins of motor vehicles, a local source of noise with discontinuous characteristics due to the propagation of sound waves in the air and in the structural structure makes it practically impossible to determine its location organoleptically. An additional difficulty is the limited space of the cabin and some of the materials creating partitions that strongly reflect sound waves (e.g. car windows).

To a first approximation, the best solution to the problem of locating noise sources seems to be the use of methods based on determining the directionality of sound propagation. Currently, devices using beamforming (acoustic cameras) are becoming more and more common, in which the recorded sound pressure can be superimposed on the image of an object in order to illustrate the sound pressure distribution. Thanks to the acoustic camera, you can "see" the location of the noise source.

In the conducted research, a number of experiments were carried out to assess the possibility of using an acoustic camera to locate noise sources in the vehicle cabin. For this purpose, two sound sources were designed and manufactured. The main assumptions regarding the designed sound sources concerned their dimensions and the emitted acoustic power. The size of the sound source allows it to be placed in selected locations in the passenger car cabin (including inside the cabin ventilation openings). The acoustic power value was regulated using a built-in amplifier. Generally, the main assumption regarding emissions was to make the sound audible to people staying in the vehicle cabin. Before carrying out the basic tests in laboratory conditions, the sources were tested with an acoustic camera equipped with a microphone array the same as the one used later in the experiments inside the cabin. The obtained results of preliminary tests were then verified on a real facility. Research was carried out to identify noise sources in the vehicle cabin during normal operation.

## 2. ANALYSIS OF SOUND SOURCE DETECTION METHODS

The basic scope of application of acoustic cameras is the location of sound sources. Detecting the source may also be the purpose of detecting changes in the technical condition of the object. An acoustic camera is a device containing elements that allow the recording of images and sound pressure waveforms. The acoustic camera matrix consists of several dozen microphones appropriately placed relative to each other and a centrally located video recorder. Measurements are carried out by pointing the matrix at the test object, the video recorder allows you to display the measurement area online, which makes it easier to set the matrix in the appropriate position. Starting the measurement triggers the recording of the sound pressure by each microphone and the recording of an image or video from the tested object.

Entering parameters such as the distance of the camera from the sound source, temperature and selecting an appropriate computational algorithm, most often beamforming, allows the recorded sound pressure to be superimposed on the image in order to generate an acoustic map showing the sound pressure distribution (Figures 1 and 2). The principle of beamforming is beam shaping by delay and summing [8].

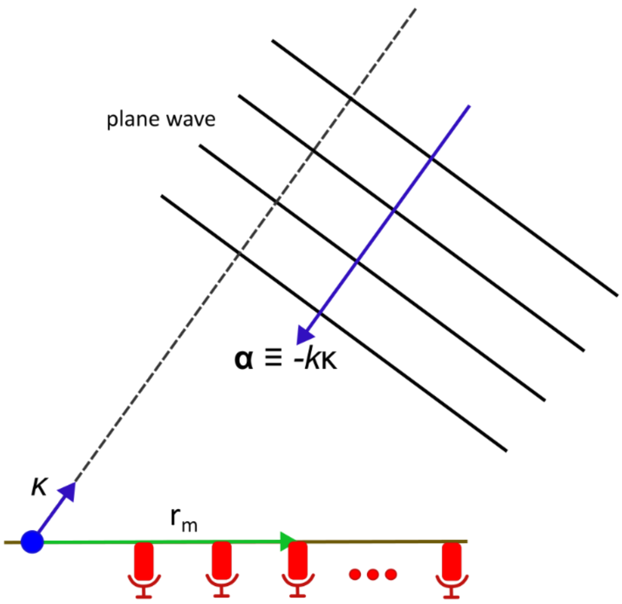


Fig. 1. A microphone array, a far-field focus direction, and a plane wave incident from the focus direction

A measurement matrix composed of M microphones located in locations $r_m$ $(m = 1, 2, ..., M)$ in the *x*-*y* plane of the coordinate system. When such a surface is used for Delay-and-Sum Beamforming, the measured pressure signals pm are individually delayed and then summed:

$$b(\kappa, t) = \sum_{m=1}^{M} w_m \, p_m\big(t - \Delta_m(\kappa)\big) \tag{1}$$

where: $w_m$ - the set of weighting factors applied to individual signals from individual microphones.

The individual time delays $\Delta_m$ are chosen with the aim of achieving selective directional sensitivity in a specific direction, characterized by the $\kappa$ vector (fig. 1). This is achieved by adjusting the delay times so that the plane wave signals originate in the $\kappa$ direction and are aligned in time before they are summed.

$$\Delta_m = \frac{\kappa \cdot r_m}{c} \tag{2}$$

where: $c$ - speed of sound.

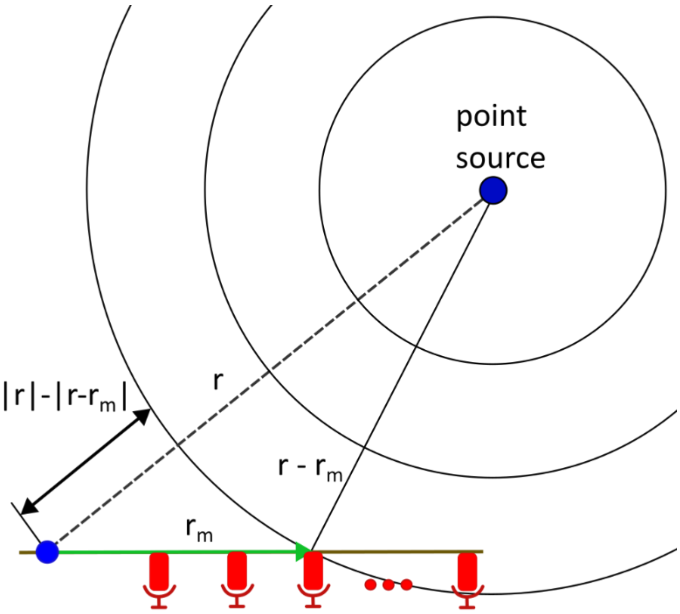


Fig. 2. In near-field focusing, spherical waves emitted by
a monopole source at the focus point *r* are assumed

When the near field occurs (Fig. 2.), then for a point source the time delays $\Delta_m$ depend on the distance r:

$$\Delta_m(r) = \frac{|r| - r_m(r)}{c} \tag{3}$$

where: $r_m(r)=|r-r_m|$ is the distance from microphone *m* to the focus point.

