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Non-invasive method of measuring the liquid level in refrigerant receivers

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Abstract

Natural refrigerants are becoming increasingly important as more attention is being paid to environmental protection in the use of refrigeration systems and heat pumps, and the associated regulations (e.g. the F-Gas Regulation and in the future the REACH Regulation). However, these refrigerants are typically flammable and/or toxic. This has led to strict regulations and increased demand for leak detection. A low-cost sensor that can measure the liquid level of refrigerant in receivers or accumulators would facilitate the development of refrigeration circuits and remove barriers to the use of natural refrigerants

As part of the 'CLEAR' project, various non-invasive measurement methods for level measurement in refrigerant tanks were investigated in order to trigger a potential sensor development.
With a non-invasive technique a potential sensor would not be exposed to the pressures and temperatures in the refrigeration circuit. This potentially enables a cost-effective sensor design. Furthermore, a sensor could also be retrofitted into existing refrigeration systems. The investigated methods can be used for a continuous determination of the liquid level and/or act as level switch in receivers of refrigeration systems and heat pumps during operation. The availability of such a sensor would enable condition-based diagnostics and open the door to further applications such as predictive maintenance.

As part of the 'CLEAR' project, various measurement principles were evaluated and tested on different test benches. This article summarizes how the most promising measurement method works on the test rig and highlights some of their advantages and disadvantages.

Keywords: Non Invasive sensing, level measurement, refrigerant receivers*;*

1. Introduction

This paper deals with the verification of non-invasive measurement principles for liquid level measurement in liquid receivers integrated into a refrigerant circuit. The reliability and efficiency of heat pumps and refrigeration systems are important for their successful use in future energy systems. A common fault that negatively affects both is the loss of refrigerant via leakages [1]. Not enough refrigerant, known as an undercharge, may lead to a decrease in the system's capacity and efficiency [2]. Thus, it results in higher energy consumption and, depending on the refrigerant, a direct environmental impact [1].

1.1. Condition-Based Monitoring

To handle these issues preventatively, the industry is moving towards condition based monitoring (CBM) [1]. The technical basis for CBM is provided by Fault Detection, Diagnosis, and Evaluation (FDDE) systems. These systems use data to detect, identify, and evaluate faults in real-time [2].

1.1.1. Classification of Diagnostic Parameters

A reliable FDDE system uses a baseline model that predicts healthy operation. A fault (e.g.: leakage of refrigerant, fouled heat exchangers, etc.) is found when measured parameters are different from this predicted baseline. Indirect fault detection operates on the principle of deviation analysis [3]. A fault is not identified by absolute parameter values but by a significant deviation of a measured parameter from an expected "baseline" that corresponds to healthy operation. This baseline is not static; it uses a dynamic model that predicts the healthy state based on the current operating conditions, such as ambient temperature and system load. These conditions are essential model inputs, not fault symptoms themselves.

The parameters can be put into three separate groups:

- Operating Conditions:
  These are external factors that cannot be controlled. They describe the operating situation for the system.
  - Examples: Outdoor and indoor air temperatures, humidity, and user settings (load).
  - Role: They are the main inputs for the baseline model. They define how a healthy system should act under the current conditions. They are not signs of a fault.
- Control Response Indicators:
  These are the active control actions the system uses to meet the demand. They show the "effort" the system is using.
  - Examples: Compressor speed, expansion valve position, and fan speed.
  - Role: If these indicators are different from their predicted baseline (for example, a higher compressor speed than expected for a certain load), it is a sign of a fault that reduces performance [4].
- Thermodynamic State Indicators:
  These are measurement data that show the results of the system's operation. They describe the physical state of the refrigerant circuit.
  - Examples: Superheat, subcooling, evaporating and condensing pressures, and compressor discharge temperature.
  - Role: They are the classic symptoms that show the results of a fault.

1.1.2. Application of Parameters to System Architectures

How useful these indicators are for leak detection depends heavily on the system's design, especially if it has a refrigerant receiver.

- For Systems without a Receiver:
  In these systems, any refrigerant loss immediately results in difference between the “healthy” and the actual refrigerant flow. The system's reaction is immediate and can be seen in two steps.
  The control system tries to fix the problem. This causes the Control Response Indicators (e.g., expansions valve opening, compressor speed) to deviate from their baseline. This action is not enough. This leads to problems in the thermodynamic cycle, which can be seen as a change in the

Thermodynamic State Indicators (e.g., higher superheat, lower pressures). These indicators are immediate and effective signs for finding a fault.

