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TOWARDS AN IN-SITU MEASUREMENT PROTOCOL FOR SOUND FROM DOMESTIC AIR SOURCE HEAT PUMPS

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Abstract

In the planning of noise impacts from domestic air source heat pumps (ASHPs), compliance criteria typically refer to a single value in dB(A). Manufacturers provide laboratory test data based on reference thermal conditions, defined flow and return temperatures and single operating points, but in-situ environmental conditions vary widely and continuously, while system characteristics, settings and demands lead to wide variations in operational patterns. To demonstrate compliance with design criteria, a protocol for the measurement and assessment of in-situ sound emissions is required. A framework based on the highest daily $L_{Aeq,1hr}$ sound emission is proposed; regression against the daily minimum temperature enables the emission to be expressed at 7°C, the laboratory reference condition. Spatial, temporal and environmental contamination factors are discussed. Pilot measurements at eight installations, comprising more than 1,200 hours of monitoring, illustrate three distinct operational sound emission profiles – unimodal, bimodal and continuously variable – and the potential to use a short-term measurement of a hot water cycle to infer longer-term emission is explored. Two dimensions along which in-situ operation may diverge from the part-load laboratory test condition are discussed qualitatively. A complementary qualitative protocol, based on narrative interviews, is described for use where the effect of an installation on residents is in question.

Keywords: *ASHP, sound power, in-situ noise*

1. Introduction

The UK aims to rapidly scale heat pump deployment, but acoustic planning rules are emerging as a practical barrier. Under current Permitted Development rules, installations must comply with the MCS-020a sound calculation [1] to proceed without a full planning application. That calculation, and acoustic design more generally, relies on a single laboratory-derived A-weighted sound power level to characterise the acoustic emission of the unit.

Manufacturers must declare a sound power level under the Energy-related Products (ErP) labelling legislation [2], from tests conducted at an ambient air temperature of 7 °C. The 2022 revision of EN 12102-1 [3] requires that, for variable-capacity (inverter-driven) units, the test is undertaken at the declared part-load condition (Condition C) established in EN 14825 [4], which is approximately 35% of the unit's rated design heating capacity. Prior to the 2022 update, units were tested at rated load capacity; as inverter-driven compressors became standard, testing at rated power operational points was considered potentially punitive and unrepresentative of real-world thermal demand.

The part-load test characterises the unit at a single defined operating point, corresponding to the lowest load at which a variable-capacity unit is required to operate at 7 °C. Two dimensions of in-situ operation therefore lie outside the condition described by the test: operation at higher loads at 7 °C, and operation at ambient temperatures below 7 °C. In some jurisdictions manufacturers additionally declare a "Maximum" sound power level, for example via the German Heat Pump Association (BWP) sound calculator, under a voluntary industry agreement: however, there is no published standard or test method defining a common operating state for this maximum value, and the basis of declaration is not consistent across the market [5], on the published evidence reviewed here. The industry may also be in a state of transition: where ErP and Max values are declared identically, it is considered that the ErP figure may derive from the pre-2022 full-load test regime.

In-situ operations vary as environmental conditions and demand for heat vary continuously; the sound emission is a function not only of the unit but of the connected system, control strategy and fluctuating

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demand. There is currently no standardised guidance on how to systematically measure and assess the in-situ sound emissions of ASHPs.

This paper proposes a robust, reproducible framework for measuring and assessing in-situ ASHP sound emissions, based on pilot field measurements at eight installations comprising more than 1,200 hours of monitoring. It describes how the spatial, temporal and environmental-contamination challenges of field measurement can be methodically addressed, presents the operational sound emission profiles observed, considers how in-situ operation may diverge from the laboratory test condition, and outlines a complementary protocol for the qualitative assessment of resident experience.

2. FIELD DATA ACQUISITION

2.1 Site selection

Eight ASHP installations were measured. Six were selected on the basis of opportunity - these were at properties of acoustics professionals or ASHP installers, with no subjective noise issues raised; two were selected on the basis of a noise complaint or report of dissatisfaction. All are current ASHP models except one complaint site, where the unit has been superseded. Monitoring periods ranged from a single two-hour hot water cycle to 23 days of continuous logging, with most sites monitored over around 4 days. The sample is one of convenience rather than a statistically representative selection of the installed stock, and the observations that follow should be read as indicative of the range of behaviours encountered rather than of their prevalence.