In the article [1] there is an example of an acoustic camera for detecting the failure state of an electric motor. The work focuses on detecting eccentricity, as it is one of the most common failure states of an induction motor. The presented measurements made with an acoustic camera were compared with vibration analysis as a reference method.

In the article [26], research was carried out at Amsterdam Schiphol Airport using a set of 32 microphones, during which 115 flights of landing aircraft were recorded. The aim was to determine the differences in acoustic signals for different types of aircraft and investigate the causes. It was assumed that the main cause of this variability are differences in the noise emitted by aircraft, as previous experience has confirmed that the impact of the variable atmosphere (for the distances considered) is negligible. A strong correlation was found between the noise level and the rotational speed of the turbine engine. The use of a microphone array allowed for acoustic imaging, thus distinguishing the noise of aircraft components from noise from other sound sources. It has been shown that turbofan engines are the main source of noise for many types of aircraft.

The problems of identifying noise sources in the far field are completely different than those in the near field. The problem of correctly identifying sources from a long distance was presented in detail in [18]. The presented simulation studies indicate an important aspect of the variable sound speed in an air stream with variable temperature.

In article [31], a method was proposed to locate the sound source in the frequency band from 100 Hz to 4 kHz in two dimensions using a microphone array by calculating the direction of arrival of acoustic signals. Assessing the direction of arrival of acoustic signals using a set of spatially separated microphones uses the phase information present in the signals. For this purpose, time delays are estimated for each pair of microphones in the array. Knowing the geometry of the system and the direction of arrival of the sound wave, it is possible to determine the location of the source. In the cited work, information about the phase of the signals and the direction of arrival of the signals in the microphone arrays were used to estimate the source location.

In work [39], the concept of an "acoustic camera" was used to study noise sources in railway wagons moving on the track. Instead of a visual image, sound markers placed in the wagon were used. A new adaptive "beamforming" signal processing algorithm has been developed to locate the loudest noise sources on board a rail car passing a stationary array of trackside microphones. The proposed microphone beamforming system tracks the spatial movement of the wagon using two inaudible acoustic signals placed on the board of the wagon. The proposed scheme then locates the noise sources with respect to the wagon coordinates. No supporting infrastructure (e.g. radar or video camera) is required beyond on-board navigation beacons. Monte Carlo simulations and anechoic chamber experiments confirmed the effectiveness of the proposed scheme.

Acoustic cameras are becoming more and more widely used in environmental acoustics. Reference [12] presents the results of locating the main noise sources in an industrial plant. The main noise sources were identified using an acoustic camera using the Beamforming Method. In parallel with the acoustic camera measurements, sound level measurements were made at the main noise sources. Based on the calculations, a forecast was made for noise emissions in residential buildings located near the power plant. Acoustic noise maps were made using LEQ Professional software, which takes into account the 3D geometry of buildings inside the plant. In this work, the location of the main external noise sources in the production plant was carried out using an acoustic camera. Based on the results, actions to reduce noise were proposed.

In paper [41] a new approach to monitoring vehicle traffic on a large scale was presented. To meet the growing demand for more accurate traffic monitoring, the use of road sounds has become a popular approach because they provide insight into the types of traffic occurring. This paper presents an approach to vehicle classification based on acoustic signals, using Mel frequency cepstral coefficients (MFCC) and long short-term memory (LSTM) networks. This study showed a classification accuracy of 82–86.2% in four vehicle categories: motorcycle, passenger car, truck and non-engined vehicle. The results showed that large-scale and low-cost acoustic processing can be effectively used for vehicle monitoring.

Identification of noise sources is one of the basic elements of the process of reducing hazards in the work environment. Acoustic imaging, or sound visualization, is a graphic form of presenting acoustic phenomena, in which the parameters of the emitted noise are in the form of a color map superimposed on the image of its source. In work [27] one of the main acoustic imaging techniques, beamforming and acoustic monitoring devices using this technique, i.e. acoustic cameras, are discussed. Examples of laboratory research results and practical applications are provided. The possibilities of using this technique and its application are also presented.

The work [33] presents preliminary research results on the use of an acoustic camera mounted on an aircraft. The design and implementation of an acoustic camera for direct mounting on the UAV hull was presented. The camera consists of 64 microphones, a central processing unit and data acquisition and processing software specifically developed to detect low-level acoustic signals in the far field. The built camera has an aperture of 2 m and was designed for observations from a height of up to 300 m, with a spatial resolution of 12 m. This allows for acoustic mapping of a large area, performed in a similar way to orthophotometry.

Most acoustic cameras used today are based on similar technical solutions. Despite this, research work is still being carried out to develop new concepts of technical solutions for acoustic cameras. Development works concern, for example, the miniaturization of acoustic cameras and new areas of their applications. The book [3] presents theoretical assumptions and extended analyzes regarding the basics of acoustic cameras and recognizing the location of sound sources.

Work [2] presents a new design of acoustic cameras with small dimensions. Artificial intelligence methods were used to design the optimal shape of the microphone array. The work presents various prototype versions of small acoustic cameras.

The works [6, 7] presents research results on the processing of information from the sensor matrix. In particular, the so-called blind beamforming method was used. Blind beamforming is an operation similar to conventional beamforming, except that it does not require knowledge of the sensor responses and locations. In other words, blind beamforming enhances the signal by processing only the data from the chip, without much information about the chip.

In work [14], a binaural recorder based on digital MEMS microphones was developed as part of the research. Novel approaches have been used to circumvent the shortcomings of MEMS. The proposed system offers advanced features such as real-time filtering, low-power consumption and small size. This is an example of examining the acoustic climate in the cabin of a motor vehicle.

The paper [42] describes a low-complexity field-programmable gate array (FPGA)-based prototype that computes and visualizes acoustic intensity images in real time. The system consists of 32 microphones and performs all signal processing tasks on a low-cost Xilinx Spartan 3E FPGA. The prototype calculates the intensity of images at a resolution of 320×240 pixels at 10 frames per second.

In work [35], an acoustic camera was designed and built based on hardware and software available on the market. As a result of this work, a programming environment for an acoustic camera system was proposed based on the use of a digital microphone and Raspberry Pi. The built measuring equipment makes it possible to locate the noise source to a large extent while maintaining the low cost of such a solution.

