Determination of the Sound Power Level of Modular Machines with Cyclic Operation Mode – Case Study

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Abstract

The sound power level as a parameter characterizing a sound source, as opposed to the sound pressure level, should theoretically not depend on the place of measurement and distance from the source. Therefore, it is often used as a basis for comparing machines and equipment in terms of noise emissions. Manufacturers usually specify this parameter in the technical documentation or on the equipment. The sound power level is also a necessary parameter for modelling the natural and working environment in terms of acoustics. The standards for methods of determining the sound power level define three classes of accuracy depending on the method and environment of measurement. The paper outlines the problems associated with determining the sound power level of non-standard machines in situ. The case study concerns a machine, a modular SRP (shelf ready packaging) production system that can be part of an extensive production line. Specific for this type of machine is the coexistence of many local sources generating sound of different nature, cyclic mode of operation and the possibility to set different capacity.

Keywords: sound power level, in situ measurements, survey method, tray former, forming machine

1. Introduction

The sound power level as a parameter characterizing the sound source, as opposed to the sound pressure level, does not depend on the place of measurement and distance from the source. The obligation to determine and declare the sound power level L_{WA} of machines and devices rests with the manufacturers, provided that the equivalent A-weighted sound pressure level at the workplace exceeds 85 dB [1, 2]. However, this does not mean that no acoustic tests are carried out on devices that generate significantly lower noise levels. Wherever the recipient expects the product to work quietly, manufacturers can strive to reduce the noise emitted by the device. The results of such acoustic tests are usually confirmed in the manufacturer's declaration and pose a challenge to the competition. Biomedical devices such as a smoke evacuator [3] or nebulizer [4] can be examples.

The sound power level can be determined based on measurements of sound pressure, sound intensity or velocity of a vibrating surface [5]. The standards for methods for determining the sound power level define three classes of method accuracy depending on the method and measurement environment. These are: precision methods guaranteeing accuracy up to 0.5 dB, engineering methods - 1.5 dB and survey methods of 3 dB.

The choice of the method for determining the sound power level depends, among others, on:

- the stationarity of the emitted sound, in the case of non-stationary noise in terms of amplitude and frequency, a sufficiently long averaging time is required,
- the distance between the noise level emitted by the machinery and the acoustic background; this is important when testing machinery with a low level of vibro-acoustic emission [6] and when testing in rooms with a high level of background noise, it may be necessary to switch off other sound sources in the test room,
- the presence of many local sound sources in the tested machine (device) and their location relative to each other, if relocation of these sources is possible they should be placed close together, e.g. in the case of testing vacuum cleaners the main unit and the suction nozzle should be placed next to each other and such a system should be treated as one sound source [7, 8],
- the possibility of autonomous operation (without cooperating devices),
- the possibility of transport to rooms with acoustic and size adaptation; this concerns mainly large machines [9, 10].

The aim of the study was to outline problems with meeting the standard requirements when determining the sound power level L_{WA} of a modular machine, a tray former using the survey method [11], and to propose a way to solve these problems.

2. Test object and measuring room

The object of the study was a horizontal tray former FTHT 6. It is dedicated for erecting trays of different shape and dimensions using a hot melt (an adhesive). The former is able to work as an independent unit or as a part of goods flow system. The former is shown in Figure 1. Pink gradient was added in the picture to increase visibility of guards.

