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Simultaneous energy efficiency and acoustic evaluation of heat pump systems using dynamic simulation models

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Abstract

Heat pumps are a key technology in Germany's energy system transformation process for achieving the federal government's environmental goals. A crucial factor, increasing heat pump's comfort, is its acoustics. Air-to-water-heat pumps need a compressor and a fan to operate efficiently. Both components have sound emissions that can be disturbing regarding humans' psychoacoustics. Thus, it is necessary to develop energy efficient and quiet heat pumps.

Within this work, we show that it is possible to estimate energetic and acoustic performance of heat pumps in dynamic simulation models simultaneously. Therefore, we link the Sound Source Extension Library to a dynamic heat pump simulation model, designed using the AixLib. The acoustic signatures of compressor and fan are coupled to their corresponding rotational speeds. Furthermore, we apply an Extremum Seeking Controller to operate the heat pump in an energy-acoustic optimum mode, which is specified by a predefined target function. By consequently optimizing the evaporator fan speed, we are able to reduce overall acoustic emission of the simulated heat pump by about 8 dB(A) while increasing its energy efficiency by about 4 %.

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Keywords: heat pump; dynamic simulation model; acoustic emission; noise; extremum seeking control

1. Introduction

Within Germany's energy transition process, air-to-water heat pumps are a promising technology in order to replace conventional heating systems in the building stock. To accelerate the replacement process, there is an urgent need to improve their energy efficiency and user comfort. The coefficient of performance (*COP*) is a common measure to estimate heat pump's energy efficiency. Many studies investigate the influence of used refrigerant and building's temperature levels on the *COP*. Almost all of these studies aim for a *COP* maximization by optimizing either design or operation. Simultaneously, an increasing issue related to user comfort is heat pump's noise emissions. With regard to the A-weighted acoustic emissions, the fan and compressor of an air-to-water heat pump are the main sources of noise. According to Graf [1], the evaporator fan causes 90% of the noise perceived in the neighborhood. Reducing fan's noise emission by optimal design and operation implies a great potential to increase heat pump's user comfort. Apparently, both measures depend on component design and operation. However, energy efficient design and noise emission reduced design are contrary. The same applies for energy efficient and noise emission reduced operation. Since many design studies already exist, we focus on operation optimization within this work.

On the one hand, energy efficient operation studies discuss different heat pump control approaches. These commonly differ between rule-based-control (RBC), extremum seeking control (ESC) and model predictive control (MPC). Compared to conventional control approaches, MPC shows greatest potentials in order to

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increase energy efficiency. Nonetheless, expert system understanding is necessary to set up a MPC. ESC, in contrary, is easy to implement, as it is a model-free method.

On the other hand, there are two approaches reducing noise emissions. The primary measures include the acoustic optimization of the components or the acoustic optimization of the operating point. Secondary measures decrease sound radiation indirectly through silencers and sound insulation capsules. This work focuses on the acoustic optimization of the operating point. Manufacturers have implemented measures, to reduce the sound emission of the heat pump during night, by changing speeds of fan and/or compressor. This procedure is normally done solely based on time of day, which is set by the installer or user. The mode is called differently ranging from "silent" to "quiet" mode of operation.

However, a simultaneous operation optimization of energy efficiency and noise emission reduction was not identified in the literature, yet. Therefore, we introduce an approach that concurrently takes energetic and acoustic optimal operation (EAO) into account. According to Burns and Laughman [2], it is possible to provide a constant cooling capacity at different compressor and fan speeds. These combinations imply different energy efficiencies as well as noise emissions. Using multi-objective optimization, we can determine the trade-off between energetic and acoustic optimal operation.

Therefore, this work contributes to the EAO operation of heat pumps:

- Chapter 2 gives an overview on the literature regarding energy efficient operation as well as acoustic signatures of heat pumps. Furthermore, we introduce the basics of ESC.
- In Chapter 3 we describe the energetic simulation model. In addition, we show the acoustic data and how it was measured. Lastly, we describe the coupling approach of both models and apply it to ESC.
- We apply ESC to our model in order to simultaneously optimize acoustic emission and energetic efficiency in Chapter 4.
- Chapter 5 discusses results conducted before.
- We summarize our findings and give an outlook in Chapter 6.

2. State of the Art

In order to replace conventional heating technologies such as gas- or oil-fired boilers heat pumps need to be improved economically, ecologically and user-friendly. Therefore, increasing their energy efficiency and decreasing their noise emissions have an integrated potential to accelerate the replacement process.

2.1. Energetic assessment of heat pump systems

A common instantaneous thermodynamic measure for heat pump's energy efficiency is its *COP*. The *COP* is described as the quotient of heat extracted from the condenser $\dot{Q}_{\mathrm{Cond}}$ divided by the power to drive the compressor P_{Comp}:

$$COP = \frac{\dot{Q}_{\mathrm{Cond}}}{P_{\mathrm{Comp}}}. \tag{1}$$

Different studies use the *COP* as target function to determine the heat pump with highest efficiency according to different refrigerants or operating points. Using this target function an optimization program maximizes the condenser heat $\dot{Q}_{\mathrm{Cond}}$ and minimizes the compressor power P_{Comp}.