Another concept of building acoustic cameras was presented in [25]. The purpose of this work was to use a spherical microphone array and a spherical video camera. Several different static and adaptive beamforming techniques were implemented in the system, and every effort was made to make the proposed system accessible to a wide range of acoustics practitioners. The proposed solution allows you to capture and analyze the sound scene using a microphone system, and then estimate the parameter to determine the activity of the sound source in specific directions. Additionally, the developed VST software plug-in significantly increased the real-time capabilities of the developed solution.

In article [16], a methodology for miniaturization of acoustic camera systems was investigated to improve their mobility. Generally, the problem concerns the size of the microphone array. The work proposes minimizing the physical aperture through careful selection of the position and number of microphones with adapted spatial filter synthesis. This irregular layout geometry focuses sensitivity towards the target while avoiding aliasing artifacts. The increased portability of compact acoustic cameras could expand applications in car monitoring, urban noise mapping and other industrial areas currently limited by large systems.

In parallel with the development of acoustic camera designs, methods for processing signals obtained from acoustic pressure sensors are still being developed. The article [4] presents the results of research and analyzes using acoustic cameras used to recognize various sound sources. Based on the assessment, two methods based on recognizing the energy of acoustic sources were identified as the best, i.e. the multi-resolution search method and the effective expectation maximization method.

The article [20] presents a closed, one-stage the least squares algorithm for source localization and shows that it is mathematically equivalent to the so-called spherical interpolation method, but is characterized by lower computational complexity. This approach allowed for reducing the necessary computing power in real-time acoustic cameras.

Acoustic localization allows measuring the range of an emission source along its angular coordinates. Spatially differentiated receiving units enable measurement of received signals (triangulation), i.e. the difference in arrival time. However, if there is more than one emission source and several sources are located simultaneously, undesirable line intersections may generate spectral spatial responses, i.e. location uncertainty. The work [22] focused on creating acoustic images using an acoustic camera converted to work in the biostatic mode. The proposed focalization of a bistatic acoustic camera (on nodes of three-dimensional spatial coordinates) uses both temporal and spatial information for imaging.

The work [29] presents the results of acoustic recognition using a real-time audio camera, which uses the output signal of a spherical beamforming system of microphones controlled in all directions to create a central projection. A panoramic, mosaic image of space is created with a superimposed sound intensity distribution. Since both the visual and audio images from the camera constitute a central projection, the resulting audio and video images can be recorded using standard computer vision techniques. The presented method was used to study the relationship between acoustic features and architectural details of a concert hall.

The development of methods increasing the resolution of acoustic imaging is presented in [40]. By using efficient algorithms running on dedicated computing equipment, it is possible to obtain high-resolution acoustic images while maintaining high time efficiency.

Wireless acoustic sensor networks (WASNs) consist of a distributed group of acoustic sensing devices equipped with sound playback and recording functions. Current mobile computing platforms offer enormous opportunities to design audio-related applications involving acoustic sensing nodes. In this context, the localization of acoustic sources is one of the application fields that has developed greatly in recent decades. In general, the localization of acoustic sources can be achieved by examining the energy and temporal and/or directional characteristics of the incoming sound at different microphones and using an appropriate model that relates these characteristics to the spatial location of the sound source(s). The paper [9] reviews common approaches to source localization in WASNs that focus on different types of acoustic features, namely the energy of the incoming signals, their time of arrival (TOA) or time difference of arrival (TDOA), direction of arrival (DOA), and controlled response power (SRP) resulting from combining multiple microphone signals.

The spatial localization of sound sources is increasingly used for biological research. The recent development of new, deployable acoustic sensor platforms provides opportunities to develop automated tools for bioacoustic field research. In [30] was implemented an AML-based source localization algorithm and used it to locate marmot alarm calls. The results show that the AML source localization algorithm can be used to locate real animals in their natural habitat using a platform that is practical to implement.

Paper [11] presents newly developed mapping of moving sources, including video overlay and necessary measurement techniques. Issues related to the synchronization of optical and acoustic film were discussed. The second topic was three-dimensional mapping of acoustic sources onto a 3D model of the measurement object. Simple mapping of a virtual plane at a fixed distance has now been replaced by varying measurement distances to individual points on the surface of the 3D model. Complete 3D mapping of indoor spaces depends on omnidirectional, non-planar layouts. Such mappings may be useful in car interiors, where CAD models of the driver's cabin are often available.

The work [36] presents novel probabilistic three-dimensional (3D) mapping effects that use acoustic images recorded in the underwater environment. The acoustic camera is a future-proof imaging sonar that has recently been widely used in underwater inspections. In this article, a volumetric 3D model is used to reconstruct the underwater environment, and Bayesian inference is used to update the probability of occurrence of each voxel that makes up the 3D model. To make the occupancy mapping theory more suitable for the acoustic camera, a novel inverse sensor model is designed. Using occupancy mapping theory and a novel inverse sensor model, it is possible to robustly and efficiently reconstruct a dense 3D underwater environment from arbitrary acoustic images.

Acoustic cameras are also used in sound beam mapping studies. The work [38] examined the metrological capabilities of the acoustic beamforming technique, and in particular analyzed its accuracy in estimating the acoustic power of sources and locating their spatial position. The uncertainty of the system was determined by combining the statistical effects of the uncertainty of the input parameters under the basic hypothesis that the sound source can be represented as a distribution of independent monopoles. This analysis was performed using a Type B approach based on the analytical model according to the ISO Guide for the expression of measurement uncertainty, followed by a numerical model based on Monte Carlo simulation. Systematic errors resulting from deviations in input parameters (e.g. sound speed or source-system distance) were analyzed, affecting the output level and spatial accuracy. Once these inaccuracies have been quantified, suggestions are provided for minimizing them. Finally, a criterion was developed to optimize the focusing of the beamforming technique based on maximizing the contrast of the acoustic image.

Examples of automation of measurements with acoustic cameras also appear, based on sound signal processing algorithms.

