Technology Collaboration Programme
by iea

Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

Annex 51

Acoustic Signatures of Heat Pumps

Final Report – Part 3

1.1 Measurement techniques

Editor:
Roberto Fumagalli, Politecnico di Milano
Simon Hinterseer, TU Wien, Faculty of Civil Engineering, Institute of Material Technology, Building Physics and Building Ecology
Christian Kaseß, ARI Acoustics Research Institute, ÖAW Austrian Academy of Sciences

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c/o RISE – Research Institutes of Sweden
Box 857, SE-501 15 Borås
Sweden
Phone +46 10 16 53 42

Website https://heatpumpingtechnologies.org

Production Heat Pump Centre, Borås, Sweden

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Preface

This project was carried out within the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP), which is a Technology Collaboration Programme within the International Energy Agency, IEA.

The IEA
The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a programme of energy technology and R&D collaboration, currently within the framework of nearly 40 Technology Collaboration Programmes.

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)
The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) forms the legal basis for the implementing agreement for a programme of research, development, demonstration, and promotion of heat pumping technologies. Signatories of the TCP are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

Under the TCP, collaborative tasks, or “Annexes”, in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex.

The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

The Heat Pump Centre
A central role within the HPT TCP is played by the Heat Pump Centre (HPC).

Consistent with the overall objective of the HPT TCP, the HPC seeks to accelerate the implementation of heat pump technologies and thereby optimize the use of energy resources for the benefit of the environment. This is achieved by offering a worldwide information service to support all those who can play a part in the implementation of heat pumping technology including researchers, engineers, manufacturers, installers, equipment users, and energy policy makers in utilities, government offices and other organizations. Activities of the HPC include the production of a Magazine with an additional newsletter 3 times per year, the HPT TCP webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

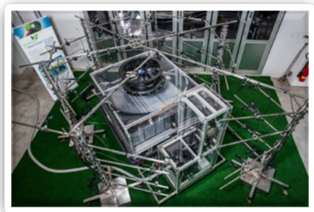
For further information about the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:

Heat Pump Centre
c/o RISE - Research Institutes of Sweden
Box 857, SE-501 15 BORÅS, Sweden
Phone: +46 10 516 53 42
Website: https://heatpumpingtechnologies.org

Acoustic Signatures of Heat Pumps

IEA HPT Annex 51

1.1: Measurement techniques



(from small study of Federico da Montefeltro)

Roberto Fumagalli, Politecnico di Milano
Simon Hinterseer, TU Wien, Faculty of Civil Engineering, Institute of Material Technology, Building Physics and Building Ecology
Christian Kaseß, ARI Acoustics Research Institute, ÖAW Austrian Academy of Sciences

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1. Introduction

In order to measure the noise produced by the sound sources, different measurement techniques are applied. Heat pumps are no exception. In this section we will briefly describe the principles and the main tools, while the list and descriptions of the main standards and certification schemes specifically addressed in the study and determination of the noise of the heat pumps are referred to section 1.2.

2. Instrumentation

2.1. Fonometers

The main instrument for determining the noise level of sound sources is the sound level meter. Leaving out the details on its operation and simplifying as much as we can, it can be stated that the sound level meter is composed by a microphone (there are different types, but those specific for acoustic measurements are always condenser microphones), a preamplifier (used as an impedance adapter and a preamplifier signal provided by the microphone), often a connection cable, and the internal sound level meter electronics that manages and processes the signal. The analog signal supplied by the capacitor is a very low voltage signal. The sound level meter is therefore built around a very sensitive voltmeter. The analog signal is then sampled, digitized, and is treated with the application of various filters that allow the application of weightings (A, C, Z or linear), frequency analysis, the application of time integration constants. (Slow, Fast, Impulse, Peak).

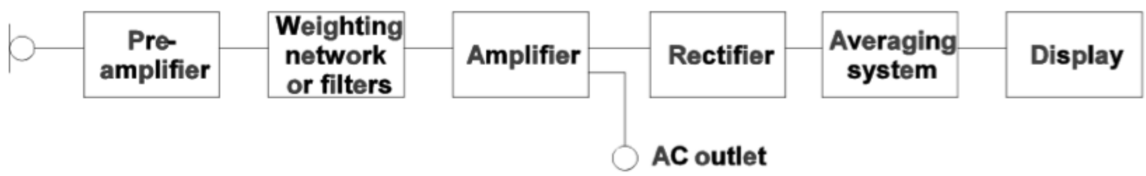


Figure 2-1: Block diagram of the sound level meter

Figure 2-2: Microphone

Figure 2-3: Preamplifier

Figure 2-4: Sound level meters

There are different models of sound level meter and can be classified according to accuracy, as summarized in the table below:

Class	Class description	Precision
0	Reference, laboratory	±0.4dB
1	Precision, laboratory	±0.7dB
2	Field measurement	±1.0dB
3	Control measurement	±1.5dB

Table 2-1: Precision classes of sound level meters

Class 0 is usually reserved for laboratories that perform periodic calibration checks and calibration operations on sound level meters. In fact, almost all the national laws and regulations require sound level meters to be equipped with a calibration certificate issued by a laboratory accredited at national level (or equivalent in the case of laboratories in other countries) that is not older than two years from the moment in which the measurement is to be carried out.

Almost all the norms instead prescribe the use of **class 1** sound level meters to perform measurements of any kind. This is the mostly used class by professionals, research institutes and laboratories. They are usually objects able to perform a large number of elaborations and have sufficient memory to save time stories, spectra, complex analyses and many derived parameters.

Class 2, on the other hand, is allowed for less precise measures (in Italy, for example, it is allowed for the assessment of noise risk in the safety topic, but the greater measurement uncertainty must be taken into account). These are much cheaper tools. Usually these sound level meters do not allow recording of the time history or spectrum analysis (they are not equipped with filter banks for octave or for third octave or for smaller octave fractions). They usually allow the reading of the sound pressure level present at that moment, displaying it on the screen, or they can measure an equivalent sound pressure level in a specific measurement range.

For **class 3**, on the other hand, those who have compiled this document admit that they have never seen declared class 3 products on the market.

Attention: the precision class is something that distinguishes not only the fonometer, but also the whole chain of measurement and the whole system: because an instrument is classified in class 1, it is necessary that all its components (microphone, preamplifier, instrument) are in class 1.

2.2.About microphones

The microphone is one of the most important parts of the sound level meter, being the transducer that converts the physical phenomenon of vibration (sound) into an electrical signal. It is therefore important to note that the right microphone for each type of acoustic measurement must be used. Hence it is appropriate to better illustrate the characteristics that distinguish the various microphones.

Main features of a microphone are open-circuit sensitivity, dynamics, frequency response and directionality. These are always shown on the microphone calibration card and determine its quality.

2.2.1. Open circuit sensitivity

It indicates the ratio between the voltage measured at the microphone output terminal and the incident sound pressure at the diaphragm level. The unit of measurement is therefore the **mV/Pa**.

The sensitivity characteristics of the microphone define the minimum level of measurable sound pressure. The open circuit sensitivity is calibrated at the frequency of 250 Hz and it is always reported on the calibration card of the microphone itself. Typical sensitivity values are between 10 mV/Pa (low) and 50 mV/Pa (high). For example a microphone with a sensitivity of 50 m/Pa, in the presence of a sound level equal to 94 dB, will deliver 50 mV, because at 94 dB the pressure is worth 1Pa. If the level rises by 20 dB, the pressure decuples, so the output signal also decuples, i.e. at 114 dB the pressure is 10 Pa and the microphone outputs has a voltage of 500 mV.