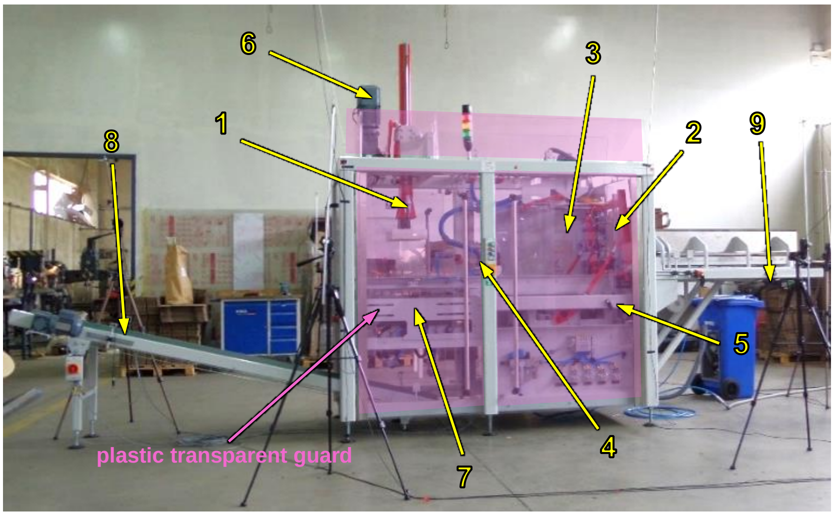


Figure 1. View of the FTHT6 former before starting noise measurements

The object is characterized by numerous local noise sources. They are:

1) a punch emitting impulse noise associated with the cardboard forming process,
2) suction cups for cardboard manipulator,
3) manipulator movement (low-frequency noise),
4) gluing system (broadband noise),
5) a servo drive for cardboard travel,
6) manipulator drives (asynchronous motors with fixed or variable speed gears),
7) a bender and pneumatic clamp (broadband impulse noise).

When determining the L_{WA} in accordance with ISO 3746 [11], it is important to consider the influence of the measurement room in the following aspects: the reflected sounds and the level of background noise.

The former is connected with a conveyor belt (Fig. 1. No. 8) which receives finished trays and in its vicinity, in the measuring room, there is a compressor (Fig. 1. No. 9) supplying the machine with compressed air. The belt and compressor are functionally linked to the former. The presence of this type of auxiliary devices being external sound sources requires verification whether they have an impact on the results of noise measurements and the determined sound power level. While the operation of the conveyor belt drive (see Fig. 1.) does not affect the value of the background noise correction K_1, the influence of the compressor operating nearby was significant. For this reason, the air compressor was switched off during the test cycle and the former was fed with compressed air accumulated in the compressor tank.

The K_2 correction determining the effect of reflected sounds in the test room, based on the experimentally measured reverberation time, was 3.8 dB. The application of the approximate method for determining the mean sound absorption coefficient $\alpha = 0.15$ (for a room with furniture; rectangular machinery room; rectangular industrial room), however, gives a higher result equal to 5.2 dB. The application of this simplification results in an overestimation of the K_2 value by 1.4 dB and consequently an underestimation of the sound power level.

Due to the high level of background noise and relatively high probability of numerous acoustic events with significant sound levels in the case under consideration, determining the sound power level of the former required switching off all the devices installed in the measuring room. In this case, measurements were carried out in the room after production had stopped. This allowed to obtain a distance between the noise level of the former and the background noise level of above 20 dB and to assume the value of $K_1 = 0$ dB. Such a procedure is not always possible under *in situ* measurements [12]. However, the aforementioned individual components of the machine work sequentially, and some of them change their position within the machine. This specific design and operation of the former in space requires a relatively long averaging time to obtain reliable measurement results. Moreover, it makes practically impossible to use the sound intensity measurements [13, 14], and in particular the sweeping method [15] to determine the L_{WA}.

3. Testing methodology

Taking into account the conditions described in chapter 2, it was only possible to apply the survey method for determining L_{WA}. However, during the determination of the L_{WA} of the former some issues were encountered related to:

- high level of background noise,
- determination of the equivalent sound absorption area of the room – A,
- the presence of additional sound-emitting equipment, indispensable in the operation of the former,
- dimensions of the reference box,
- determination of the measurement surface and space,
- selection of measuring distance – d,
- the non-stationary in the sense of amplitude and frequency emitted sound related to cyclical machine operation,
- high efficiency of the machine (limited test duration due to the number of trays produced),
- the presence of numerous local impulse noise sources with different spectral composition and sound level in the machine.