Paper [10] presents the results of research on the automation of fish detection in acoustic research conditions. A neural network was used to recognize acoustic images used in sonar research. An alternative approach to identifying traffic flows is presented in [17]. Instead of using a visual image analysis system and a computer vision algorithm, acoustic recognition was used to recognize vehicles. Acoustic traffic monitoring is cost-effective and can provide greater accuracy, especially in low-light conditions and where cameras cannot be installed. In this article, the task of classifying vehicle subtypes based on acoustic signatures allowed for the categorization of vehicles into car, truck, bicycle and no vehicle.

An interesting technical problem that can be solved using algorithms similar to those in acoustic cameras is the analysis of the climate in the cabin of a means of transport.

The article [34] presents methods of influencing the acoustic climate in vehicle cabins using active sound control. The aim is to show that automotive sound control systems are an exciting field of research that can significantly improve passenger comfort in acoustically difficult environments.

When assessing the auditory impressions occurring in the cabin of a car, a very good solution is to use loudspeaker systems with full channel separation. In the work [32], attempts were made to build a loudspeaker system that would well reproduce binaural recordings, but the proposed solutions had a number of drawbacks, which consisted in the fact that the listener's head must be in a designated place, head movements cause problems in locating sound sources, the loudspeaker system must be precisely spaced, moving them by a small angle may disturb the correct sound localization.

The work [5] presents research results related to the acoustic environment in the car cabin, which has a significant impact on the perceived quality of the vehicle. The acoustic environment in a car cabin consists of two elements: noise produced by automotive processes and the sound produced by the car audio system. In both cases, active methods can be used to improve the acoustic environment, and the paper presents research on both active car noise control and active sound reproduction systems in cars. The aim of the research was to broadly understand the improvement of acoustic comfort in the cabin.

The study [23] examined the comparison of the volume of sounds inside a car from various sound sources in situations similar to everyday life. In the described experiment, the sound sensations while driving were assessed continuously using the continuous rating method by category. This method makes it possible to evaluate sensations evoked by different sounds without paying particular attention to any specific sound in the same context, and to examine the impact of each noise individually. The results suggest that some sounds tend to be overestimated compared to background noise, while others are not. The results of this experiment can be helpful in determining the influence of various factors in the sound environment and taking effective countermeasures.

A separate, important issue related to the detection of noise sources is the use of acoustic cameras in limited spaces. In [24], a compressive non-stationary near-field acoustic holography based on the time-domain plane wave superposition method was proposed to precisely reconstruct the instantaneous sound field using a smaller number of measurement points. In the proposed method, a time-domain convolution superposition pattern is determined using the instantaneous propagation kernel to relate the time-varying pressure of the hologram plane to the pressure and wavenumber spectra of the virtual source plane.

A separate issue directly related to the study of auditory sensations in car cabins is the reproduction of the spatial distribution of sounds. Auralization is a well-known method used to create virtual acoustic scenarios. The work [13] discusses techniques for extracting binaural impulse responses inside a passenger car cabin. The article analyzes the results of noise measurements inside a battery-powered electric vehicle. Detailed methods for determining the torsional vibrations of the drive system as reference values are also presented. Moreover, a method of measuring and interpreting the path of transmission of acoustic phenomena from the drive system of a battery electric vehicle to the passenger cabin is presented.

Detecting stud sources using acoustic cameras is not a problem in the case of continuous emission sources. In this work, the research was focused on examining discontinuous sounds (unsteady noise) that often occur in car cabins.

## 3. DESCRIPTION OF RESEARCH AND ANALYSIS OF RESULTS

As part of the research conducted in the passenger car cabin, various recorded signals from transient noise measurements were used. Fragments of structural elements used in car cabins were used in the preparation of test signals. The next stage of the research was the recording of sounds coming from the collision of elements using a standard sound recording set. The signals obtained were non-stationary. Examples of time courses obtained during collisions of vehicle interior equipment elements are presented in Figures 3, 4 and 5. It should be emphasized that the collisions of elements were not periodic.