- For Systems with a Receiver:
  The receiver acts as a buffer, which hides the fault, in this case disappearing refrigerant. As the refrigerant leaks, the receiver adds liquid to the circuit and compensate the loss. This hides the fault by stopping the first symptoms from showing up.
  To detect a leakage early in these systems, i.e. before it affects the system performance, a fourth type of indicator is needed: a Mass Inventory Indicator. The liquid level sensor in the receiver is a parameter that does this job. It directly measures the total amount of refrigerant and is not hidden by the buffering effect. A steady decrease in its level is a clear difference from its baseline (a full or stable level). It is therefore a early sign of a leak [5]. The other indicators are only useful for late detection, after the receiver is empty.

1.2. Measurement principle

The evaluated principle is an active excited vibration measurement method involving excitation by an external impact. The reviewed literature suggests that the underlying phenomenon for the evaluated vibration frequencies is surface vibrations of the container, often called shell vibrations. The vibration frequency of liquid-filled containers changes with the liquid level, which acts as an added mass and alters the resonant properties of the structure. For example, the curves presented by Sanchez-Diaz et al. [6] show a similar frequency trend as a function of the liquid level to the fill-level-dependent frequencies found in the thesis of Eder [7] using a so-called natural vibration method. This paper demonstrates that the identified vibrations can be detected even under various operating conditions in an active refrigeration circuit. For this purpose, effects on the measurement method caused by cross-sensitivities from real operating conditions must be taken into account.

1.3. Excitation & data analysis

In the thesis by Eder [7], the excitation of the refrigerant receiver is performed using an impulse hammer. The data acquisition and evaluation are described in detail in the thesis [7]. For the following explanations, the most important evaluation steps are summarized in Figure 1, illustrating the step-by-step procedure. For this, Prony's method [8] was used to obtain an energy spectrum (Step 4) with various frequencies. This method models the signal as a sum of damped sinusoidal components to estimate the frequency, damping, magnitude, and phase of each mode (Step 3). After the excitation (Step 1), a time window (green, Step 2) of the decaying vibration is selected. Prony's method is then applied to create an approximation (orange, Step 3) of the original signal (blue, Step 3). Step 4 shows the energy spectrum of the vibration frequencies from the approximated signal curve. All signal energies presented in this paper were determined using the described method.

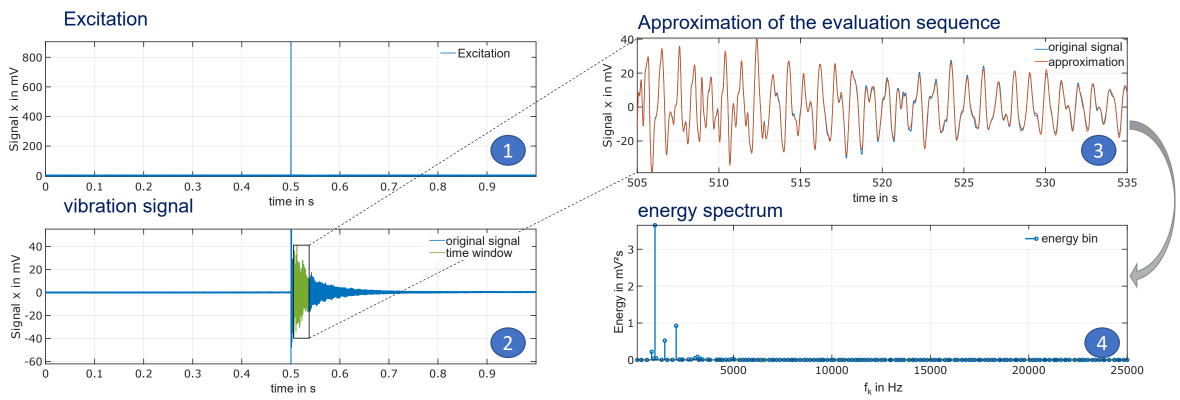

Figure 1: Sequential data analysis

2. Experimental Methodology

A test rig with a refrigerant circuit was constructed that allows the level in the receiver of the active refrigeration circuit to be varied without changing the operating parameters (e.g., compressor frequency, ambient temperature, heat source temperature, expansion valve position, etc.). The following section describes the setup of the test rig as well as the various operating points.

