Structural vibration analysis of a commercial refrigerator

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Abstract: We focused our examination on the transmission mechanisms of vibration for a commercial refrigerator. Previous studies imply that the biochemical properties of cooled goods are susceptible to vibration. In order to prevent the cooled good's quality from being degraded by external influences it is vital that optimal storage conditions are assured. Protection against ultraviolet light and minimization of vibration are a necessity for conserving quality and prolong-ing shelf life. We list different excitation sources that showed potential to affect commercial refrigerators and quantify their impact on the system behaviour. We considered the operational behaviour, surrounding influences and human interactions with the refrigerator. Utilizing previous works, we used a novel robust algorithm for operational transfer path analysis and estimated the different transmission paths within the refrigerator and its links to the environment. Operational Deflection Shape analysis allows us to combine the results of the previous Transfer Path Analysis into a mathematical model of our system that enables visualisation of points of interest. The measured data and calculated derivates are then used to propose optimisations in design and control. Finally, we investigate the effectiveness of vari-ous measures that either shift resonance frequencies of the refrigerator components into spectral ranges that show lower excitation or introduce additional damping.

Keywords: structural dynamics, vibrations, system identification, operational transfer path analysis

INTRODUCTION

A multitude of research concerning cooling devices has been performed focusing on various aspects. Most commonly the vibroacoustic analysis (Bailif and Laughlin, 1959; Tojo et al., 1980; Takushima et al., 1992; Çelikkan and Erol, 2017) elaborated on the psychoacoustics and the impact of engineering on the emission of vibrations in the audible frequency ranges. A smaller subset of studies investigates the transmission of structural vibrations (Kuyumcuoğlu and Sakalli, 2014; Sayer and Greussing, 2016) but these works tend to narrowly focus on an active component, e.g., a compressor or a fan, and its immediate surroundings.

Continuous exposure to vibration was shown (Chung et al., 2008) to affect the biochemical properties of stored wine and the changes became more significant at higher vibration levels. Optimal storage conditions necessitate (Tao, Garca and Sun, 2014) protection against ultraviolet light and vibration to prevent the reduction of aromatic components and the formation of undesirable flavor and taste. While some goods (Crandles et al., 2016) tend to be robust against these outside factors others (Nikolaev et al., 2012) are particularly susceptible to these effects. Human cells are vulnerable to cold environments and the coupling of cold storage and vibration leads to membrane rupture and cell death.

In this paper, we will investigate different sources for the vibrations inside a commercial refrigerator and propose improvements to reduce the exposure of the cooled goods within.

MEASUREMENTS AND DATA ANALYSIS

The examined cooling device of type Liebherr WTes 5872 Vinidor has a net weight of 134 kg and can store up to 178 Bordeaux bottles. We placed current-fed piezoelectric transducers (IEPE/ICP) at sensitive locations and recorded the structural vibrations. Corners of the steel-frame, the shell of the compressor and the cooled goods within the refrigerator were measured using triaxial sensors. Locations with a known mobility in a predominant direction were measured with uniaxial sensors. We constantly recorded the ambient temperature in order to consider the variations in the viscosity of the rubber dampening elements.The refrigerator was directly placed on the floor made of concrete to ensure realistic coupling to the surroundings. We selectively examined different sources for excitation:

- During normal operation, the refrigerator autonomously regulates its components. The compressor and the fans operate to keep a steady internal temperature of +6 °C.
- Using a debugging device, interior fans are selectively activated or deactivated.
- Using the debugging device, the compressor is set to several predefined running speeds.
- Utilizing an electromechanical shaker, we actuate the shell of the compressor while the refrigerator is off the electrical grid.
- External sources are simulated by walking and working in the surroundings of the device.
- External influences are measured. The refrigerator door is opened and closed. Loading and unloading of goods is investigated.

Processing of measurement data

To reliably observe low-power vibrations, we need to minimise the influence of uncontrolled additional vibrations from the environment. All measurement cycles were conducted with a vacated laboratory.

By calculating a part-transmissibility function that specifies the relation between the point of interest and a constantly measured reference point, which is fixed for all measurements, the susceptibility to external noise can be greatly reduced. The H_4-estimator (Kühlert, Markert and Witfeld, 1991) was shown to improve the performance of TPA (transfer path analysis) estimations (Hörtnagel, Plagg and Dohnal, 2021) and leads to robust results. The most important part of conducting
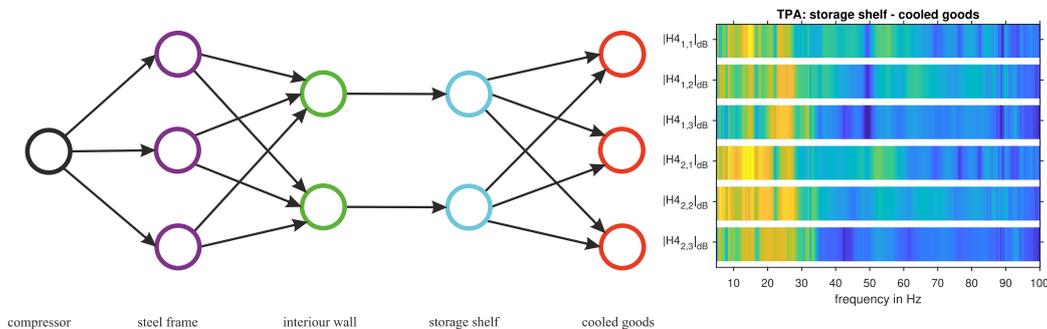