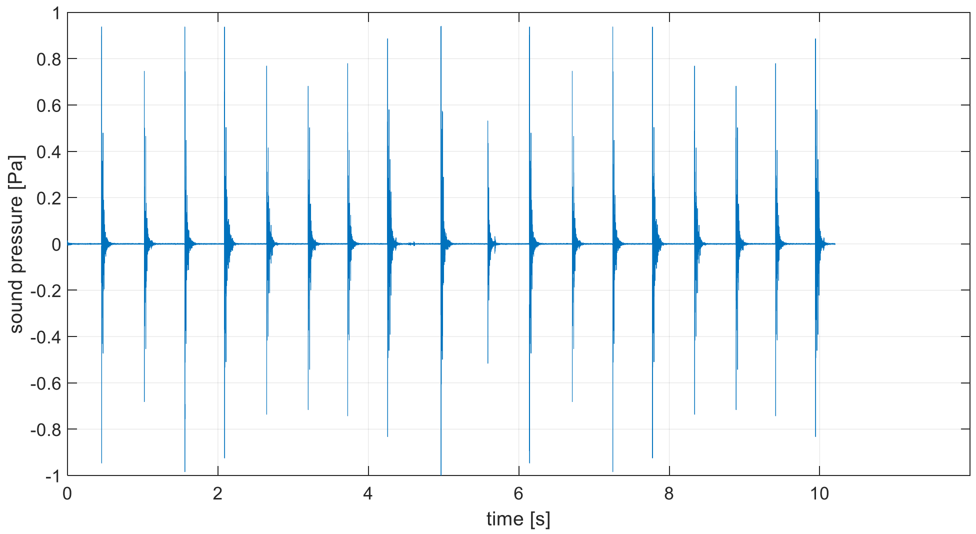


Fig. 3. Acoustic signal obtained during collisions of elements made of plastic

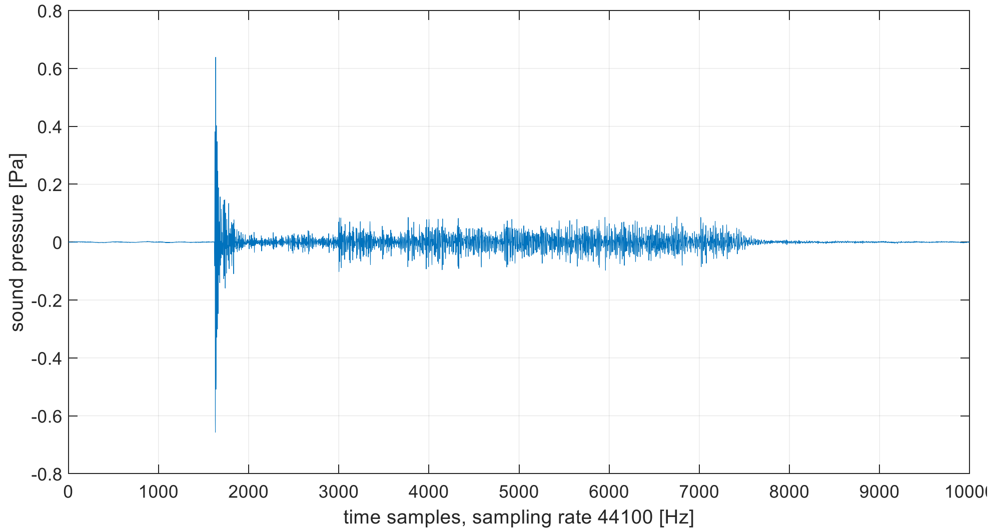


Fig. 4. An enlarged fragment of the effect of the collision of two metal elements of the interior of the cabin

The most common method of describing random signals is to provide their amplitude-time characteristics in selected intervals. By determining the values of the central moments and the autocorrelation function, it is possible to determine whether the signal is stationary. Methods for analyzing stationary signals are widely described in many works. The choice of method for analyzing a non-stationary process is primarily determined by the dynamics of changes in its parameters over time. If these changes are small enough, the process can be assumed to be stationary. In a given time interval, commonly used methods are used to analyze such a signal, e.g. frequency analysis, point measures, etc. In the case of high dynamics of changes in the parameters of a random signal, it is common practice to examine it using two-dimensional methods, e.g. using the short-time Fourier transform, Wavelet transform, Wigner-Ville transform.

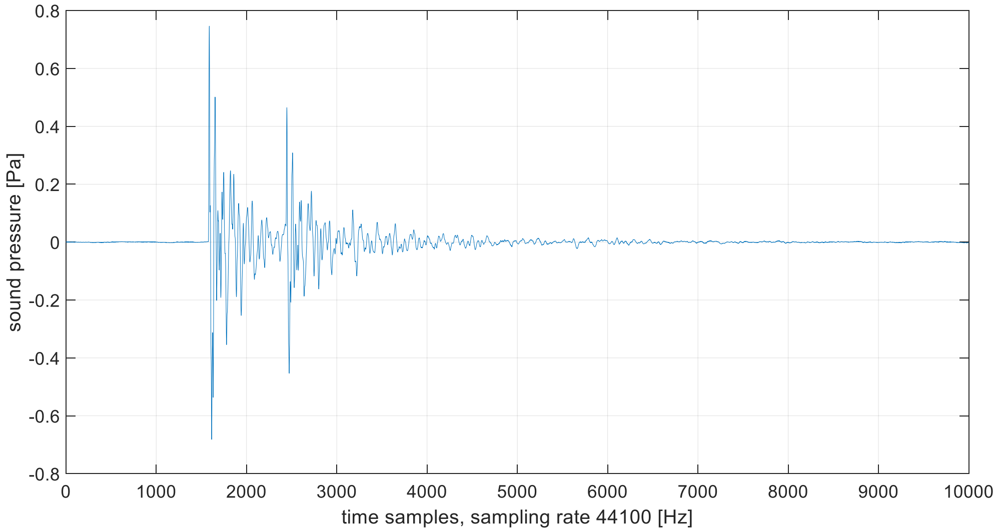


Fig. 5. An enlarged fragment of the effect of a collision between two elements of the interior of the cabin made of plastic

In the case of signals obtained from collisions of vehicle interior equipment elements, the analysis was performed using the Wavelet transform. Wavelet Analysis enables the use of windows that automatically narrow for high-frequency analysis and expand for low-frequency analysis. Both wavelets and their spectra can be rapidly decaying functions, and this makes wavelets very convenient windows for integral transformations. The Wavelet Transform is defined as follows:

$$WT(t) = \int_{-\infty}^{\infty} x(t)\Psi(t)dt \tag{4}$$

where:
*x(t)* – analyzed signal,
*Ψ(t)* – wavelet family.

Most often, the family of wavelets constituting the basis is generated using the formula proposed by Grossman and Morlet through the operations of shifting and scaling the basis function:

$$\Psi_{a,b}(t) = \frac{1}{\sqrt{a}}\Psi\left(\frac{t-b}{a}\right) \tag{5}$$

where:
$a$ – scaling parameter that implements the "change" of frequency: $\in R^{+} \wedge a \sim \frac{1}{f}$,
$\frac{1}{\sqrt{a}}$ – is the wavelet normalizing constant,
$b$ – shift parameter $b \in R$.

An inherent element of function approximation using wavelets are scaling functions. Each basic wavelet *ψ(t)* has a specific scaling function *φ(t),* the average values of which, unlike the wavelet, are always different from zero. Scaling functions are created, like wavelets, by scaling and shifting operations. The functions *φ(t)* i *ψ(t)* form pairs, based on which the families of scaling functions $\Phi_{a,b(t)}$ and the families of wavelets $\Psi_{a,b(t)}$ . are built. Wavelets with resolution *(a-1)* are a linear combination of scaling functions from level a. There are $g_k$ coefficients that meet the conditions:

$$\psi_{a-1,b}(t) = \sum_k g_k\, \varphi_{a,b}(t) \tag{6}$$

The same applies to scaling functions. The lower level $\varphi$ functions are linear combinations of the higher level scaling functions and the corresponding $h_k$ coefficients:

$$\varphi_{a-1,b}(t) = \sum_k h_k \varphi_{a,b}(t) \tag{7}$$

Using the above relationships, both wavelets and scaling functions from level a can be decomposed into a series created from a scaling function with a higher frequency resolution. Proceeding in this way, any signal *x(t)* can be decomposed into factors with graded frequency resolutions using the wavelet transformation and obtain a WT spectrum, which is the time-frequency characteristic of the tested signal.