The tested object should be inscribed in the reference box. When determining the dimensions of the reference box, those elements which are not significant sound emitters may be omitted [11]. The dimensions of the reference box are marked on the CAD model and are shown in Figure 2.

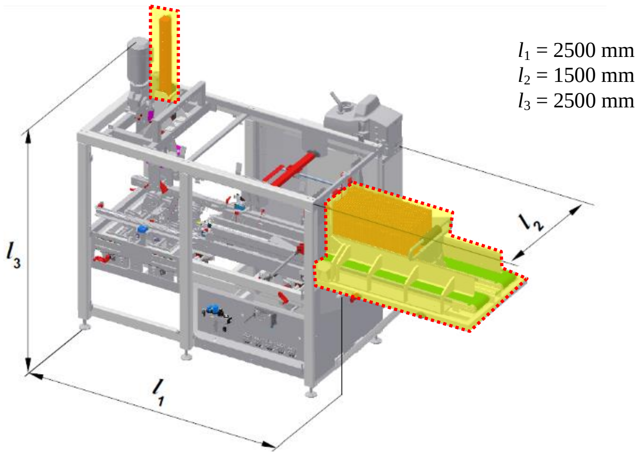
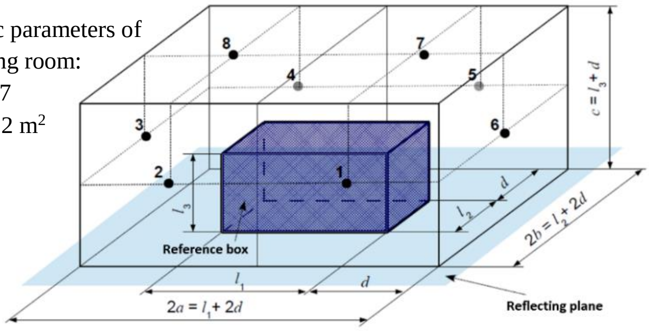


Figure 2. CAD model of the FTHT 6 former with the dimensions of the reference box

In the case of the FTHT 6 former, the punch guide, which is movable, and the cardboard feeder on the right hand side are omitted. The feeder is not a source of noise and the cardboard boxes placed thereon slightly suppress the sound. Both omitted elements have been highlighted in Figure 2.

When determining the L_{WA} by the survey method, it is recommended that the measuring distance d is equal to 1 m or more. In justified cases, however, it can be reduced to 15 cm [11]. The positions of the microphones (measuring points) and the measuring surface with dimensions are given in Figure 3. The adoption of the measuring distance d is a key problem determining the size of the measuring surface, taking into account the influence of reflected sounds and the number of measuring points. In the described case, the measuring distance d = 1.5 m was adopted. It is the shortest possible distance at which it is possible to carry out measurements in eight points according to the procedure for the determination of the L_{WA} using the survey method (according to ISO 3746 [11]).

Acoustic parameters of the testing room:
α = 0.247
A = 300.2 m^2



Dimension	Value
l_1	2.50 m
l_2	1.50 m
l_3	2.50 m
a	2.75 m
b	2.25 m
c	4.00 m
d	1.50 m
h_1	2.00 m
S	104.75 m^2

Figure 3. Arrangement of measuring points on the measuring surface

The view of the former and testing equipment prepared for measurements is shown in Figure 4. In the picture, the microphones are marked with yellow dots.

Figure 4. View of the tested object - FTHT 6 former, after preparation for sound pressure measurements (measurement points 3 and 4 are behind the former)

Increasing the distance d increases the area of the measuring surface S. It is important when determining the L_{WA}, which in this case was determined from the formula:

$$L_{\mathrm{WA}} = 10\log_{10}\left[\frac{1}{8}\sum_{i=1}^{8} 10^{0.1L_{pi}}\right] - 10\log_{10}\left(1 + 4\frac{S}{A}\right) + 10\log_{10}\frac{S}{S_0} \qquad (1)$$

where: L_{pi} – A-weighted sound pressure level at the i-th measuring point,
S – measuring surface area,
S_0 – reference surface area of 1 m^2,
A – the equivalent sound absorption area of the room.