2.1. Test Rig

For the investigation of the measurement principles a refrigerant circuit was equipped with the necessary measurement equipment (position 01 to 07 in Figure 2). The refrigeration circuit is charged with the natural refrigerant R290 (propane). The setup enables for the precise adjustment of operating conditions through a controllable heat source (50% monoethylene glycol) and its positioning in a climatic chamber, with air as heat sink.

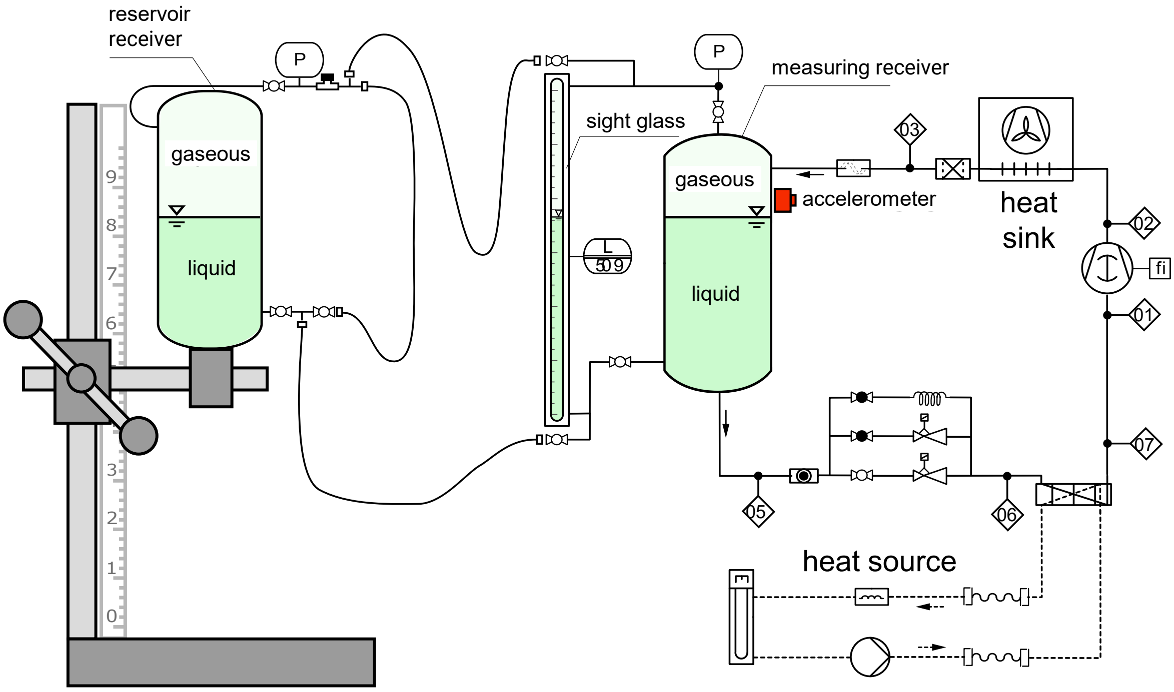

Figure 2: R290 refrigerant circuit with reference measurement and receiver for adjusting the liquid level

Compression from 01 to 02 is performed by a rolling piston compressor (displacement 17,2 cm³). The compressor speed can be varied by a frequency converter (30 to 120 Hz). From 02 to 03, heat is rejected to the air (climatic chamber) via a microchannel condenser. In the receiver (04 to 05; 0,88 dm³) the gas and liquid phases of the refrigerant are separated as long as a liquid level is present. From 05 to 06, the refrigerant is expanded through an electronic expansion valve - which is operated at a constant opening, i.e. as a fixed orifice - and from 06 to 07, heat is supplied to the refrigeration circuit via the controllable heat source.

Building upon the work of Pertiller et al. [9], the test rig was upgraded with an automated excitation system to improve reproducibility

2.2. Experimental Procedure

For the measurement campaign, the height-adjustable reservoir was connected to the refrigeration system described in Figure 2 using flexible hoses and was then evacuated. After evacuation, the reservoir and the refrigeration system were hydraulically connected by opening several ball valves. As a final step, a leak check was performed using a leak detector.

In this configuration, the refrigeration system was started up sequentially. The heat source was controlled to maintain a constant inlet temperature, and the condenser fan was activated. In the second step, the compressor was set to a constant speed for the respective test. The electronic expansion valve was operated as a fixed orifice by setting to a constant value. This ensured steady-state operation, and fluctuations in the receiver caused by transient operation of the refrigeration circuit could be minimized.