The function $\Psi(t)$ is a band-pass filter. Large values of the a parameter *(a>>1)* correspond to long-term database functions and can therefore filter out the slow-time features of the signal dynamics, in particular its steady-state behavior. Small values of the a parameter *(0<a<1)* lead to narrow basis functions that help identify short-term signal behavior. The fundamental wavelet $\psi(t) = \Psi_{1,0}(\mathrm{t})$ is characterized by scale *a=1* and shift *b=0*. The factor $\frac{1}{\sqrt{a}}$ ensures that the energy of the wavelet does not change as the scale changes. Changing the location with respect to time and frequency is done by scaling. The wavelet $\psi(t)$ in the time-frequency plane is represented by a window whose side lengths are: $\left(a\omega_t, {}^{\sigma_\omega}\!/_{a}\right)$, respectively. As a result of scaling, the window is stretched in time and compressed in terms of frequency, while the area remains unchanged. Therefore, the choice of a specific scale is dictated by the need to increase the resolution in terms of time or frequency. A feature of the wavelet transform are windows with different time carriers.

Signal expansions based on wavelet bases cannot be well adapted to the representation of signals with narrow frequency spectra located in the high-frequency range. In this case, the wavelet expansion coefficients do not clearly reflect the nature of the signal because the information about the signal is blurred throughout the database. Most of the energy of the fundamental wavelet $\Psi_{1,0}(t)$ is contained in a certain range $[\omega_{min}, \omega_{max}]$. Outside this range, its Fourier transform $\Psi(\omega)$ is negligible. Therefore, the width of the $B_0$ frequency band is:

$$B_0 = \omega_{max} - \omega_{min} \tag{8}$$

The $B_0$ band of the fundamental wavelet is the same as the window width $\sigma_\omega$ in the direction of the frequency axis.

$$\sigma_\omega = \sqrt{\frac{1}{2\pi}\int_0^\infty (\omega - \omega_0)^2\, [\Psi_\omega]^2 d\omega} \tag{9}$$

where the center frequency of the fundamental wavelet:

$$\omega_0 = \frac{1}{2\pi}\int_0^\infty \omega[\Psi(\omega)]^2 d\omega$$

Hence, for a wavelet with scale value $a$, the band $B_a$ and the center frequency $\omega_a$ are:

$$B_a = \frac{B_0}{a} = \frac{\omega_{max}-\omega_{min}}{a}\ , \qquad \omega_a = \frac{\omega_0}{a} \tag{10}$$

The Wavelet transform on smaller scales extracts the high-frequency components of the analyzed signal. Increasing the scale causes the wavelet represented by the band-pass filter to shift towards lower frequencies. At the same time, for an increasing scale, we have a reduction in bandwidth, i.e. an increase in resolution in the frequency domain. The center frequency ω0 and the bandwidth B0 depend on the selected analysis wavelet.

The result of the wavelet transform is the time distribution of wavelet coefficients for a scale that is closely related to frequency. Continuous wavelet transform converts the time signal into a scale-time distribution over a selected range. After taking into account the frequency properties of the wavelet, the obtained result can be presented in a time-frequency system. This form of presentation of the wavelet transform results facilitates the interpretation of the obtained results, in particular their frequency properties. An example result of the Wavelet analysis of the signal obtained when two metal parts collide, using the Morlet wavelet, is shown in Figure 6. The time-frequency distribution of the collision signal of plastic parts is shown in Figure 7.

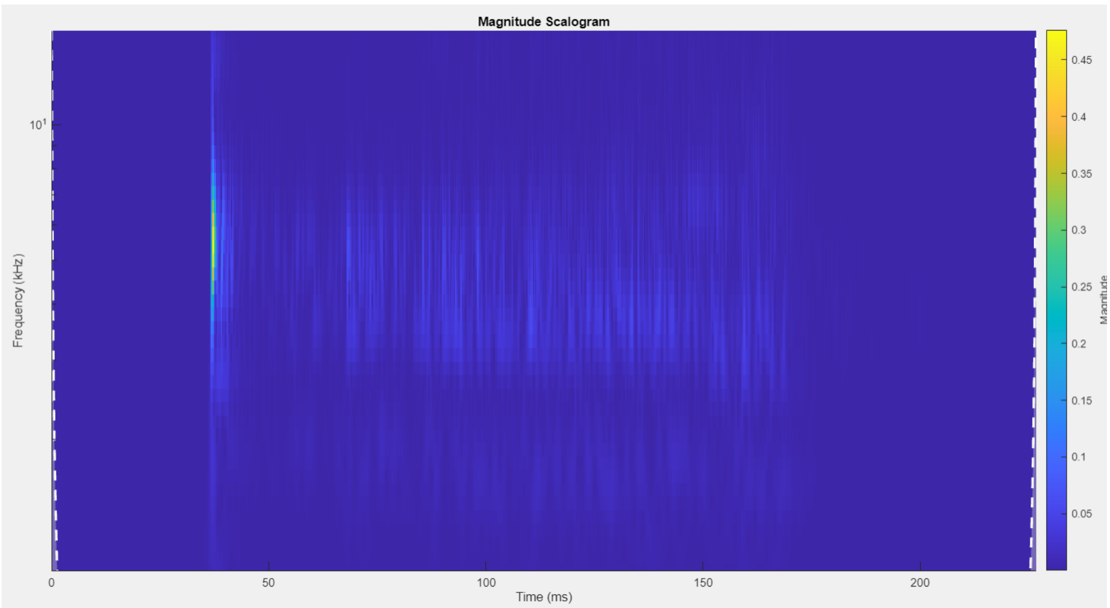


Fig. 6. Time-frequency distribution of the signal resulting from the collision of metal parts