In order to introduce a simultaneous approach to optimize energetics and acoustics, the fan power has to be taken into account as well. Therefore, we introduce the system's coefficient of performance:

$$COP_{Sys} = \frac{\dot{Q}_{\mathrm{Cond}}}{P_{\mathrm{Comp}} + P_{\mathrm{Fan}}}, \tag{2}$$

which sums up the power consumption of the fan P_{Fan} in the denominator. This consideration allows an energetic assessment of both noise sources.

Considering the heat pump as a heat supply system, however, implies that the building's heat demand is fixed. As consequence, a heat pump system has to deliver a fixed amount of heat at a minimized sum of compressor power and fan power. Since we have no heat pump prototype yet, we assess the potential of EAO in a realistic simulation study. Conducting simulation studies requires an energetic heat pump model.

In the literature, many modelling approaches of heat pumps are widely discussed. Typically, approaches distinguish between black box, grey box and white box modelling. On the one hand, black box approaches allow a fast calculation of heat pump's behavior within a certain validated scope. Results from physical extrapolations, however, are restricted applicable.

On the other hand, white box models emulate real physical system with its geometrics. Therefore, complete understanding of the system is necessary. This modelling approach reveals the advantage of perfect system behavior estimation. In contrary, calculation speed is often very low.

A trade-off between both black box and white box approach is called grey box approach. It bases on physical equations to estimate its behavior and simplifies equations at some points by mathematical descriptions. Hence, we apply a grey box approach to estimate the physical behavior of the heat pump at reasonable simulation speed. In addition, we need information about the component's acoustic signature itself in order to determine their acoustic behavior.

2.2. Acoustic signature of heat pumps

Acoustic emissions of heat pumps can be retrieved using a variety of methods. For certification purposes – depending on the acoustic characteristics of the climate chamber - sound intensity measurements using scanning techniques or sound power measurements with a number of microphones distributed in the climate chamber are performed. According to the standards – in the end – one value for the sound power level will be given on the label for the standard operating point. This also means, that the transient behavior of the sound emission, the directivity of the sound emission and the effect of operating the heat pump at different conditions is not covered. For the measurements, which are the base for the simulations presented here, an acoustic dome with 61 microphones was used to record the acoustic sound pressure level at positions surrounding the heat pump as a function of time (see Figure 1). The data can then be used to calculate the transient A-weighted sound power level.

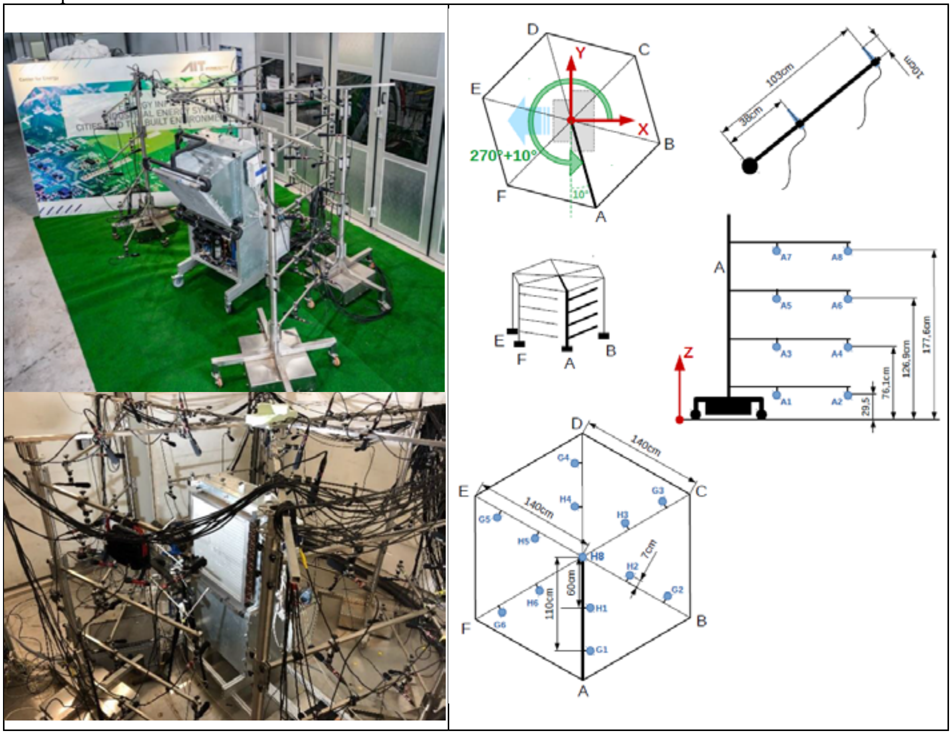

Fig. 1: Presentation image of a part of the acoustic dome around the SilentAirHP (top, left), which has been used to generate the data and SilentAirHP (bottom) in the climate chamber at AIT surrounded by the acoustic dome during frosting experiments; Geometrical setup of the acoustic dome. 48 microphones are placed on the sides, 13 microphones above the heat pump (right).