The above formula does not take into account the K_1 correction since its value was 0 dB. It should also be noted that if the sound power level is determined by the survey method, the K_2 correction (second component of formula 1) must meet the relationship: $K_2 < 7$dB. Adopting $d = 1.5$ m and taking into account the size of the measuring area and the sound absorption of the measuring room guaranteed that this condition was met, $K_2 = 3.8$ dB.

The measurement time was 80 s each time, which guaranteed that at least 30 forming cycles were recorded. The adoption of such a measurement time (averaging) was due to the non-stationary, cyclical operation of the machine and the limited supply of accumulated compressed air in the compressor tank. As part of the study, spectral analyses were performed simultaneously: octave and short-time ones. This approach also makes it possible to determine the directionality of the noise emitted by the former. The tests were carried out for 4 different machine capacities measured in number of cycles (trays produced) per minute: 25, 31.5, 35.8, 39.8. The capacity depends, among other things, on the complexity of a tray or packaging (e.g. number of folds). Under actual production conditions, the folding rate of the cartons must be adapted to the rate of production of a flow production line.

Due to the high capacity of the former and the resulting need to reduce testing time, it was advisable to use a microphone array for synchronous recording. An alternative approach could be to use a microphone antenna [16]. However, this solution duplicates the disadvantages of iterative measurements when testing objects that generate non-stationary noise. However, the main reason for the 8-channel synchronous pressure recording would be in case of other solutions the need to guarantee a huge amount of prefabricated elements and the impossibility of receiving finished trays in case of an former not connected to the process line.

The following were used to record, measure and analyse noise:

- 8 free field microphones Roga RG-50 ICP®,
- 8-channel recording unit TEAC LX–10,
- dedicated recording, measurement and analysis application developed in the DASYLab (*Data Acquisition System Laboratory*) environment.

4. Summary of research results and discussion

The test results showing the specifics of the noise emitted by the former relate to the rated operation of the machine at 25 cycles per minute.

The fact that the tested former generates non-stationary noise is exemplified by the changes in instantaneous sound pressure values recorded above the machine (measuring point 7) shown in Figure 5. The figure presents changes in the instantaneous peak and rms sound pressure values at the point where the average instantaneous peak pressure $\bar{p}_{\mathrm{IPEAK}}$ defined in [17] was the highest.