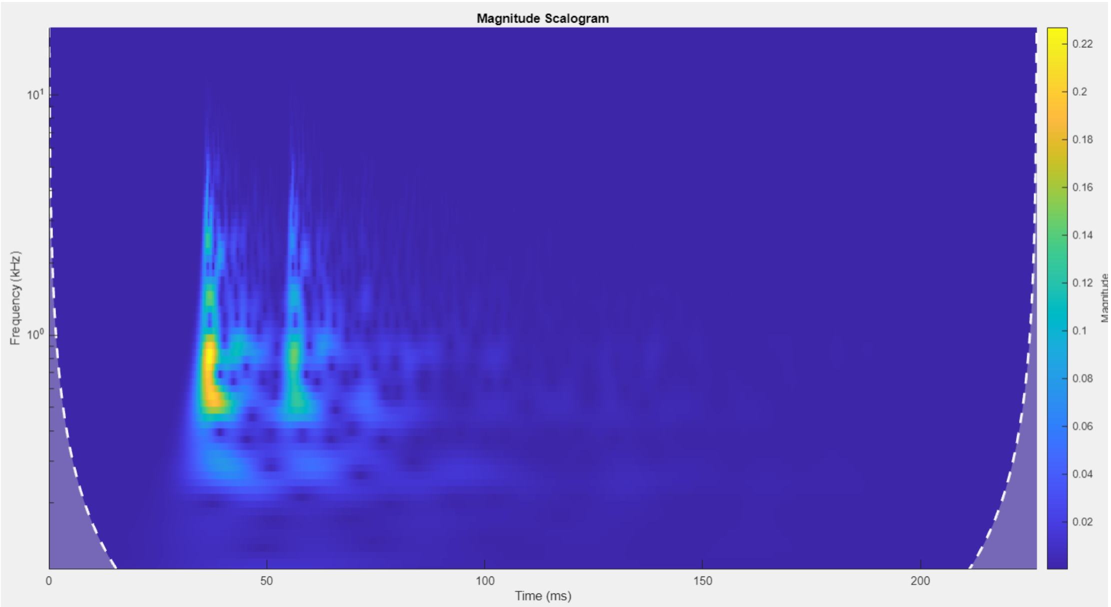


Fig. 7. Time-frequency distribution of the signal from the collision of plastic parts

The wavelet decomposition shown in Figure 6 reveals that the signal after the collision shows a dominant initial impulse, which later transforms into free vibrations of the structure. The example signal when rubbing plastic elements looks similar, but there is a reduction in the frequency range. The duration of the entire signal is approximately 150 ms. Random signals recorded in this way were used to drive micro-speakers placed in the vehicle cabin. The sound sources were placed in the car cabin. The location of the sound source was identified using an acoustic camera. The research was conducted using the SoundCam Bionic acoustic camera. A view of the location of the acoustic camera in the tested vehicle is shown in Figure 8. Due to limited space, it was decided to use a small size of the microphone array (XS matrix).

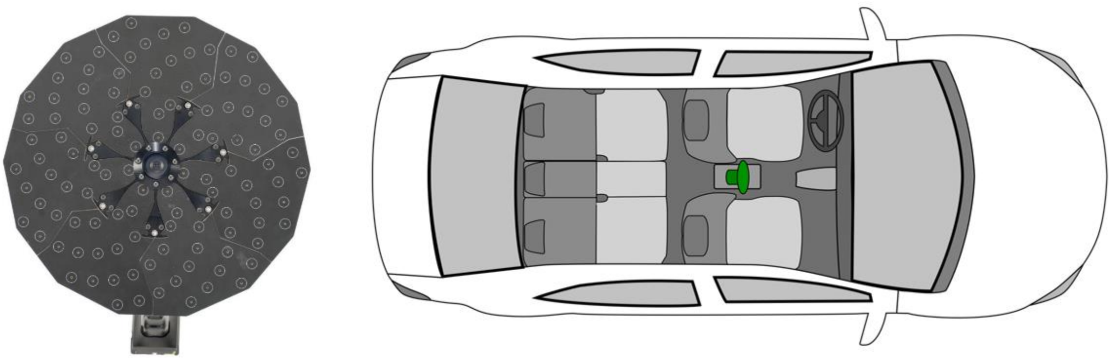

Fig. 8. View of the camera used and a diagram of the tested vehicle with the location of the acoustic camera marked in green

In the studies, the source was hidden under the interior trim elements of the vehicle, which corresponded to the most common cases of noise caused, for example, by increased clearances in the connections of elements [28]. Noisy sounds occurring in the vehicle cabin are also influenced by sources located outside, whose operation is intermittent [15, 19, 21, 37]. In the current research, the aim was to detect the source of discontinuous noise located in the car cabin.

In the first stage, the tests were carried out with the car stationary and the engine turned off. The obtained results of correct identification of noise sources are presented in Figures 9 and 10.

Fig. 9. Identification of the noise source located in the right air outlet – The sound emitted is the collision of two metal elements

Fig. 10. Identification of the noise source located in the central air outlet – The sound emitted is the collision of two plastic elements

During the research, there were also results of source identification, which indicate the occurrence of erroneous diagnoses. An example of the appearance of two locations of noise sources (real and apparent) is shown in figure 11. Figure 12 shows the identification of an apparent source, the occurrence of which is determined by the reflection of acoustic waves from the hard surface of the car's windshield.

Fig. 11. Recognition of two noise sources (real and apparent)
– The sound emitted is the collision of two plastic elements

Fig. 12. Incorrect identification of the noise source
– Only the apparent source is visible

The next stage of the research was to verify the possibility of using an acoustic camera to locate noise sources coming from incorrectly fitted vehicle interior equipment elements. For testing purposes, the screws securing the glove compartment on the passenger side were loosened. The body rocking caused by the force generated by two passengers was used as an excitation. Examples of detecting a noise source in the passenger compartment area are shown in Figures 13 and 14.