In order to simultaneously optimize heat pump's energetics and its acoustics, an optimization procedure is necessary. In this work, we therefore apply a model-free, adaptive Extremum Seeking Controller.

2.3. Extremum Seeking Control (ESC) applied to heat pumps

Common adaptive control methods, the two linear and non-linear, aim to control the output of a process to a known set point or a reference trajectory. The aim of ESC, however, is to find a manipulated variable, so that the variable to be controlled is kept at a minimum or maximum [3]. The manipulated variable is therefore disturbed periodically by a perturbation signal. This results in an oscillation of the system output. By determining the gradient between the manipulated variable and the system output, the manipulated variable can be modified so that the system output is optimized. Applying ESC, in addition to a target function t an amplification factor K and the parameters of the gradient estimator, must be determined.

In contrast to MPC, this is a model-free procedure. For the application of ESC in real processes, no model of the controlled system must exist. The method was already used in the 1950s [4] and has gained in importance due to the stability proofs of Krstic and Wang [5] in 2000. In the last 10 years, ESC has established itself as a promising control strategy for energy optimization of HVAC devices [6, 7]. In the Literature, simulation studies exist in which ESCs are tested on simulation models as well as studies in which it was implemented on test benches.

Burns and Laughman [2] applied ESC with conventional gradient estimation for the first time to a chiller in 2012. They investigated the fan's influence on the electrical power consumption of the entire plant. The temperature was kept constant by controlling the compressor speed. They were able to determine that at a constant cooling capacity different, equivalent combinations of compressor speed and fan speed exist. The electrical power consumption of the system was reduced from 700 W to 450 W by ESC. This corresponds to an improvement in the COP from 2.9 to 4.4. In their experiment, the nominal fan speed was almost doubled, and the compressor speed was reduced to the minimum frequency of 35 Hz. After activation, the algorithm took about two hours to reach the optimum.

Koeln and Alleyne [8] implemented ESC with classical gradient estimation in 2014. They investigated the influence of the expansion valve opening on subcooling. For cost reasons, the installation of a pressure sensor at the compressor outlet often is renounced. Subcooling is therefore unknown and cannot be controlled. The authors used ESC to find an optimal expansion valve opening for COP-optimal subcooling. They improved the COP by 9 %. The algorithm took three hours to reach the optimum.

The work of Xiao et al [9] deals with a multivariable ESC. By simultaneously optimizing the speeds of the evaporator's and condenser's fan of an air-to-air heat pump, the power consumption was reduced from 625 W to 325 W.

Burns et al. [10] developed a gradient estimator based on a recursive-least-square estimator. Thereby they were able to reduce convergence time by a time scale. They investigated the influence of the temperature at the compressor outlet on the electrical power consumption. By using ESC to determine the optimum target value for the outlet temperature, they were able to reduce the power consumption from 535 W to 450 W. This corresponds to a 14% improvement in COP. In subsequent work by Burns et al. [11] in 2018, the performance of ESC was further improved and the convergence time was reduced to 50 minutes in an experiment.

The literature review shows that a great potential exists to optimize HVAC systems using ESC. A contribution that simultaneously optimizes energetics and acoustics of heat pumps was not identified, yet. Therefore, we show in Chapter 3 the methodology to apply ESC in order to optimize heat pump's energy efficiency and its acoustics during operation.

3. Dynamic modeling of a vapor compression system

Since we have no prototype of a heat pump at our institute, yet, we firstly set up two heat pump models: one for its energetic and one for its acoustic behavior. In a second step, we connect both models. Therefore, we link the compressor's and fan's noise emissions according to their rotational speeds. Lastly, we define the target function and apply ESC to our simulative prototype.

3.1. Energetic Modeling of Vapor Compression System

Regarding the trade-off between accuracy and simulation speed, we choose a grey box approach to model our system's components. The used components are taken from the Aixlib [12], an open-source Modelica library. Therefore, we use following approaches to model all components.

Based on efficiency correlations, the compressor model is validated against measurement data. We use energy and mass balances according to state changes based on these efficiency correlations. We apply the same approach to model the expansion valve. The heat exchangers are modeled using the Epsilon-NTU method. At

the evaporator air-side, we implemented an additional Nusselt correlation to model the behavior of heat transfer as a function of air velocity. Applying energy conversion and mass continuity, air velocity is cubic proportional to the fan power.
A simple PI-controller controls heat pump's supply temperature by adjusting compressor's speed. Another one keeps a constant level of superheated vapor at the evaporator outlet by controlling expansion valve's opening.