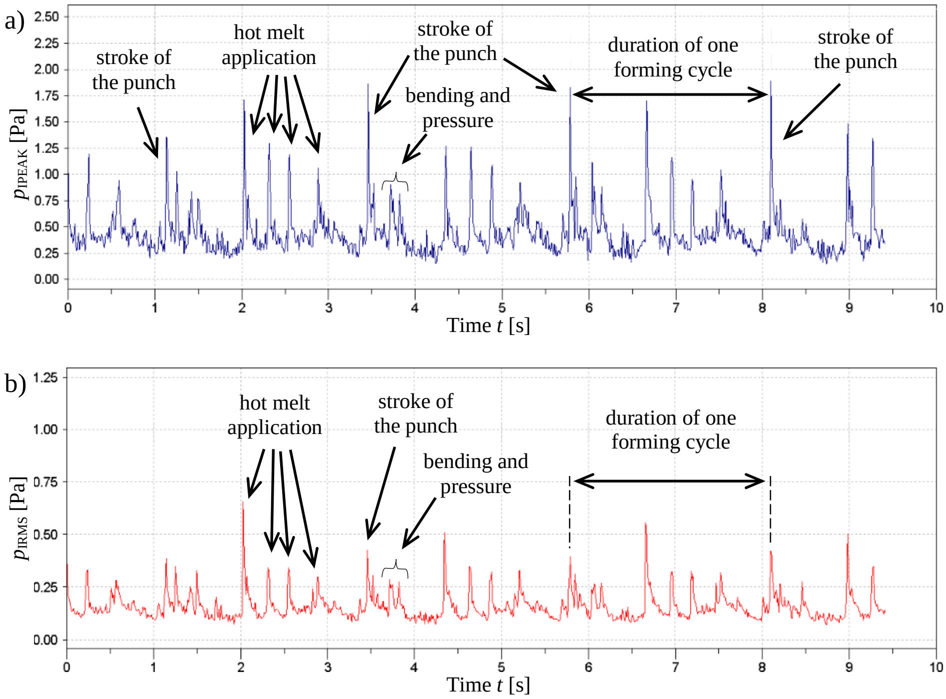


Figure 5. Instantaneous values a) peak, b) rms of sound pressure measured at measuring point No. 7 above the FTHT6 former at 25 cycles/min

It is easy to identify subsequent work cycles on the charts. The highest instantaneous peak sound pressure values p_{IPEAK} (see Fig. 5a) accompany punch strokes. After the punch stroke, the cardboard is bent and the pneumatic pressure is applied. Simultaneously with the working movement of the punch, the cardboard manipulator places another cardboard blank on the conveyor. When moving hot melt is sprayed onto the cardboard at the bonding point, which takes place each time about 1 second after punching. Different values of sound pressure at the same events in successive cycles of the former confirm the need to adopt such time of signal recording that covers a greater number of cycles and to average the results. It should be noted that increasing the capacity of the machine consists mainly in shortening the intervals between component operations.

The recorded signals allowed not only to determine the sound power level L_{WA}, but also to determine the octave and average spectra of sound pressure levels and A-sound levels sequentially. Figure 6 shows the sound levels for eight measuring points located on the measuring surface (see Fig. 3.) - averaging time: 80s.

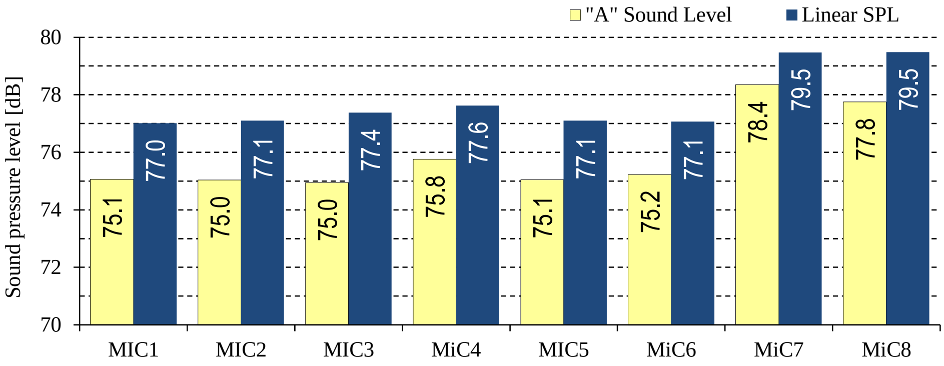


Figure 6. Linear (uncorrected) sound pressure level and A-weighted sound level at measuring points on the measuring surface

The highest pressure levels were recorded at measurement points 7 and 8. This is due to the lack of covers at the top of the former. Transparent plastic guards fitted in the outer frame of the former (see Figure 1, pink gradient), in addition to their safety function, reduce the noise propagation outside the machine. The pressure level at measurement point No. 6 is very close to the levels at points 1 - 5, which confirms the correctness of omitting the cardboard feeder when determining the dimensions of the reference cuboid.

The pressure levels averaged on the measuring surface in octave bands are given in Figure 7.