Open circuit sensitivity is not a quantity that can be used directly in practice since the microphone is always connected to a preamplifier that has a finite input impedance (while it should be, at the limit, infinite to have the circuit open). For this reason, the magnitude that is used is the sensitivity in charge, which is obtained by multiplying the gain factor G of the preamplifier (also indicated in the calibration card) to the open circuit sensitivity of the microphone.

2.2.1. Dynamic range

It is the difference between the highest and the lowest measurable sound pressure levels. The lower limit of the dynamic range represents the minimum sound pressure level that can be measured with the particular preamplifier and is reached when the electrical signal emitted by the microphone coincides with the background noise of the amplifier and of the various filters that are placed in cascade; remember then, that the electrical noise of the preamplifier depends in a relevant way also on the capacity of the microphone and decreases as the capacity increases. The upper limit of the dynamic range represents the maximum level of pressure that can be measured and is only linked to the characteristics of elasticity of the diaphragm which, after exceeding its limits, introduces distortion.

2.2.2. Frequency response

It is defined as the frequency interval in which the ratio between the amplitude of the acoustic pressure acting on the microphone diaphragm and that of the electric signal generated by the microphone itself remains constant. The frequency response curve of the microphone is calibrated at the factory with an electrostatic actuator which, placed on the microphone, excites the diaphragm similarly to the sound pressure. The response curves are drawn according to a 0dB normalization. These curves are designed to compensate for all the interference and refraction phenomena occurring at high frequencies, i.e. when the physical dimensions of the microphone are comparable to the wavelengths of the sound to be measured. The graph below shows the response curve of a free field microphone of ½ " (half an inch, or about 13 mm) in diameter, obtained with an open circuit, in the case of an incidence at 0. It can be noted that the curve remains flat up to 10 kHz but this result is valid only for an ideal microphone (from the audio field): in reality already on 5 kHz we move away from the rectilinear trend. Sometimes we intervene with specific internal circuits, in order to compensate for the drop in sensitivity that occurs for frequencies above 10 kHz.

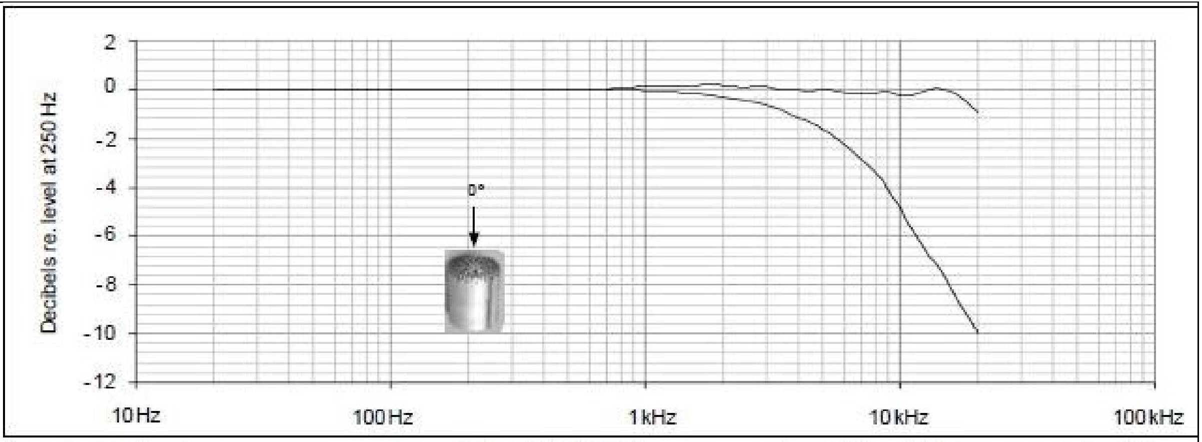


Figure 2-5: Typical open circuit frequency response of a free field microphone. Upper curve shows free-field response for 0°, lower curve shows pressure response.

The frequency response curve is also influenced by the resonance frequency of the diaphragm. The value of this frequency is established in the design phase, by controlling the mass, the voltage and the stiffness of the same, depending on the type of microphone: the resonance peak is more or less damped in order to make the response curve in frequency as flat as possible. Resonance peak damping can be achieved by varying the number of holes at the countertop level. The more holes there are, the less the damping effect on the diaphragm is. After the resonance frequency the microphone frequency response gradually decreases. The frequency at which the response curve decreases by 3 dB with respect to the reference of 0 dB is defined at high frequencies. The lowest frequency at which the microphone responds with an output signal depends on the size of the equalizing hole, which serves to maintain the same static pressure on both sides of the membrane. Below 5 Hz, strictly speaking, this hole should be closed to make the microphone suitable for the measurement of lower frequencies. Above 5 Hz, however, the dimensions of the hole are still small enough to oppose the sound waves that could enter the internal cavity of the microphone and the acoustic back pressure on the membrane becomes negligible.

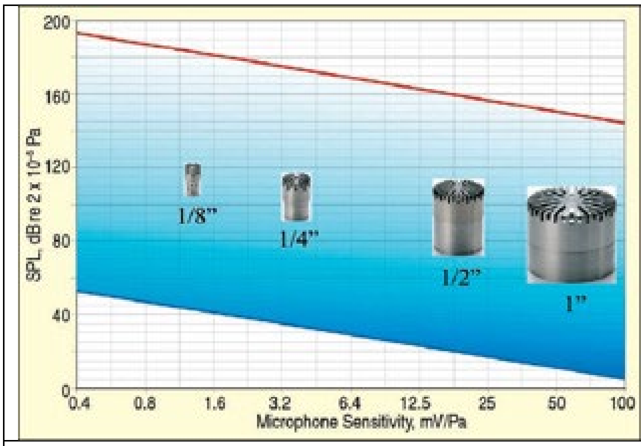


Figure 2-6: Microphone sensitivity and levels detectable according to microphone diameter

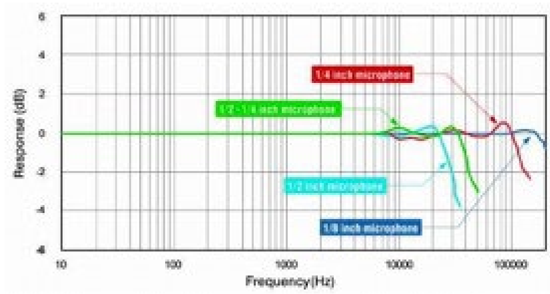


Figure 2-7: Microphone frequency response according to microphone diameter

Condenser microphones can have different sizes, from one inch to 1/8 inch. It is obvious that, based on these dimensions, there will be a different sensitivity and a different frequency response. In the above figures, for the various types of condenser microphones, the corresponding frequency and amplitude responses are shown, as well as the different ranges of measurable sound levels. It can be seen how the sensitivity of a microphone decreases when its diameter decreases while its frequency response increases.

2.2.3. Directionality

Another characteristic factor is the directionality, that is the characteristic of having a variable response depending on the angle of incidence of the sound wave on the diaphragm. There are two types of microphones on the market: the directional and the omnidirectional ones. The former present the maximum response in correspondence with a particular direction of sound incidence and this response decreases as one moves away from that direction. The latter, at least in theory, must have the same response for any direction of origin of the sound front. In reality, smaller microphones (1/4 " and 1/8 ") have the best omnidirectionality characteristics at all the frequencies of the audio band. In essence, they respond in the same way to all frequencies that come from all directions because their dimensions have no influence on the sound field at the frequencies of interest. For larger microphones, on the other hand, omnidirectional responses are provided only for frequencies below 5 kHz.