3.2. Coupling acoustic measurement data to dynamic energetic simulation model

Using a highly symmetric hexagonal setup, 61 microphones are surrounding the heat pump (see Figure 1, right). The microphones are calibrated with a 94 dB calibrator operating at 1000 Hz. Sound pressure levels are continuously recorded and later analyzed using Fast Fourier Transformation FFT techniques to be able to access the A-weighted sound power levels as a function of time.

The SilentAirHP is an experimental air-to-water heat pump which was designed to provide a heating power of 5 kW at a heating water temperature of 35 °C at an ambient air temperature of 2 °C. The refrigerant R410A was used and the entire heat pump was located inside the AIT climatic chambers during the measurements. Inside the chamber, the temperature and the humidity could be defined and kept constant. The heating water was cooled with the in-house chilled water reservoir guaranteeing a sufficient heat transfer from the condenser, whereby the back flow of the heating water was regulated to 30 °C. The compressor was operated with a controllable rotational speed (a speed of 98Hz corresponds to a 5 kW heating power at 2 °C outdoor temperature and 35 °C warm-water temperature). An internal controller, which uses the superheating of the refrigerant as reference variable controlled the degree of opening of the expansion valve. The superheating was always set to 7 °C during the experiments.

Typical experiments at a given operating point yield the transient sound power level together with the transient thermodynamic parameters of the climate chamber and the heat pump (see Figure 2).

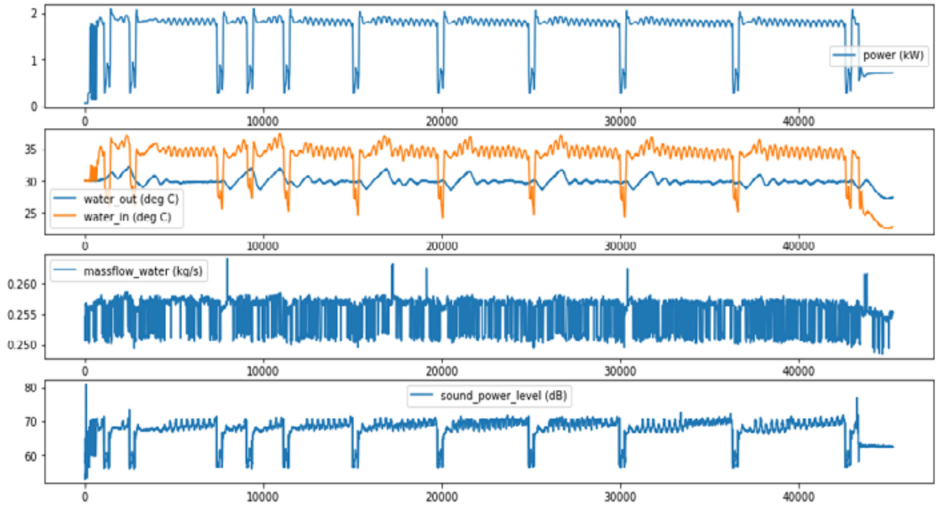

Fig. 2: Transient thermodynamic and acoustic data during a typical experiment. These measurements results are the basis of the following implementation.

In order to use these experimental sound power level results as basis for ESC, we re-write them according to their dependency of fan speed and index of third octave band. This allows us to couple the presented energetic model to its acoustic signature at a rotational speed. Additionally, increasing simulation speed, we use a fitting procedure to describe the dependency of sound power level on the rotational speed at a certain octave band. The fitting procedure increases calculation speed at an accuracy of $RMSE$ = 0.66, which is within measurement uncertainty.

Using the AIT's Sound Source Extension Library (SSELib) [13], the energetic model can be extended by an acoustic interface. The library has components that can be used to determine the propagation of sound in air, the effects of silencers and the location. In addition, several sound sources can be superimposed. In order to couple acoustic measurement data with an energetic simulation model, the acoustic signature is correlated with the rotational speed of the respective component.

This coupling of energetics and acoustics enables us to underline the conflict between energy efficiency and sound emissions. Regarding a common operating point at an air temperature of 7 °C and a water temperature of 50 °C (short: A7W50), our model is now able to calculate its energetic and acoustic performance, which are shown in Figure 3. According to a fixed heat demand as discussed in Chapter 2 and in Burns and Laughman [2], there are many combinations of compressor speed and fan speed to match the demand. By increasing the fan speed at a constant heat demand, the heat transfered from the ambient to the refrigerant increases so that compressor speed can decrease. In addition, this causes an increase in *COP* (blue dashed line). Applying systems *COP* (blue line) one can observe an increase to a certain maximum. After that the system *COP* decreases again. This means up to this maximum the power consumption of the fan increases more than the power consumption of the compressor decreases. The maximum is the energetic maximum in this operating point.