2.2 Acoustic characterisation

All measurements used calibrated Class 1 sound level meters, logging A-weighted broadband levels and 1/3-octave band spectra at 1-second intervals ($L_{Aeq,1s}$). A single microphone was deployed at approximately 1 m from a dominant noise-emitting face of the ASHP (typically the front or the compressor side). Pre-pilot testing indicated that 1 m provides a reasonable balance of signal-to-noise ratio while avoiding near-field effects; even at 1 m, the sound from an ASHP is often quieter than extraneous environmental sound.

The 1-second data were processed to a one-minute statistical metric, the $L_{A90,1min}$. When measuring in close proximity to a continuously operating source, the L_{A90} descriptor serves as an effective proxy for the underlying steady-state emission, inherently filtering transient acoustic events (passing vehicles, aircraft, intermittent wind) that inflate the L_{Aeq}. During night-time periods with low extraneous noise, the difference between $L_{A90,1min}$ and $L_{Aeq,1min}$ reduced to less than 1 dB for significant periods, supporting the validity of the approach. A limitation is that the $L_{A90,1min}$ will not capture short-term sounds; defrost events are also outside the scope of the protocol proposed here.

2.3 Spatial considerations: directivity

A single measurement position raises the question of directivity error. Analysis of the 2011 Building Performance Centre field study for DECC [6] indicates that, for conventional arrangements, the error in using a single measurement on the compressor side is less than 1 dB (standard error 0.35 dB across six sites; 95% confidence interval -0.69 to +1.09 dB). Sound intensity data from AIT and CETIAT [7] show that the rear (heat exchanger) face most frequently has the highest emission; as this face is typically against a wall, side measurements capture reflections from it. Even taking the maximum possible error of measuring on the quietest side with no reflections, the mean error across that database is calculated to be -0.52 dB (95 % CI −1.83 to +0.78 dB). Anechoic directivity measurements at RWTH Aachen [8] in 30° increments show a standard deviation of 1.1 dBA for a randomly chosen horizontal angle. Giving most weight to the in-situ evidence, in-situ measurements are likely to carry a sound power uncertainty of less than 1 dB when using a single position and assuming omnidirectional radiation.

2.4 Multi-day monitoring

A fundamental finding of this work is that isolated, short-term "snapshot" measurements can be unrepresentative of an ASHP's longer-term acoustic emission. Sound emissions are fundamentally driven by external thermal conditions and fluctuating demand for central heating (CH) and domestic hot water (DHW). Extended measurement periods are required to capture variability in thermal demand across CH and DHW cycles, environmental variation (maximising the probability of capturing high-load operation in colder conditions) and, where complaints are investigated, the diurnal cycle of the prevailing background sound level.

2.5 Supplementary data streams

Sound level data are of limited analytical value without synchronous operational and environmental context. Where available, high-resolution operational telemetry - compressor frequency, fan speed, flow and return water temperatures, electrical power input and DHW charging indicators – was obtained via manufacturers' cloud platforms or external monitoring, ideally at 10-second resolution or faster. These allow the acoustic time-history to be categorised into active (CH or DHW), idle and defrost states. Where telemetry was limited, flow and return temperatures alone were usually sufficient to identify operational mode periods. ASHPs' own external temperature sensors were found to be unreliable. Underlying meteorological conditions were therefore derived from open-source meteorological sources: dry-bulb air temperature, wind speed and direction, and precipitation. These were used to help identify and exclude periods where wind- or rain-induced noise corrupted the acoustic dataset, using machine learning models to predict ASHP sound levels based on the operational data. The mode classification for analysis comprises CH, DHW and idle/background; idle periods are valuable for observing the underlying environmental sound level and confirming that measured operational sound genuinely exceeds it. Defrost cycles are beyond the scope of this analysis.