Figure 1 – A constellation of connected paths for a TPA (left) and an examplary result of the calculations (right) that visualizes the transfer paths between the wooden storage shelf and the cooled goods. The light colored areas in the plot indicate frequencies that are only weakly damped within this sub-path.

a TPA is the definition of the investigated pathways. Having a clear path is more important than utilizing all available sensor positions. One problem is the overlapping influence of different vibration sources. When using external sources, e.g., an electromechanical shaker, the strength of the respective input may be disproportional to its operative behaviour. It is thus advisable to calculate independent transfer paths for each source instead of combining it into one complex model. The mathematical workflow for a TPA as described in (Gajdatsy et al., 2010) can be summarized in the following way, that utilizes Tikhonov regularization.

If the transfer pathways are determined, the core issue of a TPA becomes estimating multiple-input-multiple-output dependencies $\mathbf{T}$ between an input $\mathbf{X}$ and an output $\mathbf{Y}$. Finally, the results are visualized in false color plots as seen in Fig. 1.

Operating deflection shape analysis

The ODS (operating deflection shape) analysis is used to visualize the spatial movement of the investigated object and is similar to the modal analysis. It works best in static operation conditions but if the internal excitation is too weak, an additional external excitation can be necessary. Using a shaker at static frequency one can calculate the Fourier transform of all signals for the chosen frequency. Variation of the excitation frequency enables the calculation of a spectral frequency response that should be refined through the previously mentioned H_4-estimation process (Kühlert, Markert and Witfeld, 1991). The positions and the measuring directions of all sensors are known and can be input into a spatial model of the device. The calculated transmissibility functions from the reference point can then be visualized as a spatial distortion that is dependent on the frequency of the excitation. Using an arbitrary scaling factor all sensor positions are moved according to this transmissibility function in a sinusoidal way. The amplitude indicates how big this movement should be and the phase is a delay. The frequency of the visualized oscillation is not relevant.

The resulting images can be put side by side or an animated video can be produced that shows the movement of the device at this frequency. If the investigated frequency is a natural frequency of the device, distinct modal shapes will be visible. Otherwise, the modal shapes will overlap into the cumulative behaviour. Figure 2 shows a high mobility of the shelves and slight bending of the entire frame. This can be used as the basis for future design decisions.

IDENTIFICATION AND QUANTIFICATION OF VIBRATIONAL SOURCES

The different sources should be identified as independently as possible. The following workflow was used.

Several acceleration sensors are evaluated simultaneously, one is placed at the selected site of excitation and the others are unevenly distributed on the cooled goods. For the first measurement, the refrigerator was off the grid and the laboratory was vacated. The base excitation through the surroundings was measured including the measurement noise of the sensors. Then we measured the impact of different isolated external sources by selectively performing different tasks in the vicinity, opening the refrigerator and manipulating the cooled goods. Next, the refrigerator was plugged in and switched on. A debugging device allowed the deactivation of the compressor and the selective activation of the fans. Then the fans were deactivated and the compressor was set to work at varying frequencies. Finally, the refrigerator was

activated to hold a temperature of 6 °C autonomously without interference. A long-term measurement was conducted to show the impact of uninterrupted operational conditions and to observe the autonomous activation and deactivation of the compressor. We used the measured data from the selective activation of the compressor to substitute the movement by externally exciting the compressor with the electromechanical shaker, thus isolating the compressor movement from the subsequent movement of the cooling fluid within the pipes. This procedure allows us to prioritize the development time efficiently and quantify the impact of different vibrational sources.