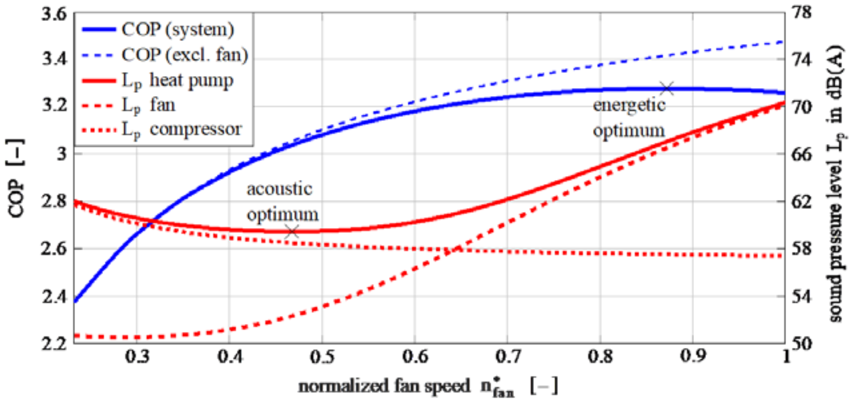

Fig. 3: The conflict of objectives between energetic efficiency and acoustic emissions of an air-to-water heat pump. The heat pump control provides constant heating output and a superheat of 5K. Above a threshold value, the increase in electrical power of the fan is greater than the resulting decrease in electrical power of the compressor. This point represents the energetic optimum of the system. The varying speeds of compressor and fan result in different acoustic emissions of the components. The noise level of a heat pump (compact design) is determined by the logarithmic addition of the compressor and fan emissions. For this operating point (A7W50), the acoustic optimum is at lower fan speeds compared to the energetic optimum.

The varying speeds of compressor and fan lead to different acoustic emissions of the heat pump as well. An increase in the fan speed leads to an increase in the sound pressure level caused by the fan. The effect of the compressor is the opposite: as the fan speed increases, the compressor speed and thus, also the emitted noise decreases. Both sound sources were added logarithmically. Since the components were measured individually and under the same structural conditions, this is permissible. Due to the acoustic dominance of the fan, the acoustic optimum lies at lower fan speeds. The simulation study shows that the operating points for the acoustic and energetic optimum do not coincide, resulting in a conflict of objectives.

Furthermore, the Figure shows a Pareto effect between energy efficiency and acoustic emission: A comparatively small deviation from the energetic optimum results in a disproportionately reduction of sound emission. For a normalized speed of n^{*}_{Fan} = 0.7, the coefficient of performance of the system is reduced from $COP_{Sys,energ.}$ = 3.27 to COP_{Sys} = 3.23. This means a reduction in energy efficiency by 1.22 %. The acoustic emission drops from $L_{p,energ.}$ = 67.24 dB(A) to L_p = 62.2 dB(A). Thus, by reducing the system efficiency by 1.22 %, the noise level emission can be reduced by ΔL_p = 5.04 dB(A). This Pareto effect is used in the following sections to achieve EAO.

The respective optima are strongly dependent on the ambient temperature and the heat demand. This results in the optima shifting during heat pump operation. In order to solve the conflict of objectives, a real-time-capable, adaptive optimization algorithm must therefore be selected. In addition, the procedure should be easy to implement and operate without complex measurement technology in order to enable economical application in new heat pump systems. One possibility is MPC. However, this technology has very high requirements on model accuracy and model speed, which makes practical implementation more difficult [14]. For this reason, research on model-free adaptive optimizers has intensified in recent years. This includes ESC, the suitability of which to solve the described conflict of objectives is examined in the following.

3.3. Extremum Seeking Control Design

In order to apply ESC, it is important to define a gradient estimator and an objective function. In our case, we use a simple benchmark model to identify the gradient estimator that fits best. Common gradient estimators are a combination of high-pass and low-pass filter (simple perturbation PB), a recursive-least-square method (RLS) and a Kalman filter (Kalman).

Former researches showed the functionality of a gradient estimator using a simple so called Hammerschmidt model [10]. Using this model, they were able to benchmark different gradient estimators.

The results of the three ESCs are shown in Figure 4. Models are started with a constant value of u = 2. After 100 s, ESC is activated and all ESCs converge to the optimum at y* = 1. The curves of the RLS-ESC and PB-ESC correspond to the literature [10]. The control signal u of the PB-ESC oscillates strongly according to its parameterization. This results in the oscillation of the output signal y. The control signals of the RLS-ESC and the Kalman-ESC also oscillate. Due to the lower magnitude of their amplitudes, this is not visible in the Figure. The PB-ESC converges after 470 s (not shown in the Figure), whereas RLS-ESC and Kalman-ESC show similar convergence times about 35 s. Concluding this test, we use the Kalman filter as the gradient estimator in the following simulation studies.