3. DATA PROCESSING AND PROPOSED ASSESSMENT PROTOCOL

3.1 Data synchronisation

The foundation of the analytical protocol is temporal synchronisation of the acoustic measurements with operational telemetry and local weather data. Different streams use fixed time bases or event-based logging; quantising all data to discrete one-minute periods aligned with the $L_{A90,1min}$ sound profile inevitably involves some loss of precision, as a one-minute period may straddle two compressor states; this represents a balance between operational precision and a suitable acoustic perspective of the underlying ASHP sound. Figure 1 illustrates the synchronised data streams, with potentially wind-affected periods identified for exclusion.

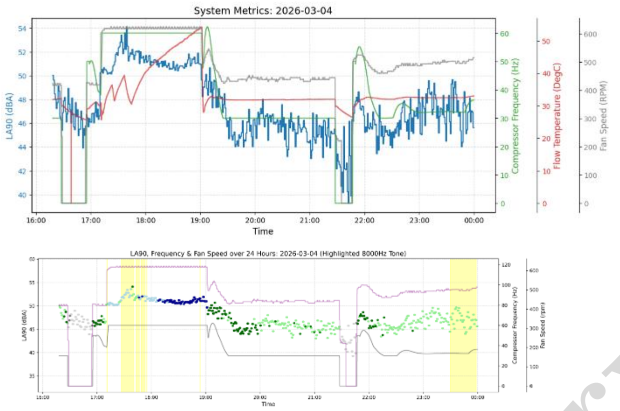


Figure 1. Synchronised time history of sound level and operational parameters; shaded periods are identified as potentially wind-affected and excluded.

3.2 Daily aggregation

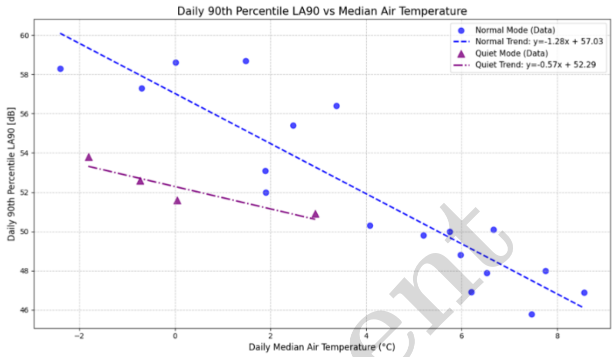
For each 24-hour period, two methods were considered to derive a sound level that may represent the impact on residents. The loudest operational hour is identified as the $L_{Aeq,1hr}$, calculated as the logarithmic average of the operational $L_{A90,1min}$ values over the hour. Where the ASHP operates for only part of the hour, the energy-average is correspondingly reduced. The one-hour reference period is familiar to UK practitioners and ties in with the BS 4142 methodology [9].

An alternative daily descriptor, the 90th percentile of the daily operational $L_{A90,1min}$ values, was also evaluated. Across the sites the difference between the two approaches is less than 1 dB in most cases; the loudest-hour method is taken forward as it aligns with conventional UK assessment practice.

3.3 Thermal regression to the 7 °C reference

Each day is characterised by its highest $L_{Aeq,1hr}$ and its minimum daily temperature. A linear regression of the daily loudest-hour level against temperature enables identification of the sound level at 7 °C, the laboratory reference condition, so that results from different sites and monitoring periods may be expressed on a common basis, as illustrated in Figure 2. Where there is no clear temperature dependence, a simple linear average of the daily values may be taken.

Figure 2. Regression of the highest daily $L_{Aeq,1hr}$ against daily median temperature, from which the sound level at 7 °C is identified.



The choice of temperature statistic matters. Correlation with the coldest (0th percentile) daily temperature optimised the regression fit (highest R^2); since the coldest temperature is always lower than the median, its use characterises the measured emission as lower at 7 °C. The measurements should span days with minimum temperatures both above and below 7°C.

3.4 Seasonal sound emission assessment

The regression for the highest daily temperature associated with the daily median or minimum temperature can be used to predict the sound emissions over the heating season. This currently relies on extrapolating sound levels at higher temperatures (as these conditions did not occur during monitoring at this particular site), although the lower sound levels are likely to be of less interest than the higher sound levels. Figure 3 illustrates a sample extrapolation over the heating season, to illustrate the question: how should seasonal sound levels be assessed?