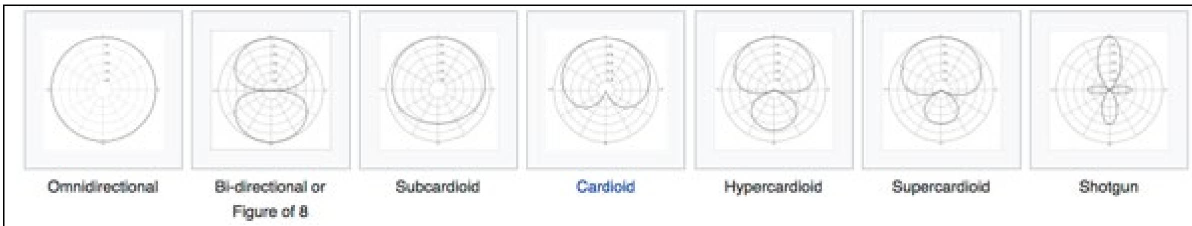


Figure 2-8: Microphones polar patterns

For higher frequencies variations of the response are observed depending on the angle of incidence. The above figure shows the directional characteristics (polar diagram) of a microphone for free field, omnidirectional, of ½ inch of diameter, as the frequency varies. The 0° - 180 ° direction corresponds to the direction perpendicular to the microphone diaphragm.

In the case of measuring microphones the most used types are those for free field and for diffuse field. These are all omnidirectional microphones, but their response curves are slightly different. Although it would be correct to use microphones for free field in environments that simulate that type of field (like anechoic rooms), and to use those for diffuse field in reverberated chambers, in reality this is not a request made explicit by the various standards.

2.3. Acoustic calibrators

Mainly due to the enormous sensitivity of the voltmeter on which they are based, the measurement of the reference electrical quantity could be influenced by the environmental conditions. Although some instruments are very stable over time, all the reference acoustic standards recommend to perform a check of the correct functioning before the measurement. This is done using acoustic calibrators, portable objects in which the microphone is firmly inserted into a suitable housing. The most common sound calibrators simply provide a reference signal at 94, 104, 114 dB at 1.000 Hz. This makes it possible to verify that the sound level meter performs correct measurements (without overestimating or underestimating the sound pressure level). Moreover, both due to the climatic conditions during campaigns of measures, which sometimes last even hours or days, changing can result in the value read, both because the microphone are still very delicate instruments, as well as sensitive, all the acoustic standards and laws recommend that at the end of the measurement operations, once again the calibration of the measurement phonometric chain has been checked by a calibrator. This is important because variations of 1 dB, would not be acceptable, although there may not be any evidence to the operator of the change in reading: even in stationary phenomena the difference of 1 dB is difficult to be perceived even by experienced operators, while standards consider acceptable measures for which the difference between the two calibration checks (before and after measurements) is less than 0,5 dB.

	
Figure 2-9: Example of calibrator	*Figure 2-10: Use of calibrator with: a microphone, an adapter, a fonometer, an head and torso simulator*

Precision classes exist for calibrators, as for microphones. So class 0 instruments are used by the calibration laboratories, while for the measurements all the standards recommend that the checks described above are carried out with class 1 calibrators. Not only that, standards often have a more stringent request than the sound level meters. In fact, usually, the calibrator requires a calibration certificate that must be not older than one year.

2.4. Intensity probe, array and others devices

With the use of the previously described sound level meters, equipped with simple microphones, it is possible to perform measurements of the acoustic pressure only. As described in section 1.0, acoustic pressure is a scalar quantity: we simply know that at a certain point (where the microphone is located) there is a certain sound pressure. Especially if the microphone is omnidirectional (all measuring microphones are omnidirectional, or very little deviate from that type of response). This instrumentation therefore does not provide any information on the direction of origin of the sound. We are not able to measure the acoustic intensity which, as shown elsewhere, is a vector quantity.

Differently than in the case of microphones, there will not be a complete discussion of the intensimetric probes, referring to the abundant literature on the subject.

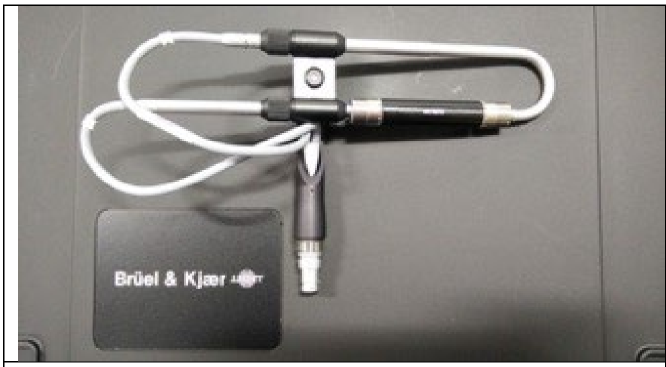


Figure 2-11: An example of P-P sound intensity probe

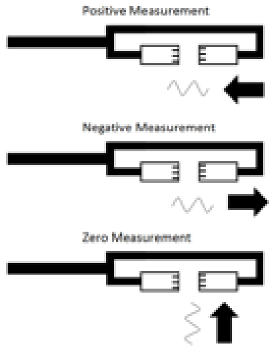


Figure 2-12: Scheme of measurement directions

There are currently two approaches applicable to measure the sound intensity: using 2 or more microphones (probes called P-P), so with two aligned microphones it is possible to determine the pressure gradient in that particular direction and from it to the sound intensity; or using a pair of sensors that can read the pressure (one microphone) on one side and on the other, the velocity of the air particles (something very similar to a hot-wire anemometer, which is why they are called P-u probes). In the latter case, the intensity is calculated directly as a product between the velocity of the air particles and the pressure measured by the microphone. Currently only P-P type probes are covered by standardized measurement methods and have a longer measurement tradition. The probes of type P-u (which currently seems to exist at one manufacturer), are more recent, have strengths and weaknesses but above all are not mentioned or admitted by any standard of measurement, especially for what concerns the determination of sound power level.

The principle of the P-P probe is quite simple: by positioning two microphones at a precise distance from each other (for this purpose special spacers are used) it is possible to calculate the vector of the sound intensity on the directions that joins the two measurement points. The most common intensimetric probes are the monoaxial probes. There are commercially available triaxial probes made by combining 6 microphones in three pairs, but they are probes affected by problems of mutual interference caused by the presence of the microphones themselves. The best solutions for three-dimensional probes are the use of 4 microphones placed in a tetrahedral configuration (one microphone for each vertex of a regular tetrahedron). There are very interesting tools on the market that are able (with a number of microphones ranging from 4 up to 32 or more) to reconstruct the spatiality of the sound over the solid angle in which they are placed, being able to make acoustic maps, in real time or not, of the whole surrounding environment, determining very quickly the direction of origin and the spectral characteristics for the whole space surrounding the microphone array.

An example is the Soundfiled microphone (for more in-depth information, multichannel surround-type recording techniques are referred to as B-format, ambisonic, ambiophonic).

Figure 2-13: A Soundfiled (4 microphone capsules)

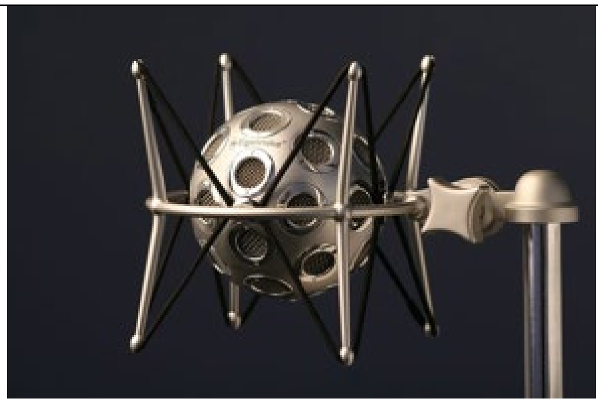


Figure 2-14: A surround mic (32 microphone capsules)

Instead, by combining more microphones in planar arrays, it is possible to realize acoustic holography: in other words, it is possible to determine the intensity mappings on surfaces parallel to those of the microphone array.