For the experiments, the level in the receiver was adjusted using the height-adjustable reservoir. Once the desired level was established, the reservoir and the refrigeration system were hydraulically isolated by closing two ball valves to minimize any potential influences from this connection.

Using a script, the measurements required were performed:

- Capturing the reference level
- Performing hammer strike experiment for the active vibration measurement
- Finally, capturing the reference level again

To add further insights to the promising findings from Pertiller et al. [9], various aspects were systematically investigated. For this purpose, 33 liquid level measurement points were performed per measurement series (Figure 3, left). Since frequency converters are often used in heat pump applications, assessing the influence of different compressor frequencies (f_{comp}, 40 Hz, 50 Hz, 75 Hz, and 90 Hz) is of high interest. These four measurement series were conducted at a constant climatic chamber temperature (t_{amb}, 25 °C) and a constant evaporating temperature (t_{evap}, 10 °C). To assess the influence of the excitation position, for the 50 Hz compressor frequency series, the excitation position was changed to 60° (φ, Figure 3, right), to ensure comparability all other measurement series were exited with the excitation position 90° (φ). To estimate the influence of temperature on the measurement, two additional operating points were performed at a 50 Hz compressor frequency. For this, a low "machine room temperature" of 5 °C (climatic chamber temperature, t_{amb}) was set, and the evaporating temperature was reduced to -10 °C (t_{evap}). For a high "machine room temperature" of 40 °C (t_{amb}), the evaporating temperature was set to 15 °C ($t_{evap'}$). This results in a total of 1155 individual measurements, derived from the 7 described measurement series, 33 liquid levels (measurement points) per operating point, and 5 measurements (impacts) per fill level. Table 1 summerises the Conditions for each measurement series.

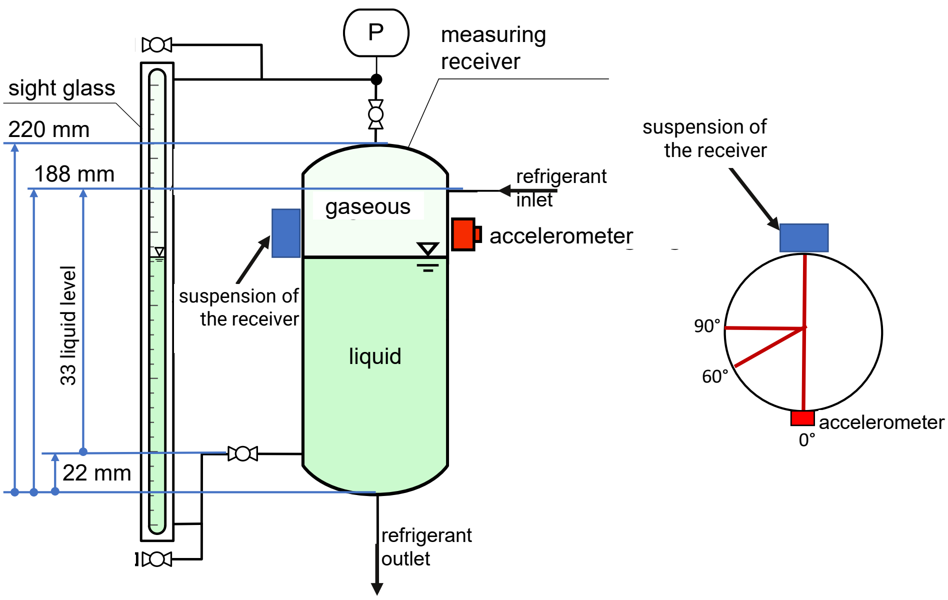

Figure 3: Close-up of the receiver (left) and variation of the excitation position (right)

Table 1. Measurement table: for each series 33 liquid levels and at every level 5 impacta (measurements) were performed.

measurement series	f_{comp} (Hz)	t_{amb} (°C)	t_{evap} (°C)	φ (°)
1	90	25	10	90
2	75	25	10	90
3	50	25	10	90
4	40	25	10	90
5	50	25	10	60
6	50	40	15	90
7	50	5	-10	90

3. Results

In order to keep the 1155 individual measurements comparable, each measurement was "normalized". For this purpose, the maximum energy value of the individual measurement was set to 1 and all other values (of this measurement) were referenced to this value. Figure 4 shows an example. For the overview in Figure 5, only the energy bins above 0.2 (red line in Figure 4) were shown as colored ring, for all individual measurements.