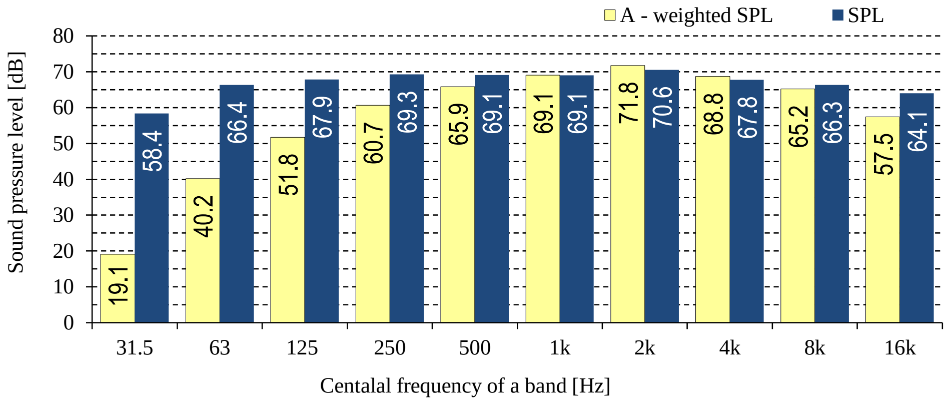


Figure 7. Octave spectrum - averaged sound pressure levels on the measuring surface (uncorrected and A-weighted) in the octave bands

From the octave spectrum it can be concluded that the machine generates broadband noise. The highest levels were recorded in the band of the highest sensitivity of the human hearing organ. This was mainly due to the operation of pneumatically driven systems.

The second important aspect of the research was to determine the relationship between the capacity parameter – cycles per minute of the machine and the sound power level. The determined sound power levels as a function of the set capacity are shown in Figure 8.

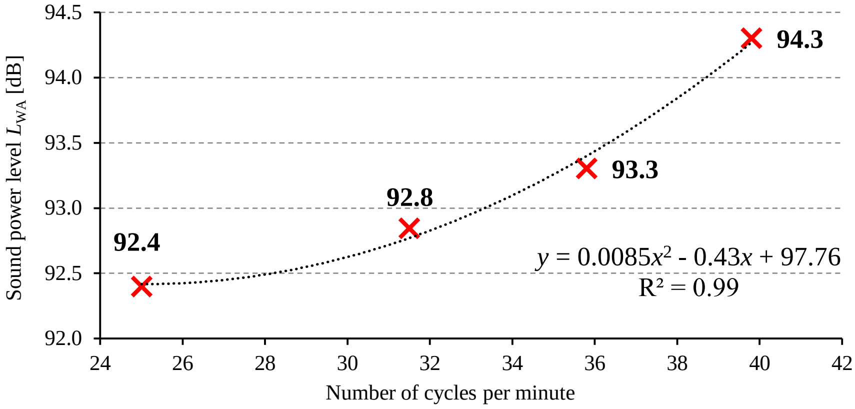


Figure 8. The sound power level of the FTHT6 former as a function of the number of cycles per minute

It should be noted that the noise generated by individual events during operation of the former is almost constant and does not depend on the number of cycles per minute (performance). However, as a consequence of reducing the duration of the work cycle (increasing the number of short-time events per unit of time), the average level of emitted noise increases. Analyzing the data (Fig. 8) it can be stated that the sound power level of the FTHT6 former depends quadratically on the capacity and increases with its increase (coefficient of determination R^2 is 0.99).

This relationship therefore makes it possible to estimate the sound power level for various forming capacities. Another benefit of conducting the recording according to the presented methodology is obtaining a set of data which additionally enables to determine the directivity of noise emitted by the former. On this basis it is possible to identify noise hazard zones and safety zones and to optimize machine construction in acoustic aspect. Sequential short-time parameterization and analysis gives information about the duration of individual events and their spectral composition (flows, knocks, gluing, impulse strokes - benders). Such a set of results can be the basis for undertaking actions to minimize the emission of noise by the machine by e.g. installation of an additional housing or suppressing noise with sound-absorbing materials and identification and silencing components having a key share in the final L_{WA} value. In order to formulate conclusions from the research carried out it was helpful to compare the conditions of conducting sound pressure measurements for the purpose of determining the L_{WA} by means of a survey method for typical machines / devices with - in the discussed case - a specific machine, which is a former. This comparison is shown in Table 1.