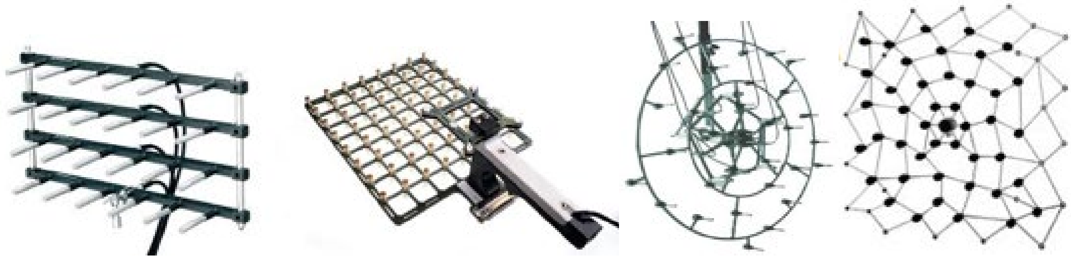


Figure 2-15: Examples of planar microphone arrays

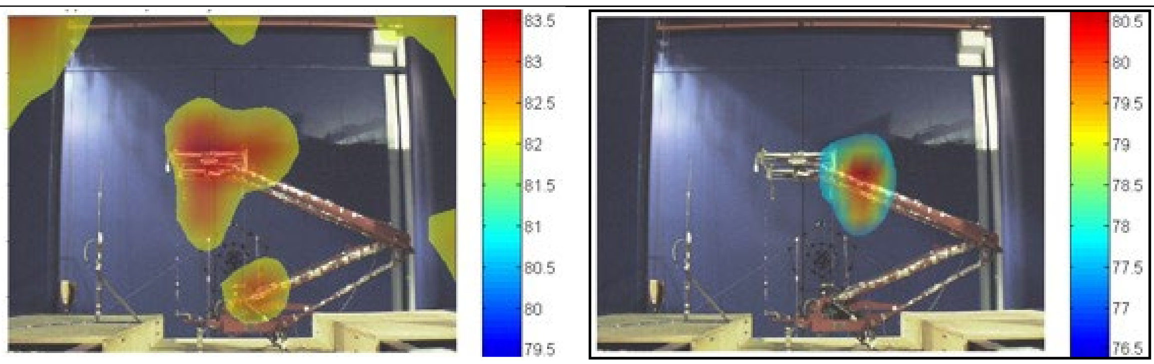


Figure 2-16: Examples of sound mapping (acoustic holography)

It should be remembered however, that the use of simple **P-P probes** (only two microphones) is the only recalled and admitted measurement standards (for example the family of **ISO 9614** standards, **parts 1, 2 and 3**). All the other instruments such as P-u probes and microphone arrays, on the other hand, are excellent tools to search for sound sources (frequency by frequency), to understand which components of a machine are the noisiest, to monitor start transients, to look for anomalous acoustic behaviors, and for research and development in general.

For use in arrays, but especially for P-P mono-axial intensity probes, it is important that the behavior of the microphones is as similar as possible. For this reason, the microphones used for intensimetric probes are usually of higher quality. Furthermore these microphones are all tested individually and then coupled two by two, selecting pairs of microphones with very similar responses in phase and frequency. This helps to ensure a more precise measurement.

Since the intensimetric probes are even more sensitive instruments, they need suitable calibrators that can verify not only the value of the pressure level read by the probe, but also the good coupling of the microphones in order to guarantee a correct value also of the sound intensity. Moreover, due to the definition of acoustic intensity as a product between pressure and velocity of the vibration of the particle, the measures of acoustic intensity suffer in environments with presence of air velocity. Typically, the standards require an environment with a maximum air speed of 2 m/s for intensity measurements, against requests of 5 m/s for simple pressure measurements.

There are several methods to examine the surface vibrations of a body. In laser scanning vibrometry the vibrations of a flat surface are being analyzed. For this purpose a grid pattern of measurement points on the surface is defined. The movement speed and distance over time of every grid-point is then successively being measured by a laser. Through the analysis of these single measurements a vibration model of the surface can be rendered. This model shows vibration frequencies and amplitudes of the surface. Another method is the attachment of accelerometers to a vibrating surface. However the attachment of small masses (~10 g per sensor) has an influence on the vibration. Furthermore feasibility dictates that the number of sensors that can be used is far smaller than the number of grid points used in laser scanning vibrometry. Amongst the advantages of accelerometry are the possibility to examine warped or transparent surfaces as well as the lower cost of the equipment.

Finally, the binaural heads or the most complete binaural mannequins used for binaural recordings are reported. These kind of microphones are named **head and torso simulator (HATS)**.

These objects are made up of anthropomorphic heads (more or less stylized) equipped with pinna in soft material (usually rubber). Behind the pinna are placed microphones very similar to those used for acoustic measurements, therefore very linear as a frequency response.

Figure 2-17: Examples of head and torso simulator (HATS)

This type of instrumentation has less the purpose of recording acoustic quantities such as the sound pressure level. They are more often used for psychoacoustic investigations. Thanks to the position of the microphones and their insertion into a head, tracing the position of the human auditory apparatus, this type of microphones allows a stereo recording that has the ambition to follow the human feeling of listening very faithfully. This happens because the sound hits the two microphone at different times (due to the relative distance between the two) and the two signals shift in phase from each other due to the presence of the pinna and the whole head. The audio recordings that are obtained therefore also possess all the information of phase shift and micro delay between the two signals that allow the human brain to process the spatiality of the sound. This only occurs if the listener uses an headphones to play the binaural stereo track (without adding changes, delays and phase shifts due to the presence of the listener's ears). The use of HATS therefore claims to make a recording of the sound event as faithful as possible to the original.

This type of recordings are widely used, as mentioned, for psychoacoustic investigations, where in addition to sound pressure levels or sound intensity levels, it is also important to have audio recordings of a product that can be played back and at last have judgment from a listening panel, which can express subjective opinions on the feelings of pleasure, annoyance, perceived quality of a product, and so on. These opinions are then correlated with measurable objective quantities (loudness or perceived volume level, sharpness or high frequency tone content, roughness and fluctuation strength or sound stability over time. For further information we recommend starting from the objective metrics proposed by H. Fastl and E. Zwicker) to find out what the potential for sound more welcome or more indicated to inform about the functioning status of a product. This type of survey is widely used in the automotive field, for research and development or even for marketing. It is also possible to hypothesize the use of similar investigations for the heat pump sector with similar objectives: to look for the less disturbing type of noise, to establish a product rating based also on the perceived (subjective) noise as well as the sound power level (objective), look for which sounds could give indications (or perceptions) on the correct functioning of a product.

3. Measurement methods

The measurement methods can be classified in different ways. They can be classified according to:

1. purpose of the measure:
    - Determining the sound pressure level at a certain point or distance;
    - Determination of sound power level;
    - Acoustic mapping for purposes of characterization or research and development;
    - Study of acoustic directivity;
    - Psychoacoustic investigations aimed at marketing or product development;
2. measurement method or type of sensor used:
    - pressure measurements;
    - measures through intensity;
    - measurements with microphone arrays / holography;
    - binaural recordings;
3. measurement environment:
    - measures in a specific controlled environment
        - environments that simulate free field (anechoic and semi-anechoic chambers, or outdoor environments on free surfaces; standards ref. **ISO 3744, 3745, 9614**);
        - environments that simulate the reverberated field (reverberating rooms and indoor environments with rigid walls; standards ref. **ISO 3743, ISO 3741**);
    - generic environments, in situ machinery installations (Standards ref. **ISO 9614, 3746, 3747**).