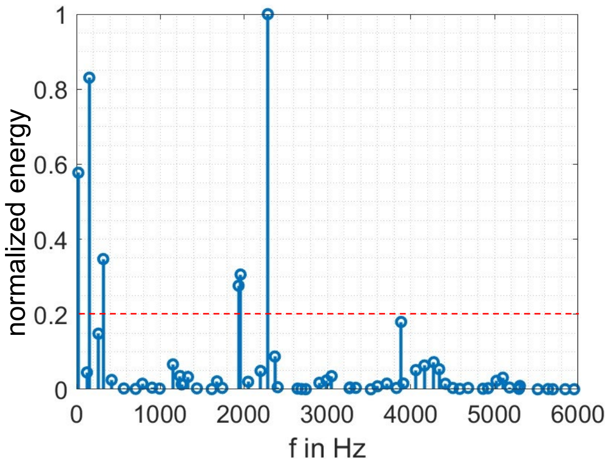

Figure 4: Signal energy bins for an exemplary measurement (measurement series 2, liquid level 150 mm, impact 4)

3.1. Overview

Consistent with the hypothesis that the underlying effect is a surface vibration, the analysis of the signal energies reveals distinct frequency bands. These bands might correspond to the natural vibration modes (shell vibrations) of the container's structure. The resonant frequencies of these modes are known to be sensitive to the liquid level, as the liquid acts as an added mass that alters the dynamic properties of the structure. Shell structures, such as the receiver, exhibit various mode shapes (e.g., circumferential and axial modes), each with its own characteristic frequency. Therefore, the appearance of several distinct, liquid-level-dependent frequency bands in the experimental data supports the initial hypothesis.

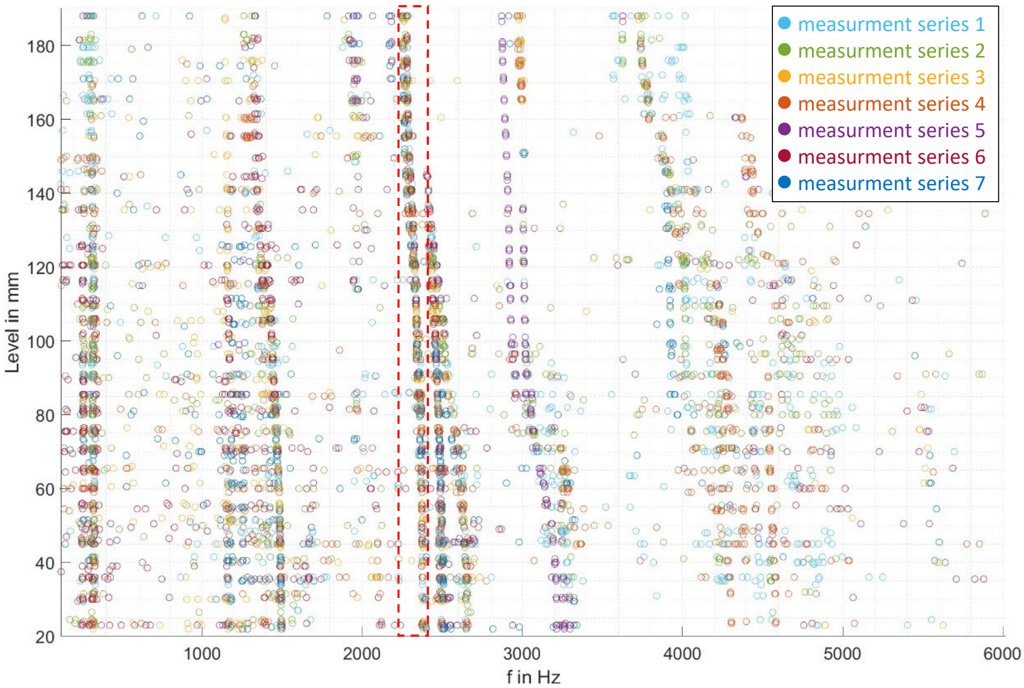

Figure 5: Signal energy bins (above 0,2) for all measurement series

Figure 5 shows the signal energy bins for all 1155 measurements. It is evident that energy bins occur at different frequencies. This leads to the conclusion that the value of signal energy bin alone is an insufficient indicator for the evaluated spectrum, which was low-pass filtered above 6,000 Hz. The band marked in Figure 5 (2240 to 2400 Hz) is particularly notable because the energy bins occur in a similar form in all measurement series (1 to 7).