Table 1. Comparison of measurement conditions for the purposes of determining L_{WA} in a typical and the discussed cases

	Typical case	This case – Horizontal tray former
Sound source	1 or more placed close together	Multi-source design, sources can change location in space
Auxiliary devices	Do not occur	Necessary verification of the significance of the influence of auxiliary equipment
Operating mode	Continuous operation	Cyclical operation, possible capacity change
Emitted noise	Stationary	Transient
Restrictions on working / testing time	None	Time of work / research limited by the availability of the semi-finished product and receipt of finished products
Background noise	Background level at least 10 dB lower than the average sound level on the measurement surface	Tests after stopping the work of other devices in the measuring room
Type of measuring surface	Hemisphere or parallelepiped	Parallelepiped
Measuring distance *d*	*d* not less than 0.15 m, preferably 1 m	*d* = 1.5 m – determined by the dimensions of the machine
Number of measuring channels	At least 1	The need for synchronous multi-channel signal recording
Number of measuring points	Depends on the type of measuring surface and distance *d*	Limited by the number of measurement channels for synchronous recording (8 measurement points)
Spectral composition of the noise	Quasi-stationary	Non-stationary, cyclically variable in time
Measuring equipment	At least 1 sonometer	A set of 8 microphones, an 8-channel signal recorder and signal analysis system
Possibility to relocate the machine to a room with acoustic adaptation	Usually, yes	No
Length of the recorded signal	No requirements, just a few seconds	Possibly long recorded signal, at least 30 cycles
Environmental correction K_2	The average sound absorption coefficient α can be read from the table	Determined experimentally on the basis of measurement of reverberation time
Reference box	It is tangential to the outer edges of the device	Determined excluding the machine parts which are not sources of noise

Generally, it is required that the sound power level L_{WA} declared by manufacturers be determined under the most stable operating conditions [11]. Due to the specifics of the former, providing one L_{WA} value does not give complete information about the acoustic parameters of the machine. The emitted noise may change not only due to the set capacity but also depending on the equipment installed (different types of cartons). It is necessary to consider that the technical documentation regarding noise emissions should contain not only one number - L_{WA}, but a set of L_{WAi} values for different variants of capacity. Providing extended information for this class of machines will enable more detailed design of acoustic climate in the work environment [18].

When determining the sound power level L_{WA} of this class of machines, with many local noise sources and cyclical operation mode, it is important to:

- record signals synchronously at all measuring points,
- analyze the stationarity of the signal to determine the time of recording (averaging) the signal,
- select the measuring distance d based on two criteria: so that d is as small as possible and the number of measuring points does not exceed the possible number of channels for synchronous signal recording,
- omit the parts of the machine which are not related to noise emissions when determining the reference box,
- determine additionally the equivalent sound absorption area of the room A based on the measurement of reverberation time in order to obtain more reliable results.

5. Summary

It is not advisable to include in the technical documentation the sound power level L_{WA} of machines with cyclic operation mode with the possibility of setting capacity (CPM) as a single value. Moreover, this does not provide a basis for reliable forecasting of acoustic interactions and modelling of the environment or acoustic climate in industrial halls. The sound power level emitted by the former can have different values depending on the equipment installed (different types of cardboard trays) or its capacity. It should be considered to provide extended information on the L_{WA} for different accessory variants, capacities and types of formed packaging in the technical documentation. The observations from the acoustic testing of the former can be useful to teams testing machines with similar design and functional characteristics. During testing, it is important to take into account additional accessories and equipment emitting noise which are essential for the proper functioning of the device. It is worth noting that if the influence of these devices cannot be omitted, we may be dealing with a DESS (Device with Extensive Soud Sources) class source.

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