×   point of measurement

⊗   non-measured symmetry-point

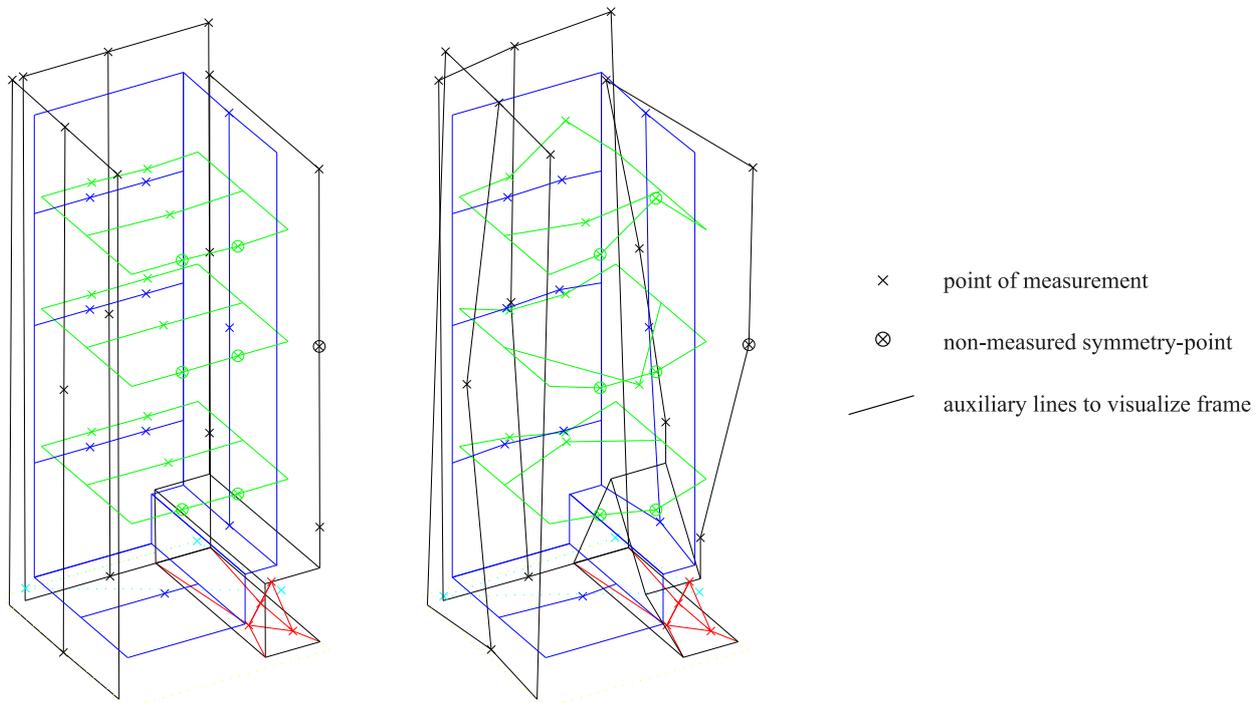———   auxiliary lines to visualize frame

Figure 2 – Visualization of a ODS analysis at a specific frequency. All points are measured and the lines connect the sensors to aid visualizing the original form of the device. High mobility of points indicates low stiffness and low mobility indicates that the points are only weakly excited by the measured source. This visualization can be helpful for future design decisions, e.g., stiffening of mobile areas.

RMS (root mean square value) measurements of the vibration of the cooled goods are the simplest way to quantify the impact of different vibration sources but these numbers are not to be used directly. We assumed the squared RMS-values of the combined excitation to be the sum of the squared independent excitation sources. This allows the reduction of the operational RMS-measurement by the base measurement, acquired in the previously mentioned first measurement cycle, and enables us to independently quantify the impact of the cooling fluid moving through the pipes by comparing the active operation of the compressor with the substituted shaker movement.

Now that the immediate impacts of all sources are quantified it is necessary to make assumptions about the general use-case. How will the behaviour average over 24 hours? How often is the door opened? How often will someone walk by with light/heavy steps? Opening the door resulted in oscillating spikes of 8500 mm/s^2 that were fully damped within 2 s. The impact of these numbers highly depends on the rate of occurrence. We assumed that within 24 hours the door is opened 10 times, for 5 hours there is light work in the surroundings with people walking lightly and for 15 minutes each day there is heavy lifting in the vicinity.

RESULTS

Utilizing the discussed methods, we calculated the impact of the different vibration sources. This study established that only 29% of the vibration at the cooled goods can be attributed to the operation of the compressor. By quantifying the source contributions, we could prioritize future development and suggest likely solutions. The calculated transmissibility functions for vibrations that are excited by the compressor show that this device has several natural frequencies in rpm-ranges that are suitable for compressor operation. Operation within selected frequency bands hardly excites the cooled goods, minimizes the exposure to vibration and has the additional potential to reduce the audible noise. The optimisation of the rotational speed could reduce the source impact of the compressor by 80%.

We attempted to reduce the vibrational impact from external influences by introducing elastic rubber plates below the refrigerator. The plates were 20 mm thick and have a spring constant of 300 kN/m. Using these additional dampeners reduced the susceptibility to vibrations from external sources by 52%. With the help of data analysis gained from the

TPA and ODS, new areas of interest have been identified that will be addressed in design reviews. By combining these optimisations the cooled goods will be exposed to significantly reduced amounts of vibrations. These improved conditions facilitate long-term storage without degradation of quality.

CONCLUSIONS

In this paper, we investigated various methods to analyze vibrations within multi-body systems. We have listed possible workflows and explained the applicability of the methods for different circumstances. Using our investigated refrigerator model we have shown clear results of our measurements and suggested immediate solutions. Various parameters can be optimized in order to reduce the exposure to vibration. The multi-lateral source investigation enables a prioritization of development resources and highlights areas of interest.

ACKNOWLEDGMENTS

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