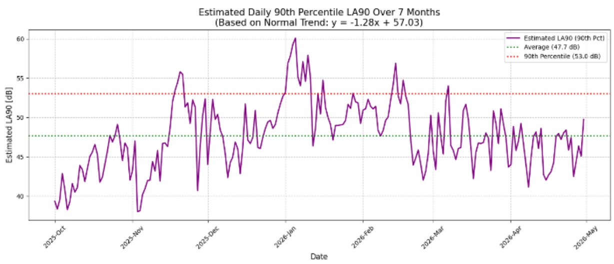


Figure 3. Extrapolated daily 90th percentile sound level emission over the heating season.

4. FIELD MEASUREMENT RESULTS

4.1 Three operational sound emission profiles

Modern inverter-driven ASHPs do not exhibit static sound emissions. A 2011 survey of ASHP sound emissions [6] found unimodal behaviour, with levels varying by only a few decibels over a week of operation; however, design and control have developed substantially since that time. The pilot measurements reveal three broad patterns.

Unimodal. At one site, the emitted levels are essentially constant regardless of operational mode (CH or DHW) or ambient temperature (Figure 4). This behaviour is attributed to a specific control setting (‘thermostatic pump blockade’) in which a room thermostat directly enables and disables the heating circuit, producing abrupt start/stop cycling at a fixed operating point rather than continuous modulation. While simple to characterise acoustically, this configuration is unlikely to be optimal from a thermodynamic efficiency perspective. System efficiency was not assessed in this work, and no wider inference is drawn about the design of the installation.

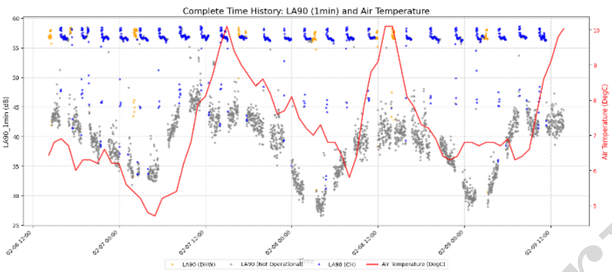


Figure 4. Unimodal sound emission pattern: sound levels (CH in blue, DHW in orange) are essentially constant regardless of ambient temperature (red line).

Bimodal. At four sites, sound levels cluster around two distinct peaks, with a discrete step-change in emission capacity below a site-specific temperature threshold, as illustrated in Figure 5. At that site the upper band, centred around 10 dB above the lower band, and ceases to occur when daytime temperatures exceed 11°C; at another, a step change of 12 dB appears below 4°C. Notably, neither band is observed to be temperature-dependent in itself - there is simply a threshold below which the upper mode occurs. Bimodal behaviour is also apparent in published laboratory data [8], where operational modes are described as “high power heating” and “maximum capacity (winter mode)”.

Continuously variable. At two sites, sound levels modulate continuously with demand around a single peak, generally increasing as ambient temperature drops, typically at around 1 dB per degree (Figure 6). For these units, assigning a single static sound power level is challenging and potentially unrepresentative.

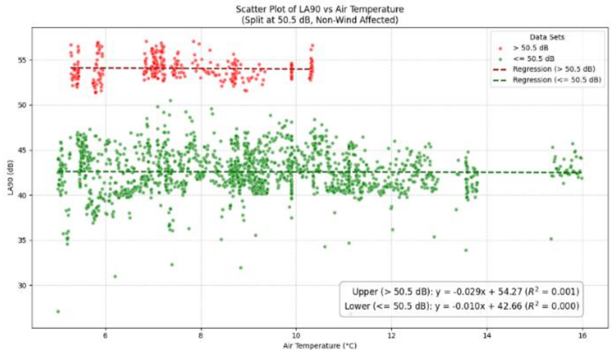


Figure 5. Bimodal sound emission pattern: sound level versus ambient temperature, with two distinct bands of levels centred approximately 10 dB apart.