In the following subsections, the highlighted "band" are processed for measurement series 2 and are then supplemented with the mean values from the measurements of the remaining series.

3.2. Analysis of the frequency band 2240 to 2400 Hz

Figure 6 shows the analysis of the data points for the measurements of the previously described exemplary measurement series 2 (ambient temperature 25 °C; compressor frequency 75 Hz; 10 °C evaporating temperature; 90° impact position). The green circles correspond to the mean values of the five impacts, while the transparent markers each represent a single impact. The bars correspond to the difference between minimum and maximum of the measurements from the corresponding mean value. The blue diamonds correspond to the trimmed mean of the five measurements, calculated by ignoring the maximum and minimum values, i.e. a mean value of 3 data.

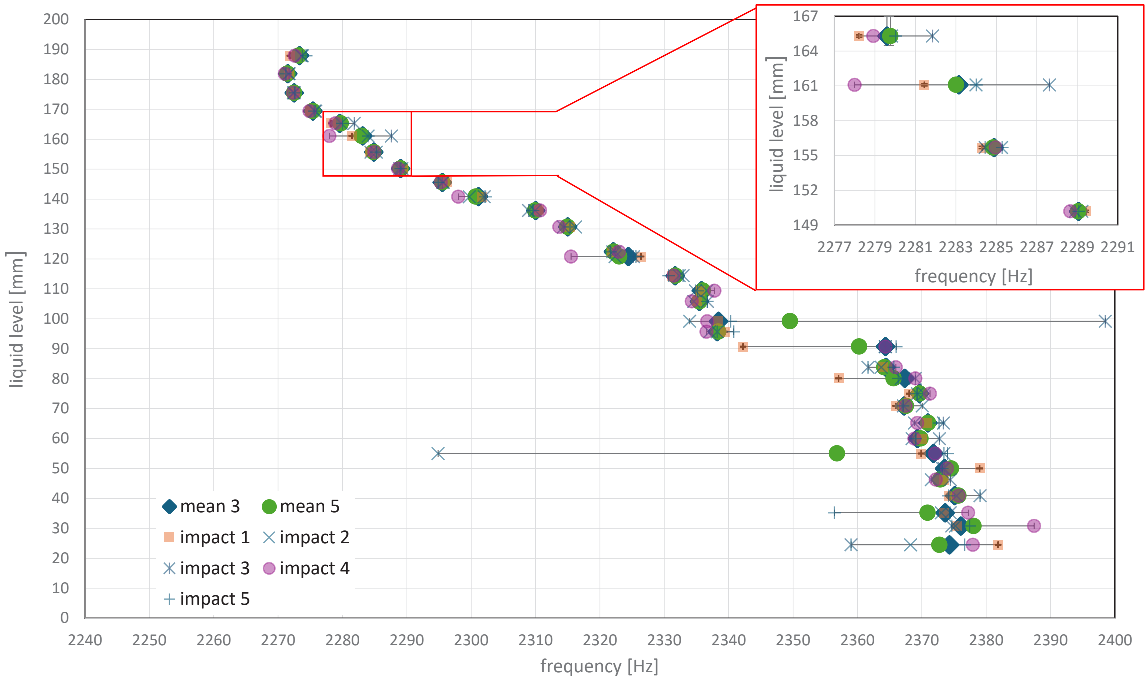

Figure 6: Frequency-liquid level correlation (2240 to 2400 Hz) for measurement series 2 (at ambient temperature 25 °C; compressor frequency 75 Hz; 10 °C evaporating temperature; 90° impact position)

As can be seen in the section highlighted in red (Figure 6), all measurements have been entered. Since many of the individual measurements are very close to each other, there are hardly any differences from the mean values (mean 3 & mean 5). This in turn indicates good reproducibility of the measurement principle near the sensor position. In the boundary regions (at low liquid levels), this relationship becomes not clearly recognizable, and the measurements can no longer be uniquely assigned to a specific level. This scatter can be reduced by calculating the mean value, a common technique to improve signal quality by mitigating the effect of random errors and outliers.