3.1. Purpose of the measurements

The purpose of the measurements performed has an important impact on the choice of instrumentation, suitable environments, the information that can be obtained and also the degree of precision expected.

3.1.1. Sound pressure level measurements

The simplest measures possible are sound pressure level measurements. For smaller products they are often measured at 1 meter distance or at 3 meters and reported by calculation at 1 meter distance. As mentioned also elsewhere it is important to make sure that the microphone is positioned far enough from the near field. The typical recommendation is to position the microphone at least 10 times the characteristic length (usually the larger side of the parallelepiped that inscribes the source). Often for heat pumps, especially those of large sizes, values are found in the technical documentation, measured or reported by calculation sound pressure levels at a distance of 10 meters or 30 meters. Sometimes the documentation found is not precise and the distance to which reference is made is not specified, the methods and calculations with which this result has been achieved.

It is important to note that pressure measurements can be carried out by performing a simple single measurement, positioning the microphone at x meters from the source. The same criteria for positioning the microphone influence the result. You can position the microphone frontally to the side considered the front side. You can place the microphone in what you think may be the direction of maximum emission to consider the worst case (to do this you need a preliminary test performed even with a simple subjective listening of the source). A good compromise is often made by executing 8 measures according to 8 directions (separated by 45° angles) and indicating maximum, minimum and mean values. The measurement environment also influences the result. It would be a good idea to perform measurements by positioning the source in free field and on a reflecting surface. This practice is not always followed and any reflections on surrounding walls or objects present near the source increases the measured pressure level. This makes such measures unrepeatable. It is for these reasons that the certification schemes do not allow this type of measurement as acoustic characterization of the sound sources. All this is also valid in the specific case of heat pumps.

Since these measures are quite quick to accomplish they are measures that do not provide much information on the directivity of the source and it may happen that operators do not pay much attention to the environments in which they are made. These are sufficient measures to estimate what could be the noise expected at a certain distance, but with high uncertainties. This type of measures can be a tool for production control or for the preliminary study of prototypes and pre-series by manufacturers. The typical case is the use of class 1 or class 2 sound level meters to measure sources placed in squares or parking lots sufficiently distant from other buildings, and preferably at times of the day when the background noise is sufficiently low to allow a significant measurement .

Moreover, these measurements are often sufficient to research or reveal the presence of tonal components (high emissions in particular frequencies.) In the case of heat pumps, tonal components can be determined by the rotation speed of the fans or the rotation speed of motors and pumps in general).

Since these measures are quite coarse overall, standard details are not usually followed.

3.1.2. Sound power level measurements

Unlike the sound pressure level, the sound power level does not depend on the measurement point, but is an intrinsic property of the source. This causes the sound power to be a more significant quantity. On the other hand, it requires longer and more elaborated procedures for determining this value.

The assumption that is made is that each sound source emits a certain sound power that depends on the angles of emission. The source is therefore enclosed in an ideal control surface which encloses it completely. The value that is obtained integrating the outgoing intensity onto the area of this ideal surface is the value of the outgoing sound power.

Therefore, three ways of determining the sound power can be followed:

- directly use an intensimetric probe and take measurements around the source. The measurement is more precise in the free field or in an anechoic chamber, but the intensimetric method can also be used in any environment: if there are other sources of noise around the measured source the external intensity that would enter the control volume defined by the ideal surface, it would turn out on one side and out of the opposite side, making a very modest net contribution. The reference standards for this type of measurement are **ISO 9614**, **parts 1, 2 and 3**. They are well detailed and precise and have different control procedures (K_1, K_2, K_3 and K_4 control indices) to validate the quality of the

measurement. Unfortunately, according to many experts, often these field parameters are rarely satisfied in any environment and sometimes even in controlled environments such as free fields and anechoic chambers. Furthermore, to make measurements using an intensimetric probe, is necessary to include the source in a volume delimited by a reference surface (typically a box or an hemisphere). This reference surface need to be subdivided in portions of small areas, and each area does not exceeding 1 m^2. Every small area constitutes a different point of measurement. This makes measurement operations time increasing with reference surface area (that is, at the size of the source increases). This method is also affected by the response limits on the spectrum of the probe itself and the spacer used between the microphones. Usually, significant values are obtained only for the 50 - 6.300 Hz spectrum (a band sufficient to characterize the noise of the heat pumps). According to some Round Robin tests performed in the field of heat pumps it seems that this method leads to a slight underestimation of the value obtained.
With this method we obtain the mappings useful to determine the origin of the sound produced by the source and its directivity (this is even more true the more the environment is close to the free field conditions).
Finally, this method lends itself well to the study of real installations in place (useful for installations that are too large that cannot be inserted in the most common anechoic and reverberant chambers).

- use pressure methods in free field environments. This method starts from the assumption that in the free field and at a sufficient distance from the sound source (far field) the sound pressure and the sound intensity have the same value. This assumption allows to follow procedures very similar to the previous ones: an ideal surface is again used to enclose the sound source and again called reference surface, and measurements of sound pressure level are performed on the reference surface. Again, the sound pressure value is integrated into the area of the reference surface, finally achieving a value of sound power level. There are some differences compared to the intensimetric probe method:
  - simple microphones are enough and an intensimetric probe is not needed;
  - it is necessary (mandatory!) to carry out the measurements in an environment that simulates or approximates as much as possible a free field;
  - there are fewer problems related to air speed (the presence of A/W or A/W heat pump fans would become a problem in the case of intensimetric methods);
  - the method is less sensitive to changes in temperature, pressure and sound velocity during the measurement campaign.

  These methods are well described in the **ISO 3744** and **ISO 3745** standards.
  It is also possible to use much less precise methods for control measures in less controlled environments. These methods are described in **ISO 3746** and **ISO 3747**. These latter methods are much less precise and follow simplified procedures, with a very small number of measuring points. Because of this they are not usually admitted by certification or marking systems.
  Also with this method it is possible to obtain acoustic mapping of the reference surface which can be useful to determine the origin of the sound produced by the source.
- use pressure methods in a reverberant environment. In this case the free-field hypothesis can not be followed. The assumption that follows is that of the diffuse field. In this sound field the value measured by a sound level meter positioning a microphone within this field becomes independent of the measurement point: if it is a diffuse field, in every point the sound level meter will always measure the same value (this is the definition of diffuse field in fact). The determination of the sound power level is made by placing some microphones (or a single microphone that moves along one or more defined trajectories, typically one

microphone positioned on a rotating rod) and measuring the sound pressure values. Then with absolute methods (**only ISO 3741**) or with comparison methods (**ISO 3741, ISO 3743**) with a **reference sound source** (**RSS**) that has a sound power level known and certified by accredited measurement laboratories, it is possible calculate the sound power level of the source through a sort of proportion between the sound pressure values of the two sources (the reference one and the other).

This method is very convenient because:

- it can be very fast, since multiple microphones can be used at the same time or even a single microphone placed on a rotating microphone stand can be used;
- it can be used in air-conditioned rooms with less risk of changes in the thermo-hygrometric conditions during the measurement, also by switching off any auxiliary sources for conditioning the environment (useful operation to reduce the background noise that disturbs the measures);
- it requires fewer measuring points in total.

However, it becomes necessary:

- provide a reference source with calibration certificate;
- if multiple microphones are used simultaneously, multi-channel acquisition systems are required, which are usually more complex and expensive than simple sound level meters usually equipped with only one channel.

With this method it is also not possible to have any information on the directivity of the source. It is not possible to know which zones have the greatest or lowest sound emission due to the reverberant field present.