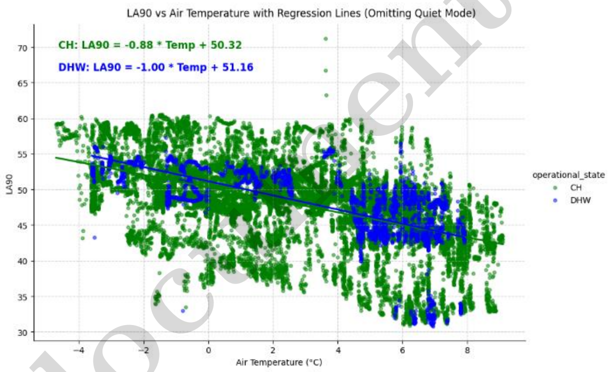


Figure 6. Continuously variable sound emission pattern: sound level modulates with demand and increases as ambient temperature falls.

Where both compressor and fan speed data were available, the measurements at one site show compressor speed more highly correlated with sound level than fan speed (regression coefficients 0.73 vs 0.45). This contrasts with published laboratory data in which fan speed dominates the overall output [10]. Fan-dominated behaviour can explain both the unimodal and bimodal patterns (discrete fan speed states), while compressor-dominated emission produces the more continuously variable profiles over a wider range of levels.

4.2 Divergence from part-load laboratory test

The in-situ measurement proposed here and the part-load laboratory test describe different things: the protocol identifies the highest daily one-hour level expressed at 7 °C, whereas the laboratory test characterises a single defined part-load operating point at the same ambient temperature. Divergence between them is anticipated rather than an anomaly: the laboratory test cannot be replicated in-situ.

Two dimensions of divergence follow - the first is load. At 7 °C an installation may operate anywhere between the part-load condition (although likely at a different flow temperature) and the maximum capacity of the unit, depending on the heat demand of the dwelling, the emitter design and flow temperature, the control strategy and the domestic hot water schedule. Across the pilot sites, emissions expressed at 7 °C were found both above and below the corresponding declared ErP values. Given the small number of sites, and the two declaration regimes described in Section 1, this comparison is indicative only; no systematic relationship between in-situ emission and declared values should be inferred from it. The second dimension is ambient temperature: operation below 7 °C lies outside the range of the laboratory test condition altogether, and the effect of falling temperature differs markedly between the three operational profiles, as described below.

At one site, a well-designed installation with underfloor heating operates at flow temperatures well below the 55 °C required for the laboratory test, and the measured emission was correspondingly low, suggesting the acoustic benefit of a thermally efficient system design. At another, a short measurement of a single DHW cycle was constant and steady throughout charging, suggesting the potential for a short-term hot water cycle measurement to infer longer-term emission for units that behave in this way, although this cannot yet be generalised. At a third (continuously variable) site, the relationship between DHW cycle level and ambient temperature resembled that between the highest daily $L_{Aeq,1hr}$ and minimum daily temperature.

Any comparison with declared data must also recognise that declarations currently derive from two different test regimes: part-load testing under EN 12102-1:2022, and the preceding rated-load test point, with no clear means of identifying which applies to a given unit. This limits what can be concluded from any comparison between measured in-situ and declared values.

4.3 Operation below 7°C

Below 7°C, three behaviours are observed, mirroring the three profiles: no change (***unimodal***); step-change increases of 8–12 dB below site-specific temperature thresholds (***bimodal***); and a steady trend of increasing level with falling temperature, typically around 1 dB per degree (***continuously variable***). Operation below 7 °C lies outside the range of the current laboratory test condition. The temperature dependence also implies that an identical installation in a colder climate is likely to emit more sound over the heating season than one in a warmer climate, raising the question of whether assessment should account for the prevailing climate, although the data and framework to do so at the design stage are lacking. The step changes and gradients reported here are drawn from the pilot sites and characterise the behaviours observed; they are not offered as values representative of the wider population of units.

5. SUBJECTIVE ASSESSMENT OF RESIDENT EXPERIENCE

5.1 Rationale and frameworks

Objective measurement alone does not explain why some installations give rise to disturbance and others do not. For well-researched sources such as transportation noise, sound level accounts for only about a third of the variance in reported annoyance; a further third is attributable to non-acoustic factors, and the remainder is unexplained [12], [13]. An ASHP in a residential setting is likely to carry more meaning for a listener than a transportation source, so individual responses may vary more widely still. A qualitative pathway is therefore proposed alongside the objective protocol, for use where the effect of a particular installation on those living near it is in question.