The measurements indicate that reproducible frequency curves as a function of the liquid level are achieved when the liquid surface is near the sensor. However, at low liquid levels, where the distance between the sensor and the liquid is greater, the reproducibility of the measurement results decreases.

The following figure 7 shows the mean values of the five impacts per liquid level for all seven measurement series at 2240 to 2400 Hz.

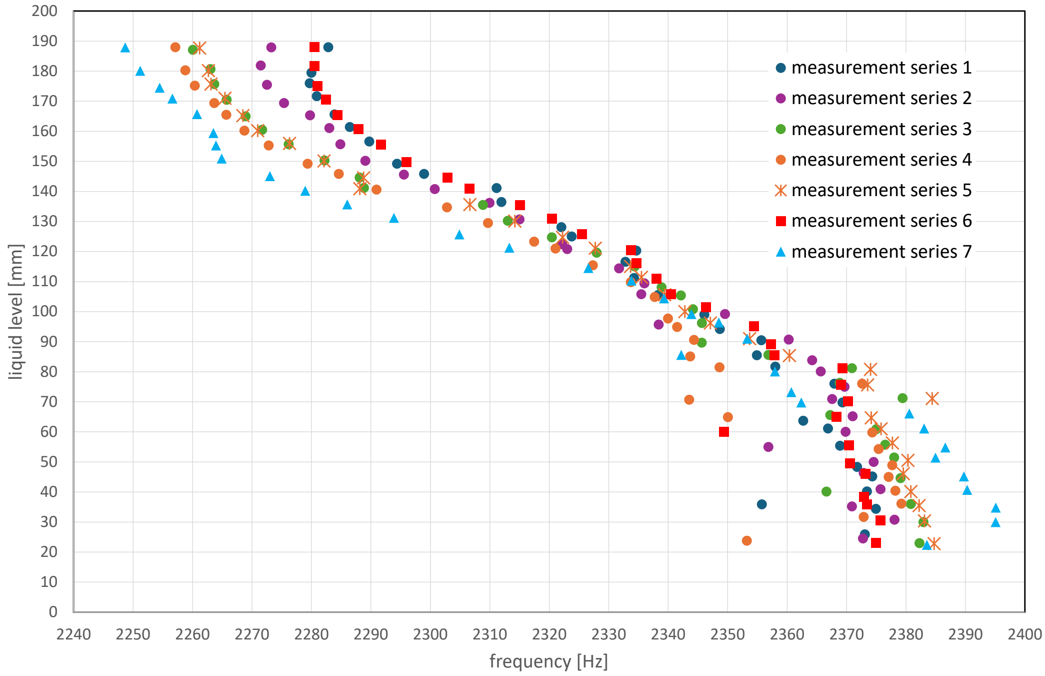

Figure 7: Frequency-liquid level correlation (2240 to 2400 Hz) for all measurement series

At different operating points, a frequency drift can be observed at high fill levels. A possible explanation for this behaviour is the influence of refrigerant liquid density, which varies with saturation pressure. At high liquid levels, the total mass of the liquid has a stronger impact on the measurement result. Consequently, the frequency curves are more significantly affected by changes in liquid density. This corresponds with the plotted limit curves for the minimum (red square) and maximum liquid density (blue triangle). The measurement series 3 (green dot) and 5 (orange cross) differ only in the impact position. The other operating parameters were identical in the measurements, which were carried out independently of each other. The curves are close together, which indicates good reproducibility.

Based on this finding, further investigations will be conducted with different sensor and impact positions in the next step to improve the sensitivity at low liquid levels.

4. Discussion & Outlook

The measurements presented in this paper demonstrate the fundamental suitability of actively induced vibration measurement for non-invasive liquid level detection. The basic feasibility was proven using an impact excitation. Initial analyses indicate that cross-sensitivities, such as compressor frequency and ambient temperature, appear to be manageable; however, this requires more detailed investigations in the future.

Future work will focus on several key areas. First, the precise operating range for clear level detection must be defined, and the optimal sensor position must be identified. For a practical implementation, the impact excitation must be replaced by an alternative method; the use of a transducer represents a promising option. Further measurement series will be conducted to validate the results from the modified excitation position under various operating conditions. In parallel, modal analysis simulations will be employed to verify the hypothesis that the measured frequencies are attributable to surface vibrations of the system.

Finaly after clarifying some of the described questions a project dealing with the sensor development is planned.

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