All the standard methods for determining the sound power level are described in **ISO 3740, 3741, 3743, 3744, 3745, 3746** and **ISO 9614**. In particular, **ISO 3740** introduces the topic and gives summary tables that help in choosing the method summarizing in a very concise manner the above. For a quick summary but complete overview, we recommend consulting these tables.

3.1.3. Acoustic mapping and study of the directivity of the sources

As already explained in the previous point, it is clear that the study of directivity can be performed both with microphones and with intensimetric probes. It is important that the measurements take place in an environment that best approximates the free field conditions (anechoic chambers or open-air squares with low background noise present in the environment). In addition to the above, the use of microphone arrays can be remembered. If we think about the case of heat pumps, for which we source all in all fairly circumscribed in space, the arrays of planar microphones that can be used for acoustic holography in near-real time are very useful, which allows to identify very quickly points weak and low emissivity points.

The problems related to the use of microphone arrays are the following:

- usually many microphones are required (the higher the number of microphones, the higher the resolution);
- consequently, an acquisition and processing system is needed that is capable of managing many channels at the same time (expensive systems);

- a specific processing software system is also needed to be combined with the aforementioned hardware (sometimes not easy and often expensive).

All this makes the use of measuring microphone arrays, very useful in the research and development phase, but are also the prerogative of specialized research centers (equipped with both the instrumentation and the specific skills to manage measures that are somewhat different from those reported in the standards).

An example of the use of a microphonic array for the characterization of sound sources is that of the acoustic dome shown in Figure 3-1. This system is composed by 64 microphones. This acoustic dome is used to capture space, time and frequency resolved acoustic emissions of heat pumps. The simultaneously measured data allows also for calculation of a time dependent (direction independent) sound power level without repeatedly using alternative measurement methods (like scanning, with intensity probe or methods with single microphone). This system can be used for ISO 3745 in free filed environment, but instead of 10 o 20 microphones, with the simultaneous use of 64 microphones, it is possible to have a lot of information also on the direction of prevalent emission of the sound, making research and development investigations quick and easy, being able to immediately concentrate on the weak points, points from which the majority of the sound radiates.

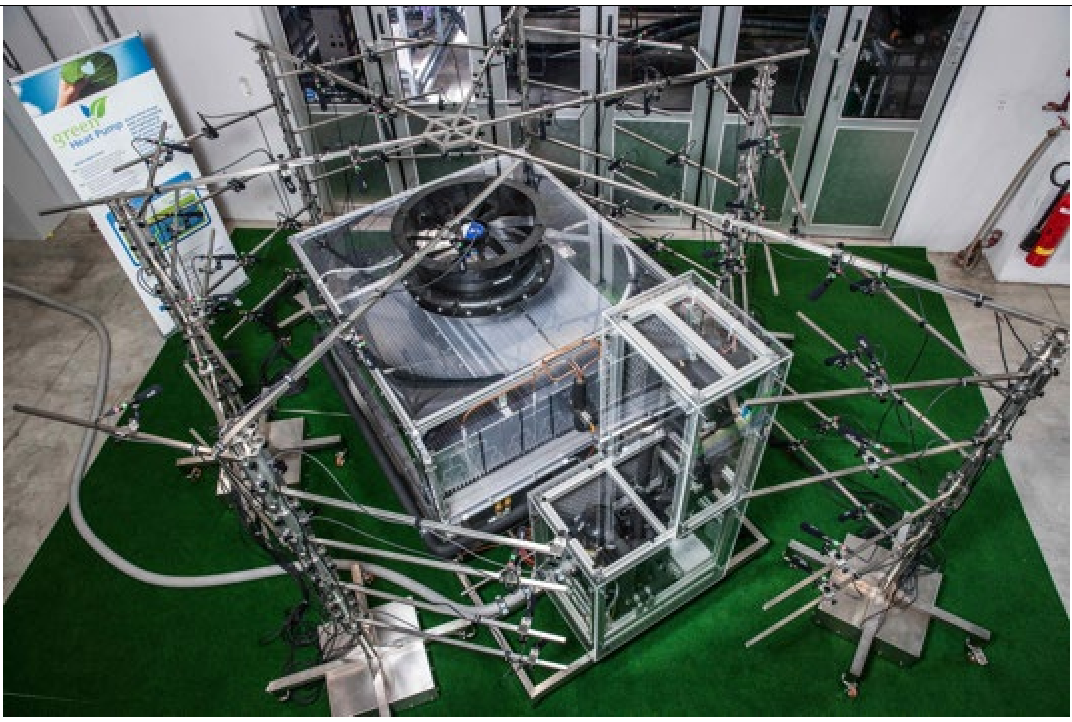


Figure 3-1: The acoustic dome and its 64 microphones positioned around a heat pump prototype

Another example of the use of arrays that is very useful when researching heat pumps is made up of this circular array made up of 64 measuring microphones. In this case, being a planar array, acoustic holography techniques are used. By the use of acoustic holography it is possible to reconstruct the vector maps of the acoustic intensity on any plane parallel to that of the microphones. This is very useful for investigating emission surfaces near the heat pump boundary surfaces. In particular, its circular shape allows the insertion in the area inside the microphones of cameras (to be able to superimpose the acoustic maps on the photos of the measured object), or also a thermal imaging camera, in order to have a double simultaneous survey: acoustic and thermal, allowing to investigate possible correlations on weak points both in terms of noise and energy losses. This array, shown in Figure 3-1 is named “AIT 64 Kanal Ring” and it is used by the AIT research team.

Figure 3-2: The AIT 64 Kanal Ring, 64 microphones array used for acoustic beamforming

3.1.4. Psychoacoustic investigations and Sound Quality

This type of recordings have already been described previously. For this type of activity it is necessary to use a dedicated HATS. Good results are also achieved with the use of cheaper headphones equipped with microphones that can be worn to make binaural recordings. For a correct use it is necessary to set up a volume adjustment system to re-propose the same sound event (the same also as regards the volume present during the event). For the rest there are no standardized procedures for making binaural recordings or for their use.

The HATS manikin is ultimately a very special microphone (a stereo microphone). It is rarely used, like other microphones described above, to determine the simple level of sound pressure. Its specificity is that of realizing audio recordings. The behavior is obviously no omnidirectional, but is affected by the presence of the ears, the head and usually also the bust. In this case the sound signal is subjected to delays and phase shifts due to the objects surrounding the actual microphones as described in the previous chapter. Although they are aimed primarily at audio recordings their acoustic response is different from that of the microphones used in the music world. At sound engineering courses, sound designers, or phonic courses teach that "linearity is not beautiful", this is because in the world of music production the most beautiful or captivating sound is sought, the one that most pleases listeners, the one that brutally "sells more". Those involved in measures must necessarily have a different approach. It is important for an acoustic technician and each person involved in measurements to have the most accurate measurement possible. For this reason the linearity of frequency response, which in the world of musical recordings may not be a good thing (except perhaps for classical music and jazz), becomes absolutely necessary when you want to make acoustic measurements. Thus, the microphones that are used in the HATS mannequins are microphones similar to those normally used in sound level meters and in measuring instruments (phonometers) in general. At most they can be coupled to have a very similar behavior and do not introduce distortions, as happens with the microphones used in the intensimetric probes. Usually, however, any gain or phase differences between two microphones of a HATS can be corrected either by using a good microphone conditioner (especially to equalize the gains), or by correcting the response of a microphone on the other microphone's response (with the creation of appropriate inverse filters, starting from the recordings of the impulse responses of the two microphones. For further details see for example the documentation of Prof. Angelo Farina and its free software plug-ins "AURORA" to be used with the software opensource Audacity at his website).