Three frameworks inform the approach. The soundscape paradigm of the ISO 12913 series [14], [15] re-frames sound as a holistic, context-dependent experience and places the lived experience at the centre; a residential setting typically carries an expectation of tranquillity, and a mechanical source may be perceived as an intrusion irrespective of its absolute level. Psychoacoustic description recognises that the character of a sound, such as tonality, roughness, and the fluctuation strength associated with fan or compressor modulation, may be more noticeable, and correlate more strongly with annoyance, than the A-weighted level. ISO/TS 16755-1 [16] categorises the non-acoustic variables shaping context and perception as personal (e.g. noise sensitivity, perceived control), physical (e.g. spatial layout relative to the source), social (e.g. perceived fairness, trust) and situational (e.g. time of day, interference with activities).

5.2 Narrative interview protocol

A standardised narrative interview protocol was developed and piloted. It avoids leading questions and the imposition of technical vocabulary (e.g. 'hum', 'throb', 'low frequency') so that the participant's own descriptors are recorded. It progresses through four phases: Context, establishing baseline physical and situational factors and habitual use of indoor and outdoor spaces; the Sound, eliciting perceived character and temporal behaviour directly from the participant; the Person, distinguishing coping behaviours from perceived coping capacity and from perceived control; and History and Process, mapping the timeline of awareness, prior expectations and any pre-installation consultation which bear on perceived fairness and trust.

5.3 Triangulation and pilot observations

The interview material is read against the synchronised acoustic, operational and meteorological record. The purpose is not to validate or invalidate the participant's account against the physical data, but to characterise the relationship between exposure and lived experience; where the two diverge, that divergence is itself recorded as a finding. The one-minute time history supports this, since participants describe particular operating states rather than average conditions.

Three pilot investigations were undertaken; given the number of cases, the observations are exploratory. In the two cases where the sound was reported as disturbing, participants identified the loudest operating states, which occur for only part of the year, as the source of the difficulty, and both noted the unpredictability and intermittency of those phases as an obstacle to habituation. Both were aware of the unit running at other times without difficulty. In one of these cases no formal complaint had been made, the participant placing a high value on preserving relations with the neighbour; the third case concerned a formal objection raised before any unit had been installed. These observations suggest that the presence or absence of a complaint may not be a reliable proxy for measured acoustic impact, and support gathering qualitative and objective evidence together. With three cases, this is a proposition to be tested in a larger study rather than a general conclusion.

6. CONCLUSIONS AND FURTHER WORK

The proposed protocol using the $L_{A90,1min}$ statistical processing of continuous 1-second logging, synchronised with operational telemetry and meteorological data, aggregated to the highest daily $L_{Aeq,1hr}$ and regressed against the daily minimum temperature provides a robust, reproducible framework for characterising in-situ ASHP sound level emissions at 7°C, while filtering extraneous ambient sound. Regression is not meaningful for unimodal or bimodal operational patterns where there is no clear temperature dependence of operation.

This protocol is intended to quantify acoustic impact, hence the establishment of the highest daily sound level; this evaluation is not anticipated to correlate with part-load laboratory tests at 7°C.

Divergence between the in-situ measure proposed here and the part-load laboratory value is therefore to be expected rather than treated as anomalous, and it has the two dimensions described above: load at 7 °C, and operation below 7 °C. The extent of that divergence depends on the operational profile of the unit and on the design and control of the system it serves. Characterising it across a representative sample of units and installations is a matter for further work.

Further work should extend monitoring to a larger, more representative sample of ASHPs across a broader range of weather conditions, and develop a framework for assessing seasonal sound impacts [10], [11], for which no method is currently proposed. More fundamentally, socio-acoustic surveys of ASHP neighbours are needed to establish exposure-response relationships and appropriate impact thresholds. Any move towards a more complete characterisation of in-situ sound emissions needs to be accompanied by a parallel re-evaluation of suitable sound level limits, so that the outcome neither increases adverse impact nor adds unnecessary barriers to installation.

7. ACKNOWLEDGMENTS

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