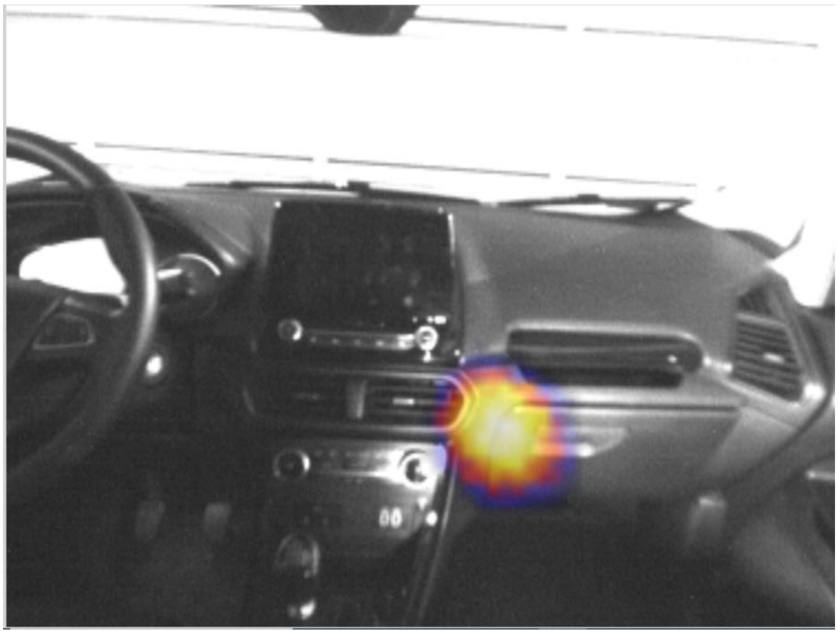

Fig. 13. Detection of the noise source during tests on the test stand

Fig. 14. Detection of the noise source during tests at the test stand

As can be seen, by selecting the frequency band range and determining the distance from the source, the precision of detecting the place of sound emission can be improved (Fig. 14). The described procedure was validated in road test conditions, which are the most common area of occurrence of bothersome sounds in the vehicle cabin. The tests were conducted during normal operation (during road tests). Due to the assumption that such a method could be used to detect noise sources in vehicle workshop conditions, the camera was not mounted in a holder. Measurements were made using the camera manually. An example of detecting the location of the noise source in the car cabin during road tests is presented in Figure 15.

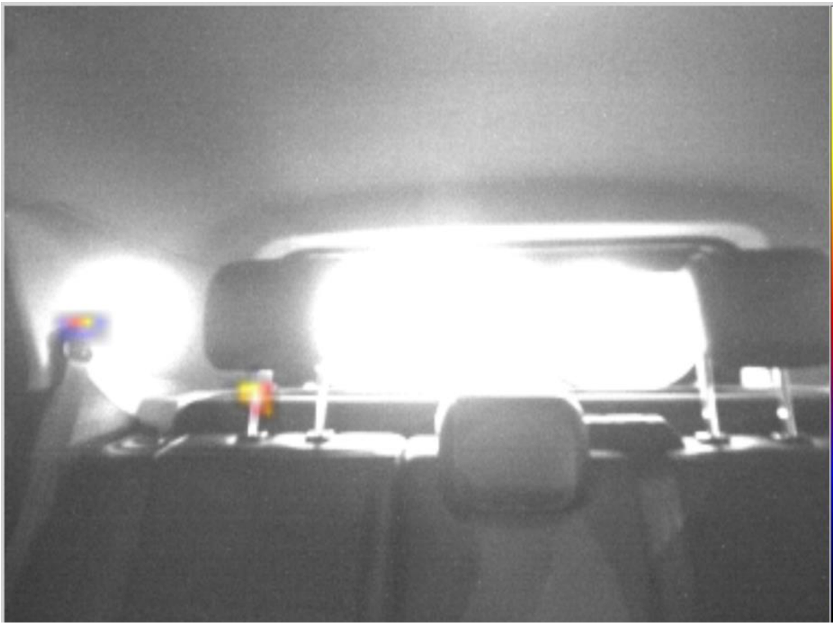

Fig. 15. The location of the noise source at the junction of the rear trunk shelf with the left rear body pillar – Result obtained during the road test

The problem of incorrect identification of source locations was also observed in road tests. An example of incorrect detection of the place of sound production is shown in Figure 16.

An acoustic camera seems to be a useful tool for improving the acoustic climate in car cabins. Its use allows you to locate the place where bothersome noises occur. Thus, by using an acoustic camera after detecting a place, you can focus on removing the direct cause of the sound. Sometimes it is enough to properly fit the vehicle's interior equipment. The obvious issue is the size of the microphone array. Due to the lack of space, small matrix sizes should be used, which unfortunately translates into the spatial resolution of the source location. Optimization of microphone signal processing algorithms should be considered in terms of interpolating the spatial resolution, taking into account the short duration of the acoustic signal. The author intends to address this issue in further research.

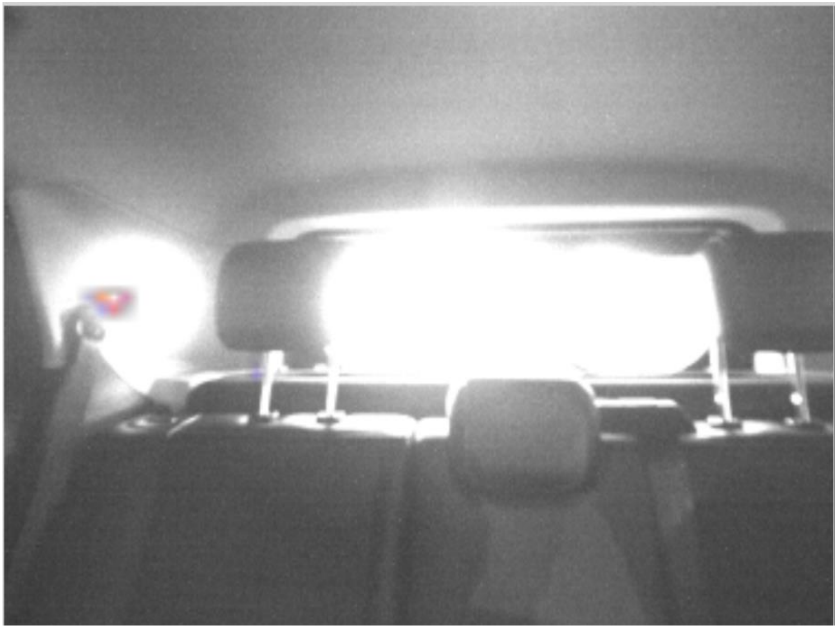

Fig. 16. Incorrect identification of the location of the noise source on the rear side window – Result obtained during the road test

## 4. SUMMARY

The acoustic climate in car cabins is often dependent on the occurrence of not very loud but annoying noises. The reason for the occurrence of such intermittent sounds is the general technical condition of the vehicle's interior equipment. This technical condition is influenced, on the one hand, by normal operation, but also by various activities related to the disassembly and reassembly of cabin interior equipment elements. The problem of various "strange" noises is often reported by vehicle users.

The use of an acoustic camera allowed for the detection of the location of the noise source, but the results obtained in some cases of the analyzed frequency band settings revealed the effect of an apparent sound source occurring in the vehicle cabin.

The obtained results confirmed the usefulness of using an acoustic camera in identifying noise sources. However, the presence of apparent noise sources may in some cases result in incorrect diagnoses. Source location verification should be evaluated using expert knowledge about the structural structure of specific solutions used in the vehicle under test.

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