Once the recording system has been set up, this guarantees, as already mentioned, one of the recordings of the sound event as faithful as possible, provided that this recording is played back on the headphones.

As a matter of fact, the sound is modified by the presence of obstacles. The path of the sound wave that reaches the right microphone/right ear is different from that which reaches the left microphone/left ear. This allows our nervous system to process the two different signals by reconstructing the spatiality of the environment that surrounds us and the direction of origin of the sounds we hear. The original signal is therefore modified by what is called a "transfer function". Each electronic component that makes up the entire measurement chain has its own transfer function and the component changes the original sound a lot or a little. The best and most linear components have transfer functions that change the signal only a little bit. A HATS manikin has a very peculiar transfer function called HRTF (head related transfer function). In reality, each person has a unique head and unique shape of the ears, so there is an HRTF for each of us. Fortunately, all heads have transfer functions very similar to each other, so the use of a dummy instead of a custom HRTF (yes, there are tools to determine your own HRTF), still guarantees good results.

Much could still be written on HRTF, on merits and limits. This is a recording technique used for decades and a lot of literature is available on the subject. What is important to underline now is that the playback of a binaural recording (performed with a HATS manikin, or simply convoluted using digital HRTF filters), is very different from any other stereo recording using the various recording techniques. This is because normal stereo recordings are designed to be reproduced by a pair of loudspeakers, preferably placed according to a certain geometry in front of the listener. Prolonged listening to these headphone recordings can make even the most passionate audiophile weary. The sensation reported is often that the sound comes from inside the head. The sound image can come from the left or the right, it can move from one side to the other, but the perception is always that the sound comes from the inside (of the head). Using the binaural recording techniques instead, the sound image moves to the outside of the head. Not only that: the perception of the place of the sound source moves to the distance between HATS and sound source was at the time of recording. The sound is more natural. The sound event can be less intense (with a smaller volume if you aim to reproduce the sound event even with the same volume present during recording) or less rich in low frequencies, since not equalized (the equalization can be also due to the non-linearity of the same microphone used: the HATS mannequins are equipped with linear microphones), but certainly more enveloping or “three-dimensional” (if it makes sense to talk about three-dimensional sounds). This is the reason why these types of techniques are used in the automotive sector, where the sounds are very important for marketing and the TV commercials try to convey sensations rather than technical details.

The process of a psychoacoustic investigation is usually the following:

1. Identification of the field of investigation;
2. Campaign of binaural acoustic recordings;
3. Definition of the so-called subjective metrics;
4. Playback campaign by an appropriately selected or segmented panel of listeners and data collection concerning subjective metrics;
5. Possible analysis of the records and if necessary definition of so-called objective metrics;
6. Possible search for correlations between objective metrics and subjective metrics.
7. Formulation of a sound quality index

Identification of the field of investigation

In a psychoacoustic investigation it is important to define what you want to look for: the quality of a product? The sonic sensations that a product arouses? What kind of sound is associated with a product?

Psychoacoustic investigations may have the aim of characterizing a product based on the sensations that arise from the sounds emitted. Or understand what is the "best" sound for a specific range of products (we could define it as "better sound", that sound that is more pleasant, or that is what makes the product have better characteristics: more robust, more reliable, more pleasant, that works well). Or again we could look for the sound that a product in the design phase could have to be perceived better than other products already existing.

Binaural acoustic recordings

The binaural recordings are carried out with the instrumentation described in the previous chapters: HATS mannequins, microphone conditioners, HRTF hardware filters, audio sound cards, pc.

It is important to place sources and HATS in the most real conditions possible. The source must be placed in its usual place, for example a kitchen or its best approximation if it is a dishwasher. And even the HATS mannequin must be positioned in the position where a possible listener would be: not only at the correct distance, but also facing the correct position. In the case of heat pumps the most significant recordings could be carried out outdoors, since in case of indoor installations it is very likely that these are dedicated technical environments and that people are not allowed to stay in this type of environment. In this case it would make sense to perform free field recordings or in anechoic rooms, environments that simulate installations of this type of object at ground level or on the roofs of buildings.

Definition of subjective metrics

With "subjective metrics" we mean that kind of quantities that do not have a physical, univocal and objective definition. They are quantities or qualities that depend a lot on impressions, perceptions, or even on the listener's mood. "Perceived quality", "robustness", "durability/reliability", "pleasantness" are all feelings that can come from one type of sound or another. The typical example is the sound perceived by the closing of a car door. Sometimes it is not important if that sound is related or not to the robustness of the car. In this phase, it is simply investigated whether a certain sound makes a person thinking of a robust or a fragile machine regardless of whether they really are robust or fragile: this is because the possible buyer can hear the sound and get an idea, but can not verify whether the stain is actually robust. His choice, however, will be influenced by his state of mind and by the sensations that the peculiar sound just eared have suggested to him.

According to the purposes of psychoacoustic research, therefore, subjective metrics are defined, which usually coincide with the sensations that the recorded audio tracks could cause.

Playback by a selected listening panel

In this very delicate phase the binaural recordings are submitted to listeners because they express the judgment. It is very delicate because it has to take many aspects into account:

- The test should not be too long (some authors recommend a maximum of 20 minutes), because the attention may fall and with it the mood may change. In case of evaluation of many audio tracks the last answers could be affected by fatigue, the drop in attention etc ... making a comparison between the answers so difficult;
- The listening test must be easy to understand;
- The test must be as identical as possible for everyone. Usually a single audio track is prepared with a guide voice that introduces the actual listening tests. The environment used for playback must be identical for all listeners, must be neutral, must not provide too many stimuli or inputs (shapes / colors / smells) that could affect the answers;
- The audio tracks must be calibrated because all the people listen, not only with the same volume, but also with the same volume present in the recording phase: the listener must have the same recorded sound event, just as if he were present on site;
- The listening panel must be appropriately selected, both for market needs (possible purchasers of a product or possible future users of a product), must be acoustically standardized (people with hearing problems may provide unrepresentative answers);
- Each listener must be able to evaluate only the sounds produced and no other characteristics of the investigated products: In the case of a heat pump survey should not receive any stimulation from other senses that may make listeners thinking of the heat pumps: no images of heat pumps should be proposed neither the presence of this type of object is admitted, since the answers could be influenced by what is seen and the subjective judgment expressed could be dictated by their preferences on the shapes or color seen.

These are just some of the aspects that must be taken into account in the preparation of listening tests, to minimize and normalize the subjective components, which will necessarily be introduced and on which there is no type of control (think of the listener who will present to do the test after having drilled a car wheel on a rainy day, probably will not respond like the others... even if we might not even notice it).

Definition (if necessary) of objective metrics

Depending on the purpose of the investigation you want to do, this part may or may not be present. The "objective metrics" describe quantities of which it is possible to provide a univocal objective definition (just think of all the physical quantities to have an example of objective metrics). Usually in psychoacoustic are also called objective Zwicker metrics to because Eberhard Zwicker and Hugo Fastl are the first two researchers who have defined these quantities that we only list here: Loudness, Sharpness, Roughness, Fluctuation Strength. These are the main ones. Others can be added from the literature and new specific metrics can be defined for specific intents/goals.

The recorded audio tracks are analyzed with appropriate algorithms to obtain the numerical value of the objective quantities of each recording.

Search for correlations between objective metrics (if defined) and subjective metrics

The previous phase, however, as mentioned, may not be necessary: if you want to characterize a family of products, may have been made different registrations of existing products and then subjected them to a relative judgment: “listen to the two sounds, sound A and sound B. Which you prefer?” Therefore, relative reference scales could be made based on direct comparisons. Otherwise in the listening phase you may be asked for votes: “from 0 to 5 what grade would you give to sound A?”. If instead the survey aims to construct a tool for forecasting products not yet realized or not yet distributed, it is important to be able to characterize the sounds heard and subjected to subjective evaluation, also linking to values of subjective quantities.