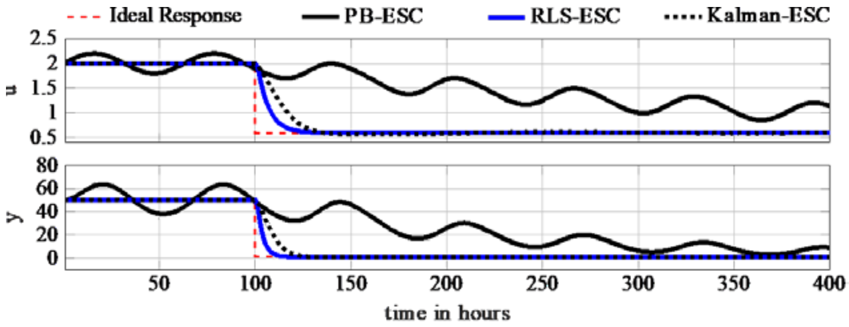

Fig. 1 Graph of the manipulated variable u and output variable y with ESC on a Hammerstein model. PB-ESC has a significantly slower convergence time than RLS-ESC and Kalman-ESC. RLS-ESC and Kalman-ESC show simuliar performances with convergence times about 35 s.

Additionally, ESC requires an objective function to be implemented. In order to consider the compromise between energetic efficiency and acoustic emission in the simulation model, a corresponding objective function is defined (Equation 3). The *COP* is not suitable to evaluate the energetic efficiency of the heat pump, as the transferred heat output at the condenser must be determined for this purpose. The flow temperatures and the mass flow of water must be known (or alternatively the condensation temperature and the mass flow of the refrigerant) respectively. Measuring the mass flow is particularly complex and therefore expensive. With respect to our optimization problem, electrical power data of compressor and fan, on the other hand, have the same informational content to implement the target function. In addition, the electrical power of both can easily be measured or recorded without great effort, which makes this approach favourable. Therefore, the minimization of compressor's and fan's power consumption defines the first part of the objective function. The acoustic emission of the heat pump is specified by the sound pressure level and depends on the design. We distinguish design between compact and split design as it is common in air-to-water heat pumps. Regarding both, the target function (TF) is defined as follows:

$$TF = \min a \underbrace{\frac{\sum_i P_{\text{el,i}}}{\sum_i P_{\text{el,max,i}}}}_{\text{Energetic}} + (1-a) \underbrace{\frac{\sum_i L_{\text{p,i}}}{\sum_i L_{\text{p,max,i}}}}_{\text{Acoustic}} \tag{3}$$

The left term contains the energetic evaluation of the current operating point and the right term contains the acoustic information. The terms are normalized with their maximum values for comparability. With the parameter a, which assumes values between zero and one, the operating point to be controlled can now be specified:

- a = 1: Energy-optimal operating point
- a = 0: Acoustically optimal operating point

Setting a = 1, the ESC will converge to the energy-optimal solution, while for a = 0, the quietest operating point is set. For values 0 < a < 1, a continuous weighting between energy-optimal and acoustically-optimal operating point is possible.

In general, objective functions for ESC need to be convex to ensure optimization. Figure 5 shows the objective functions for split and compact design. Compact design (left) is composed of the acoustic emission of compressor and fan. The acoustic emissions of the split design (right) are determined solely by the fan. Obviously, both are convex, since the terms used to describe energetics and acoustics are convex as well.

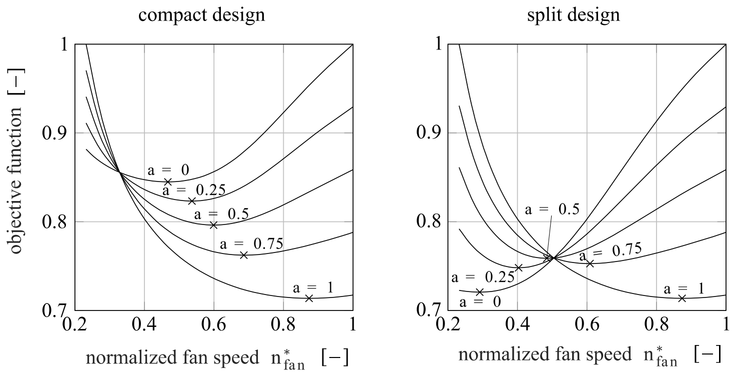

Fig. 5 The target function of the ESC at A7W50. With parameter "a", a continuous trade-off between energy-optimal (a = 1) and acoustically-optimal operation (a=0) can be achieved.

4. Simulation Study

Applying ESC to our heat pump model, we use two setups. First use a fixed condition setup to evaluate the functionality of ESC. Therefore, we choose the operating point A7W50 as it was discussed in Chapter 3 as well. After proving functionality, we discuss a use case with realistic and highly dynamic boundary conditions.