In this case we are looking for mathematical correlations that can link the measurable objective quantities (the objective metrics defined above) and the sensations and perceptions that the same sound events cause in the listeners (subjective metrics). In this way it is possible to try to understand what could be the best sound for a product that is still under development: regardless of its sound power level (almost unique parameter used today to identify the noise of a product), what kind of sound does it perceive as more or less noisy? Which acoustical characteristics must have a product in order to be perceived as a product that functions correctly, that works well, that it is performing a certain processing/operation phase? This can be a valuable aid in research and development.

Please note that some products must be able to communicate their functionality even through the sounds emitted. Not always the quietest product is the best acoustic product (a silent product is sometimes simply “mute” and does not tell us if it is switched on, off or otherwise). Heat pumps are no exception, but two type of listeners must be distinguished:

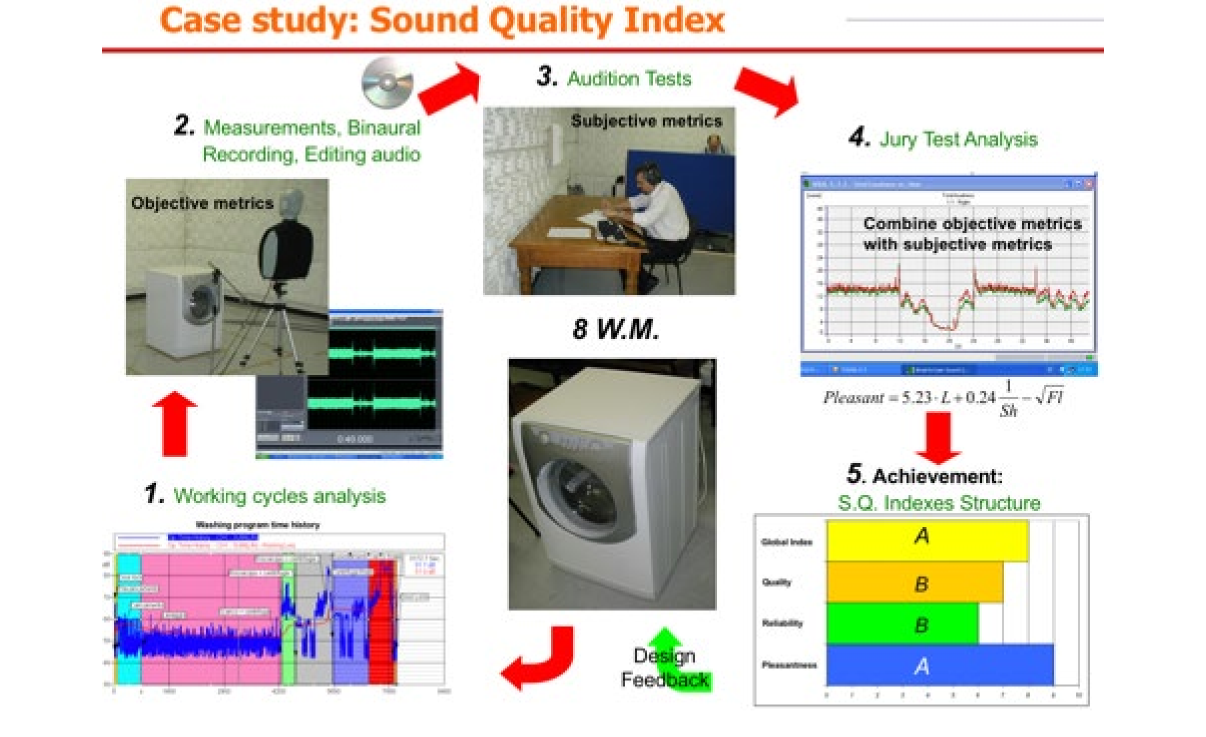
- Those who have purchased the heat pump and manage it must be able to receive information from sound emissions: how we recognize the arrival of certain models of motorcycles listening to the incoming sound, we could recognize the mode of operation from the distinctive sound of the machine, and in case if we think it is necessary maintenance interventions.
- Those who have not purchased the heat pump but live in the vicinity of an installation may only wish that the noise emissions are perceived with a low volume or that they are

not perceived as particularly annoying (another time: the perception of the annoyance is not related only to the level of sound power emitted: think of the chirping of birds, often a common listener does not even notice it, while the acoustic technician who is performing environmental noise measurements knows that this is a type of sound that can reach very high and very evident levels of sound pressure on the microphone, altering the result of the measurements, at least as regards the objective metric "sound pressure level", without raising the subjective metric "noise perception" very much).

Formulation of a sound quality index

The whole process described up to now can be called "**Sound Quality**" (SQ). The Sound Quality is in fact made up of many operations (and not all must coexist at once). The SQ lead to the study of the sound emissions of a product. The SQ looks for the sound components (and the mechanical components that produce them) perceived as more pleasant or more annoying. The SQ studies the correlations between types of sounds and degrees of appreciation, up to the use of these results in order to correct the problems of existing products, and to be able to design new better products. Once the correlations between objective metrics and subjective metrics have been developed, these correlations can be combined and weighed to reach a synthetic index that allows rapid comparison between existing objects (and this can be done directly with comparison of audio tracks by listeners), but also a prediction of the expected liking of a product, without this being registered and judged directly. In the latter case it is not even necessary that the product has already been built. An SQI (sound Quality Index) can be very useful for designing whole new products or new product components. Alternatively, an SQI can also be used as a more advanced tool to determine the degree of disturbance that a product or product family, that could go beyond the simple sound pressure level SPL to X meters or the most currently used sound power level L_{WA}. Such an investigative work and a proposal of an SQI dedicated to heat pumps could form the basis for the proposal of new standards, new laws (national or European) or even new product certification, integrating what is already existing in Europe and outside the European Community.

The Figure 3-3 shows a summary of the activities that led to the definition of an SQI. In this case, as can be seen from the image, the study was dedicated to the family product of washing machine.



$$Pleasant = 5.23 \cdot L + 0.24 \frac{1}{Sh} - \sqrt{Fl}$$

Figure 3-3: Example of SQI – Workflow for the proposal of an SQI for washing machines

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Figure 2-16: Examples of sound mapping (acoustic holography) – Politecnico di Milano courtesy (Porf. Dr. Roberto Corradi)

Figure 2-17: Examples of head and torso simulator (HATS) – from "Brüel & Kjær" documentation and "Gras" documentation, in particular the central photo's source is: http://vip.tilb.sze.hu/~wersenyi/HTML/GRUNDLAGEN%20DER%20FAHRZEUGAKUSTIK.htm

Figure 3-1: The acoustic dome and its 64 microphones positioned around a heat pump prototype – AIT Austrian Institute of Technology courtesy (Prof. Dr. Christoph Reichl)

Figure 3-2: The AIT 64 Kanal Ring, 64 microphones array used for acoustic – AIT Austrian Institute of Technology courtesy (Prof. Dr. Christoph Reichl)

Figure 3-3: Example of SQI – Workflow for the proposal of an SQI for washing machines – Politecnico di Milano courtesy (Prof. Dr. Livio Mazzarella)

6. TABLES INDEX

www.heatpumpingtechnologies.org

Heat Pump Centre
c/o RISE - Research Institutes of Sweden
PO Box 857
SE-501 15 BORÅS
Sweden
Tel: +46 10 516 5512
E-mail: hpc@heatpumpcentre.org

www.heatpumpingtechnologies.org

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