4.1. Fixed Condition

First, the general functionality of the ESC is to be tested using Kalman-filter as a gradient estimator. For a constant operating point (A7W50), the models are initialized with constant fan speed. After 200 s ESC is activated with different values of EAO factor "a". In addition, the manipulated variable n^*_{Fan} is perturbed with a square wave oscillation with an amplitude of A = 0.02 and a frequency of f = 0.06. The frequency of the oscillation is set to 0.06. The frequency of the square wave oscillation is set to 0.02. The amplification factor K is set to K = -0.0075.

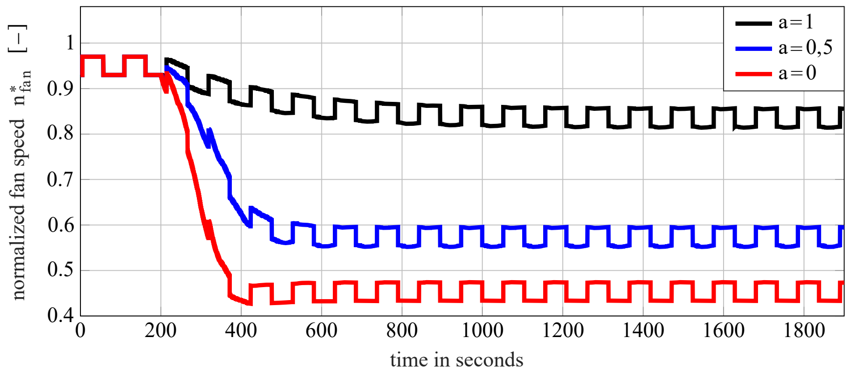

Fig. 6 Kalman-ESC with different values for parameter "a" at A7W50 and compact design. ESC is activated after 200 seconds and the steady-state values correspond to the optima in Figure 5.

According to Figure 6 energetic optimal control (a=1) fits to the corresponding energetic optimum at $n^*_{Fan} = 0.873$ resulting in a *COP* =3.27 and L_p=67.1 dB(A). Setting a=0 (acoustic optimal control), ESC finds the acoustic optimum at $n^*_{Fan} = 0.467$ with *COP*=3.04 and L_p=59.46 dB(A). In between, setting a=0.5, EAO is determined by ESC to be at $n^*_{Fan} = 0.598$ resulting in a *COP* = 3.19 and L_p=60.2 dB(A). All in all, this Figure shows a successful implementation of ESC to enable EAO.

4.2. Realistic Condition

After the basic functionality of ESC has been demonstrated, the acoustic and energetic effects for a realistic 24-hour operation will be quantified. The heat demand which is to be covered by the heat pump is shown in the Figure below (Figure 7). The ambient temperature varies between 2°C and 6°C. The maximum flow temperature is 58 °C.

Three scenarios are compared with each other for this purpose. First, the ESC is deactivated and the fan speed is set to nominal fan speed (1000 rpm). For the other two scenarios, the ESC is activated and the parameter "a" is set to constant a=1 in one scenario. This results in energy-optimal operating points. At last, the parameter "a" is varied depending on the time of day. Therefore, this day is split in three parts. At night (10 pm to 6 am), we define a silent mode at a=0.4. In the morning (6 am to 8 am) and in the evening (8 pm to 10 pm) we increase energy efficiency by setting a=0.8. At the rest of the day (8 am – 8 pm) we set a=1. The results of ESC are shown in Figure 7.

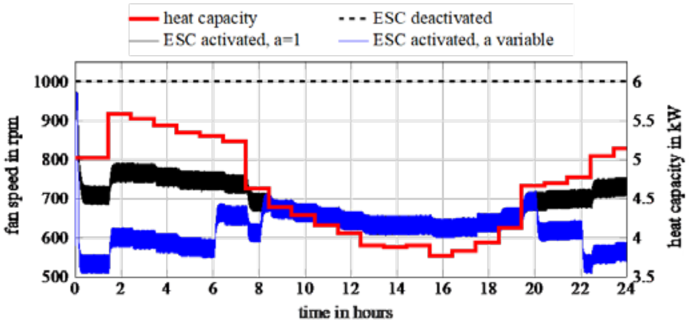

Fig. 7 ESC at variable operating conditions (24-hour heat demand profile). Fan speed curves for three different scenarios: Constant nominal fan speed (black, dashed), active ESC with constant a = 1 (blue), active ESC with daytime-dependent values for parameter "a".

When ESC is active, the fan speed is always significantly lower than the nominal speed. For scenario 3, the fan speed is lower in the morning, in the evening and at night than in the energy-optimal scenario. During the day (8 am to 8 pm), the rated speeds of scenario 2 and 3 are identical, as both are approaching energy-optimal operating points. For the scenario with constant fan speed, the compressor power is consistently lowest and the electrical consumption of the fan is constant at 200 W. If the heat output is provided in an energy-optimal way, a higher compressor output is required than in scenario 1, but therefore the fan power can be reduced significantly. For example at 4 am, the compressor power differs from scenario 1 to 2 by $\Delta P_{el,comp.}$ = 71 W, while the fan power decreases by $\Delta P_{el,Vent.}$ = 115.5 W. The comparatively high difference between the fan outputs of the two scenarios is based on the cubic relationship between fan output and fan speed. The maximum saving is 98 W. Over the entire period 1.63 kWh can be saved, which corresponds to a reduction in electrical energy consumption of 3.75 %.

In nominal operation (scenario 1) the sound emissions vary between 70.6 dB(A) and 70.9 dB(A) and are dominated by fan emissions. While the fan emissions are constant, the compressor emissions fluctuate with the heat demand. In energy-optimized operation, less noise is emitted due to the reduced fan speed. The sound pressure level varies between 65.1 dB(A) and 60 dB(A), which represents a volume reduction between 5.8 dB(A) and 10.9 dB(A). This leads to a reduction of the subjectively perceived volume by up to half. The acoustic emissions can thus be significantly reduced without the acoustics having any weight in the target function of the ESC. In this scenario, the fan is the dominant component for noise emissions. In scenario 3, noise emissions can be further reduced compared to energy-optimal operation. The sound pressure level fluctuates between 62.6 dB(A) and 59.7 dB(A). In periods where the parameter "a" does not assume the value one (0-8 h and 20-24 h), the compressor is the dominant component in noise emission.

5. Discussion

The challenges of the presented procedure lie in the implementation and parameterisation of ESC in a real heat pump. Since heat pumps have time delays due to the thermal intertia of the heat exchangers, the convergence time of the algorithm is limited. The achieved convergence times are not yet representative due to the simplified dynamic modelling of the heat exchangers. In the experiment, it has to be shown that the convergence time of the algorithm is fast enough to ensure economic use.

Experiments from the literature show convergence times between one and three hours. However, a comparison is difficult because these are largely dependent on the distance between the initial manipulated variable and the optimum manipulated variable. If it can be excluded that ESC changes the manipulated variable against the optimization direction due to measurement errors or incorrect parameterization, ESC leads to an improvement of the current state, even if the algorithm has not yet converged to the optimum.

In addition to the convergence time, the parameterisation of the gradient estimator on a real heat pump is also challenging since the dynamics of the heat exchangers slow down the parameterisation process. Because these dynamics are not yet realistically represented by the simulation model, the parameters of the gradient estimator used in this paper probably deviate from test bench parameters. It is expected that the frequency must be reduced in order to counteract the slow dynamics and a possibly poor controller design. Due to loss mechanisms, interference influences and measurement uncertainties, the course of the system output cannot be attributed exclusively to the perturbation of the manipulated variable. In order to quantify the influence of perturbation, the amplitude of the perturbation must therefore be increased if necessary.

Depending on the heat pumps surrounding's, further improvements of factor "a" estimation can additionally be deduced. Therefore, we suggest installing an internal heat pump microphone. This microphone is on the one hand able to measure the heat pump's acoustic environment. The factor "a" can be set to a reasonable value depending on environment's acoustics. On the other hand, a high frequent microphone yields to applications of predictive maintenance because high frequency changes can indicate aging effects.

6. Conclusion and further work

In this work, the conflict of objectives between energetic efficiency and acoustic emission is addressed. The analysis is based on the fact that a constant heat demand at the condenser can be realized by a multitude of combinations between fan power and compressor power. A simulation study shows that the acoustically optimal combination of compressor and fan power does not correspond to the energetic optimum, thus creating a conflict of objectives. A comparatively small deviation from the energetic optimum can reduce the noise emission disproportionately. This Pareto effect is used to achieve optimal energetic-acoustic operation. With the help of the adaptive, model-free Extremum Seeking Control, any states between energetic and acoustic optimum can be realized by means of an objective function. For the first time, acoustics is implemented as a variable to be optimized. The energetic and acoustic effects are quantified based on a realistic 24 h heat demand profile. Compared to nominal operation, the energy efficiency of the system can be increased by 3.75 % with ESC, while at the same time the noise emission decreases by up to 10.9 dB(A). This means that the subjectively perceived volume is halved.

This procedure increases the two system efficiency and user comfort. This work, thus, contributes to the development of new control concepts, which, in addition to energy efficiency, can also optimize and evaluate the sound emission of heat pumps. No additional measurement technology needs to be installed on the heat pump to apply the presented method. However, an experimental evidence is necessary to take heat exchanger dynamics into account.

For the next steps, a microphone can be attached to the heat pump to improve the assessment of acoustic emissions. This allows location-dependent factors, such as the installation location, to be considered within the optimization process. High-frequent microphones can also be suitable for predictive maintenance.

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